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Walking patterns of individuals with and
without Developmental Coordination
Disorder

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Abstract

Developmental coordination disorder (DCD) is defined by the DSM-5 as an impairment of motor coordination significantly affecting everyday activities. Given the importance of walking to access everyday activities, and the constraints to movement experienced by individuals with DCD, this area of research is particularly pertinent. This thesis aimed to investigate step characteristics in individuals with and without DCD and to identify factors linked to poor locomotor ability in the DCD group. An initial study was conducted to investigate walking patterns on *level ground*. This investigation was extended by examining gait adaptations whilst traversing an *irregular terrain*. Additionally, the effects of *visual occlusion of the feet* on gait patterns were investigated. Finally all the above manipulations were analysed *across age*.

Thirty-five individuals aged 8-32 years (children 8-12y; teenagers 13-17y; adults 18-32y) with and without DCD participated in this study. Participants walked continuously for 2 minutes around two cones placed 6m apart. A VICON 3D motion analysis system tracked the motion of small reflective markers attached to the feet, legs, trunk and head.

Findings were discussed within a hybrid theoretical framework, integrating ideas from Gibson's ecological systems (1979), Newell's constraints model (Newell 1986) and internal modelling, thus acknowledging the importance of input from several systems to enable proficient walking patterns. Findings showed that on level ground individuals with DCD walked with a reduced step length, greater flexion about the ankle, higher step-to-step variability and were more asymmetric compared to their typically developing peers. When traversing the irregular terrain individuals with DCD walked more slowly with shorter, wider steps and inclined their heads more towards the ground than their TD peers. There was no evidence to suggest that visual occlusion of the feet affected the walking patterns of individuals with or without DCD. Finally, age effects were almost exclusively noted for the teenage age group who walked with a wider step and had significantly more step-to-step variability than children or adults whilst traversing the level terrain.

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Chapter 1: Motor control and Developmental Coordination Disorder

1.1. Introduction

The ability to move is an essential skill that allows interaction with our environment. The ability to move *efficiently* and *adaptively*, improves the ease with which environmental interaction takes place. However, whilst movement is an ability many take for granted; it is not a simple task, as it involves the coordination of many different body segments. Even seemingly simple movements such as those required whilst putting on trousers or socks require the coordination of the head, trunk, arms and legs, whilst simultaneously maintaining balance over a very small base of support (the foot). Movement therefore arises from the cooperation of several processes, such as the biomechanical organisation of muscles and joints into smooth coordinated actions. It is also heavily reliant upon perceptual processes particularly proprioception (the ability to sense location, orientation and movement of the body), vestibular (sense of balance) and vision (Hulme & Snowling, 2009). When all these systems develop and integrate efficiently, motor skills manifest as accurate and fluent movements with smooth transitions from one action to another during a sequence of movements (Geuze, 2005).

Some movements occur automatically, such as blinking whilst others require conscious thought such as dressing or handwriting. Many movements are so well practiced that they appear almost automatic. Movements such as postural control and walking, whilst still voluntary, require very little cognitive input in most everyday situations. Many pedestrians can ‘subconsciously’ encode environmental conditions and adapt their posture and walking pattern to accommodate a wide variety of situations. These can vary from changing terrain (differences in gradient or texture) to the avoidance of obstacles in the pathway which may be stationary or moving.

There are, however, several constraints to adaptive movement about the environment which exist within and between the individual, the environment, and the task (Shumway-Cook & Woollacott, 2012). The processes needed to walk adaptively around the environment provide a good example of the relationship between these constraints. For example, in order for an *individual* to generate the movement (swing of leg) required to walk (*task*) within a specific *environment* (along a cobbled pavement), the individual must be able to assimilate external environmental conditions such as the gradient and texture of the pavement with any individual qualities that might constrain movement. However, in addition to the biomechanical demands required to swing the multi-segmented limb (thigh, shin, foot) forwards, this must be

simultaneously coordinated with the other leg that has to support and balance the whole body. As described above, one legged balance is challenging when standing still, but whilst walking the balance constraints are exacerbated because the movements need to be coordinated as the whole body moves forwards. These observations predict that any individual constraints to balance may negatively affect the walking task, particularly if the surface terrain is uneven which may further affect the ability to remain balanced. Therefore, the individual's ability to meet interacting task goals and environmental demands requires efficient, accurate and flexible perceptual interpretation that can be easily assimilated within the constraints of the individual's motor system.

Given the complexities of processes needed for effective walking and the importance of walking to access many activities of daily living, the subject of locomotion provides the focus of this thesis. This chapter will discuss motor control and theoretical approaches pertinent to the study of locomotion. It will continue with a description of Developmental Coordination Disorder (DCD), a population who present with reduced speed, accuracy and fluency when performing motor tasks compared to their typically developing peers (Henderson, Rose & Henderson, 1992; van der Meulen, Denier van de Gon, Geilen, 1991) and who have been shown to have difficulties integrating visual, proprioceptive and vestibular information (Wilson & McKenzie, 1998). These deficits may affect how efficiently they adaptively walk within the environment. The chapter will continue by addressing some of the issues concerning terminology, definition and the application of diagnostic criteria for DCD. Finally, using the theoretical frameworks relevant to DCD, a literature review will explore the research investigating mechanisms that might underlie the motor difficulties for individuals with DCD.

1.2. Motor control

1.2.1. Theoretical approaches

There are several different theoretical approaches pertinent to the study of motor control, which have evolved over time. Early theories, such as Reflex theory (Sherrington 1947) focussed on the Central Nervous System (CNS) and the importance of reflexive behaviour as a basis for movement. Sherrington (1947) argued that complex motor behaviour resulted from the synchronised action of individual reflexes. This theory was expanded with the idea of a hierarchical influence on movement behaviour. Hierarchical control implies that successively higher cognitive input is used to exert control over the level below, and is referred to as 'top-down' control. Magnus, (1925) proposed that motor control is hierarchically organised with reflexes contained at the lower levels. Gesell (1954) refined this hypothesis by arguing that the

development of motor skill is attributed to the maturation of the Central Nervous System (CNS). Gesell proposed that motor control is initially controlled by low-level reflexive movements, which are refined as the system matures, and higher level cognitive input takes over control. More recent theories of motor control, particularly relating to repetitive movements like walking, have explored the concept of a central motor pattern which is not entirely reliant upon reflexive behaviour. Researchers such as Grillner (1981) argue that spinal networks produce locomotor rhythm (in cats) in the absence of reflexive action or sensory input, and he argues for a Central Pattern Generator in humans which is a neural circuit within the spinal cord responsible for the stereotyped rhythmic pattern used for walking (discussed in more depth in Chapter 2). Further experiments by Forssberg (1985) showed that ‘innate pattern generators’ are present in human infants during the first 2 months of life, but are also modulated by sensory input later in life to enable a functional step pattern to emerge. If locomotion was controlled completely by central pattern generators the human body would be unable to change speed or adapt to the differing terrains and environmental conditions. In order to do this adaptively humans need sensory feedback.

Motor theory continued its evolution by considering the relationship between perceptual information, and motor control. For example, Information Processing Theory is based on the premise that humans *process* information, rather than merely responding to it. Information provided by sensory modalities (vision, audition, tactile and proprioceptive etc.) provides the ‘input’ to the brain (characterised as a computer, Haywood & Getchell, 2009), which is then processed and ‘output’ is achieved as a movement. Information processing theory predicts that as the brain matures movement improves as the ability to respond to sensory information is refined. This reciprocal arrangement between perception and movement supports the development of both skills simultaneously.

1.2.2. Dynamical Systems theory

The Dynamical Systems Approach to motor development explains how the multiple systems within the body (central nervous system, perceptual systems, muscles, joints and limbs) all interact with systems outside the body such as gravity and the environment. Dynamical systems theory differs from maturational theory in that it considers the development of many systems, rather than just maturation of the CNS, and argues that constraints to motor control change over a lifetime. The dynamical systems approach also differs from information processing theory, which implies that movements are controlled by a central executive using information received from the sensory systems. However, a central executive would be overwhelmed by the level of

processing required for each and every voluntary movement humans make, and movement controlled in this way would be highly inefficient.

Further approaches to develop understanding of movement control were proposed by Bernstein (1967) who argued that in order to fully understand movement, the body needed to be considered as a mechanical system subject to the internal forces caused by movement and the external forces of gravity. He also argued that a major constraint to the achievement of efficient and smooth movements is that the human body contains many anatomical subsystems comprising joints, segments and muscles. Bernstein's hypothesis of co-ordination dynamics (1967) compliments the dynamical systems approach as it recognises that the multiple sub-systems involved in movement are complex. Bernstein noted that the human body has many different joints which can flex and extend and also rotate independently, producing many different 'degrees of freedom' which need to be controlled. This flexibility about the joints complicates the control of movement. To resolve this problem Bernstein proposed that the sub-systems cooperate with one another to form 'synergies' or groups of muscles that work together to produce systematic and coordinated movement. This organisation reduces the many degrees of freedom around the joints (Kelso, 1995) consequently assisting in controlling the body to create a unified mechanical system that can interact efficiently with the environment.

Even though the multiple subsystems can interact in an almost infinite variety of ways, the topology of movement (the arrangement of constituent parts) tends to be organised into stable and distinctive patterns (Kamm, Thelen & Jensen, 1990). Thus one of the key elements to dynamical systems theory is defining the *collective variable*, or essence, of a particular movement. The collective variable attempts to reduce the multi-dimensional system in terms of a few key characteristics. These variables are tracked longitudinally to see if they remain stable over time and therefore become an *attractor state* representing the dynamical system (Clark & Phillips, 1993). For example, locomotion can be carried out functionally in a variety of ways, such as crawling, bottom-shuffling, bi-lateral walking, hopping etc. (Whitall & Getchell, 1995) but the multiple sub-systems self-organise themselves into the most energy-efficient behaviour (bilateral walking). These attractor states are not obligatory but the system will return to this pattern even when perturbed. For example, inter-limb coordination during locomotion does not have to alternate at 180° out-of-phase relationship, but it is known to be a stable pattern both for walking and running which is robust from the onset of walking through to adulthood (Clark & Phillips, 1993; Thelen & Smith, 1996). The development of attractor states illustrates the 'soft-assembly' (Kugler & Turvey, 1987) of mechanisms to self-organise into a preferred state within the context of a specific environment and task. Soft-assembly contrasts with hard-wiring

(Thelen, 1992) which describe behaviour controlled by pre-existing schemas such as the innate pattern generators previously discussed.

Thelen and Ulrich (1991) investigated the phasing of the two legs for infants aged 1-7 months in an attempt to identify the collective variable for walking. The infants were supported under their arms with their legs resting on a treadmill. The action of the treadmill pulled both legs backwards, and therefore facilitated the investigation of preferred response to this external motion. The infants could respond in a variety of ways; allow the treadmill to drag their legs behind them (no response); one leg steps forwards but the other drags behind (one step); one leg steps twice but the other doesn't respond (double step); both legs swing forwards (parallel steps); stepping alternately using both legs (alternate steps). However, only alternate stepping illustrates a movement that is *not* purely a mechanical response to the movement of the treadmill itself. Alternate stepping requires a stance period where one leg remains in contact with the moving treadmill and the other is moved forward. The treadmill was particularly useful in this investigation as this alternate stepping movement is not seen in infants until the end of the first year when they begin walking. The precision of the alternation can be quantified as the relative phasing of the legs (the point in the gait cycle of one leg where the other leg begins the cycle).

Thelen and Ulrich (1991) showed that infants as young as 1 month old coordinated their legs alternately and by 7 months old could consistently perform alternate stepping movements at a variety of different speeds. Furthermore in a subsequent study Thelen, Ulrich and Niles (1987) showed that 7 month old infants still alternate their legs on a split-belt treadmill where one leg is driven at a different speed to the other. Therefore even before unassisted walking begins, both legs were coordinated in a cooperative manner and could respond to changing environmental contexts. These multiple findings provide further evidence that alternate stepping is an attractor state for walking.

Clark and Phillips (1993) further defined the attractor states for walking by exploring the *limit cycle* to describe the motion of the legs. The limit cycle describes a system that is cyclic and continuously renews energy lost during movement. For example, as the legs swing back and forth during locomotion they lose energy as the heel strikes the ground. This energy has to be replenished as the toe pushes the foot of the ground for the cyclic behaviour to continue. This continual loss and replenishment of energy is known as oscillation. As each leg oscillates through its step cycle it creates its own limit cycle which, whilst independent and closed (energy in = energy out), is coupled with the other leg. Clark & Phillips (1993) argue that these oscillatory properties of the legs (making two limit cycles) predict three interrelated properties;

Phase locking whereby the coupled limit cycle of the two legs is fixed, stable and attractive;
Entrainment whereby the oscillation of one leg is matched by the oscillation of the other leg;
Structural stability whereby the phasing relationship remains attractive even when perturbed.

Clark & Phillips (1993) used a longitudinal study to investigate the development of leg coordination for 3 infants from the onset of their first upright steps to their one year walking anniversary. Three adults were also included in the study for a comparison. Analysis of the phase portraits of the shank and thigh showed that during the early stages of walking (<3months) the limit cycle system was unstable (it was 'attracted' to a similar general region as the adult profiles but the trajectory paths were far less consistent). However, after 12 months of walking the limit-cycle regime of the shank and thigh segments became more attractive finding an adult-like stability in the coordination of the two segments. Clark & Phillips (1993) argue that these phase portraits of the shank and thigh provide a limit cycle attractor for walking. Thus there is an oscillatory limit cycle both between and within the legs as they walk.

Having argued for the importance of coordination dynamics to form attractor states, Bernstein (1967) elaborated that activation of a particular set of muscle synergies (groups of muscles working together) does not necessarily always produce the same movements. He explained that as the body moves internal forces created by movement around the joints and external forces such as gravity influence the movement and provide a continually changing framework to which the body must respond.

A good example of the influence of context on movement is that of infantine stepping. This is a phenomenon that describes the well-coordinated alternate stepping movements exhibited by newborn babies which is seemingly 'lost' by 2 months of age. Thelen and Fisher (1982) investigated this phenomenon by comparing the stepping and supine kicking patterns of 8 two-week old infants using video tapes and EMG recordings. They found that supine kicks have similar kinematic patterns to those of new-born stepping, with both behaviours beginning with simultaneous flexion of the hip, knee and ankle. However, some differences are also apparent particularly about the hip which produced a greater range of motion whilst kicking compared to stepping. The authors argue that these differences can be explained by considering the differing effects of gravity on the two behaviours. For example, whilst supine gravity assists *flexion* about the hip, as once the thigh reaches 90° it is 'pulled' towards the ground by gravity. However, to lift the leg when stepping the thigh has to pull against the forces of gravity and the range of motion at the hip is therefore reduced. The contextual differences in relation to gravity can therefore change kinematic behaviours and may offer some insight into the disappearance of

infant stepping whilst gravitational and mechanical advantages of the supine position still allow the infant to continue kicking.

Thelen, Fisher and Ridley-Johnson (1984) explored the developmental course of supine kicking and infant stepping investigating the effect of weight gain during the first 2-6 weeks of life on the rate of infant stepping. Findings showed a negative correlation between weight gain and stepping frequency; the infants who gained most weight stepped less. Thelen et al. (1984) propose that stepping behaviour is temporarily lost due to an increase in adipose tissue that reduces the strength-to-weight ratio making the leg too heavy to lift when upright. This is particularly apparent between 2-4 months of age when infants experience their most rapid period of weight gain. Thelen et al. (1984) further investigated stepping behaviour by manipulating the mechanical load for 4-week-old infants; adding weights to their legs to increase the load and submerging the unweighted legs in water to reduce the load. Results showed that when infants were submerged in water stepping (rate and amplitude) significantly increased but during the increased load condition there was a reduction in stepping. The authors suggest that new-born stepping is sensitive to environmental forces such as gravity, which together with asynchronous (occurring at different times) development of weight and strength can explain the appearance and disappearance of the infant stepping behaviour. In dynamical systems terms weight and strength would be considered *control parameters* for infant stepping, as changes to these elements of the system rendered the whole system unstable. Whilst weight gain is not a specific hindrance to stepping, at a specific point in development it can re-order the stepping behaviour.

An important element to the dynamical systems approach is the concept of *nonlinearity of developing systems*, which proposes that the maturity of the body's systems needed for movement don't always mature at the same time. Slower maturing systems or processes therefore become a constraint (control parameter) to movement. For example, learning a new skill like walking for an infant will only manifest when the slowest of all the required systems reaches the specified level of maturity (Thelen, 1989). Furthermore whilst balance, strength and postural control are all argued to be control parameters for the development of upright walking (Thelen, 1986, Bril & Breniere, 1992, Clark, Whittall & Phillips, 1988; Thelen & Ulrich, 1991) they may affect the behaviour at different times. For example, new born stepping is affected by weight gain and lack of strength (Thelen et al., 1984), but stepping behaviour for a new walker is inhibited by balance and postural control (Bril & Breniere, 1992). Therefore, as subsystems (which may be in the individual, the context, or task) mature or change they can affect the

stability of the movement. It is during transition from one behavioural state to another that the system is particularly unstable (Schoner & Kelso, 1988).

From the description of infant leg movements above we can see that dynamical systems theory assumes that the relevant multiple sub-systems compress their individual degrees of freedom to self-organise into a functional coordinated movement. However, the system as a whole is sensitive to weight, orientation (in respect of gravity), and environmental context. This sensitivity cannot be pre-programmed as the impact of variables such as gravity change as the movement progresses. Furthermore, sensitivity is very fast and precise and therefore cannot be the result of feedback from the senses; rather it emerges from the interaction of several inter-related sub-systems.

1.2.3. Ecological theory

The Dynamical Systems Approach also incorporates Gibson's (1979) Ecological Theory, which proposes that the perceptual and action systems are coupled to interpret environmental constraints and produce skilled movement. Implicit in Gibson's theory is that visual perception of information needed to perform a movement is interpreted 'directly' without any need for cognition. Gibson explains that there is a symbiotic relationship between vision and action; vision supports action by providing information about the environment and the individuals' position within it. Action supports vision by accessing rich visual information as we move through the environment. Gibson proposes that if research findings are to be ecologically valid (i.e. applicable to real world situations) vision and movement need to be considered together. Furthermore, we cannot study the individual without considering the environment they inhabit.

Gibson argued that the size and shape of objects in the environment determine the task demands for the individual, and this may vary depending upon the individual's characteristics. Gibson used the term *affordances* to describe this function, for example a chair affords an adult a place to sit, but to a toddler it affords a place to stand and hold on to. The ecological approach proposes that people assess the affordances of a task and the environment in relation to their own personal characteristics (which can change over time) rather than from an objective view point (Konczak, 1990). Furthermore, ecological theory assumes that perception of objects and events are mapped directly to the action system, predicting that the planning of a movement is implicit in the perception-action cycle. Thus movement is viewed as an emergent process arising from dynamic interaction between the individual, environment and the task.

Research by Newell (1976) has developed the ecological approach by considering how constraints within the individual (flexibility, strength, motor or sensory difficulties), the environment (environmental stability, lighting, surface type) and the task itself (moving/stationary, accuracy/speed, seated/standing) affect motor movements. For example, the *individual* needs to be able to perceive (and understand) sensory information to make informed judgements for movement. Shumway-Cook & Woollacott (2012) explain that individual constraints can be divided into three sub-components; biomechanical, perceptual and cognitive, all of which need to interact to support movement (Wilson, Thomas, Shum, Duckworth, Gugliemetti, Rudolph, Mumford & Eldridge, 2006). Furthermore, the individual's perception of the functional requirements of the *task* itself can affect the biomechanical responses used to complete the movement (Davis & Burton, 1991). Finally the *environmental* context within which the action takes place needs to be considered, this might include the properties of the ground terrain (gradient, slippery, uneven, etc.), the presence of objects in the pathway or background conditions such as lighting.

Patla & Shumway-Cook (1999) demonstrated that the ability to detect small obstacles in the pathway was hindered when walking in semi-dark conditions. Davis & Burton (1991) propose that once all the processes discussed above have been assimilated the individual can then generate the movement. However, the exact movement pattern is intrinsically linked to the individual's perception of the task together with any personal constraints which might then affect the movement outcome. The Central Nervous System (CNS) must be able to tailor the motor command to accommodate the internal state of the body, task constraints, and the external environment (Newell, 1986).

1.2.4. Internal Models

The ecological approach to motor control has a lot to commend it, particularly as it acknowledges the symbiotic relationship between the individual and their environment. However, it neglects to explain the influence of top-down cognitive input (Wilson et al., 2006) needed to plan and guide all the relevant subsystems to meet the demands of goal directed movement.

One avenue of investigation exploring the effects of cognitive input on movement is the role of neuromotor processing, particularly the use of internal models (Wolpert, 1997; Wilson et al., 2006). *Feed-forward internal models* describe a system whereby a copy of the motor command (efference copy) is sent to a forward model which provides a simulated impression of the

musculoskeletal system and the environment (Wolpert, et al., 2003). 'Feedforward' models are then used to predict the expected consequence of a motor command.

The feedforward predictions can then be used to prepare the individual for any disturbances that might be created by the outgoing motor command, so that anticipatory postural adjustments can be made. This is sometimes referred to as the inverse model which, given a future desired state, generates the necessary motor command to manifest that state. For example when lifting a heavy object the system will predict (based on previous experience) the adaptations necessary to successfully achieve object lift-off. Wolpert et al. (2003) proposes that the individual compares the predicted outcome of the movement with the actual sensory feedback and if there is a discrepancy it creates an error message. This error can then be used to inform future predictions thus refining the actual movement. Therefore, top-down cognitive input is used to monitor the accuracy of intended movements towards a specific end-goal. The ability to generate an accurate forward model of a movement is an important process used to adapt to dynamic environments.

Internal models are also used to assist with processing sensory feedback as the individual negotiates their environment. Sensory feedback is used to estimate the current state of the body; 13 proprioceptive and tactile receptors are used to estimate the location and state of our limbs in space and the terrain we walk along is visually sampled to prepare the body for future events (discussed further in Chapter 7). There are considerable time delays in the integration of sensory information to the CNS. For example, it can take up to 100ms for visual feedback to be processed (Wolpert, Doya, Kawato, 2003), which, when combined with the efferent delays (nerve impulses from the CNS to the muscles and joints) associated with movement results in an appreciable delay. These delays would be very costly to the system if they actually happened, so, to explain how humans overcome this issue Miall & Wolpert (1996) propose that the individual bypasses this relatively slow process using an internal model to estimate elements of the sensorimotor loop.

To investigate the updating process of the internal model in typically developing adults (aged 21–43 years) Assaiante, Chabeauti, Sveistrup, & Vaugoyeau (2011) used a sit-to-stand paradigm. Participants were asked to sit-to-stand and move back-to-sit from a chair where the support surface was tilted 10° forwards or to the right. Kinematic characteristics were recorded using optoelectronic motion analysis equipment. Results showed that the adults adjusted their trunk to ensure vertical body orientation in line with the inclination of the support surface, for both sit-to-stand and back-to-sit movements. The authors explain that this trunk orientation was achieved through changes in the angular positions of the lower limbs and hips. They suggest

that this response to the support surface incline illustrates the ability of the individual to *immediately* synthesise the motor planning, postural control and execution processes necessary for the new body configuration to adapt perfectly with its environment. They suggest that the individual updates the internal model, based on an efference copy (or feedforward information) of the motor command which is used to optimise motor control. For example, whilst walking on an irregular terrain, the CNS can manipulate its pre-planned motor response by utilising real-time sensory feedback, allowing fast adjustments in motor control to accommodate environmental perturbations.

1.2.5. Summary of motor control theories

To summarise, it is apparent from the descriptions above that no one approach, as yet, provides a comprehensive theory of motor control. However whilst the theories differ, they are not mutually exclusive but contribute to our understanding of motor control by describing different aspects of the underlying mechanisms of movement. For example, the early theories describing the maturation of the CNS (Gesell, 1954) or the presence of central pattern generators (Grillner, 1981) provide an explanation for the initial influences required to successfully perform motor movements. However, these theories fail to acknowledge the influence of sensory information on movement. Information Processing Theory addresses this issue, explaining how humans process sensory information to further enhance the accuracy of movement. A major criticism of Information Processing Theory emanates from the assumption that all sensory and motor information is processed through the central executive. As discussed, the system would not be able to function efficiently if this were the case.

Dynamical systems theory and Bernstein's coordination dynamics (1967) provides a solution for this anomaly. Bernstein (1967) argues that the multiple subsystems involved in coordinated movement work together to form synergies, reducing the degrees of freedom that need to be controlled. The addition of the Ecological systems approach (Gibson, 1979) explains how movement is an emergent process arising from interaction between the biological system and direct perception-action coupling. Newell (1986) and Shumway-Cook and Woollacott (2012) further developed these theories by considering the interaction between the individual, the task and the environment, acknowledging the effect of an individual's ability to perceive the affordances of a motor task. However, the neglect of top-down processes needed for voluntary movement prevents Dynamical and Ecological systems theories providing a complete description of motor control. The use of internal modelling (Wolpert, et al 2003) recognises that cognitive input is necessary to process the feedback and feedforward information needed to perform goal directed movement. This blending of concepts acknowledges the importance of

input from several systems (motor, perceptual, biological, and cognitive) to enable proficient voluntary movement. Therefore, in order to provide a complete picture of motor control it is necessary to adopt a hybrid approach which integrates the principles of information processing (Hulme et al., 1982), ecological systems (Gibson, 1979), Newell's constraints model (1986) and internal modelling (Wolpert et al., 2003).

1.3. Developmental coordination disorder

For most children the acquisition of the coordination and control needed for proficient motor skill will evolve gradually over several years. Whilst proficiency is constrained by the maturational processes of the CNS (Duysens & Van de Crommert, 1998) and perceptual processes involved with the organisation of movement (Hulme & Snowling, 2009), by the age of 5 years most children are proficient in performing many everyday motor skills. These include gross motor skills such as running, jumping and throwing, and fine motor tasks such as writing (Gallahue & Osmun, 1989; Haywood & Getchell, 2001), dressing or doing up buttons. Whilst these skills may need to be refined to reach adult levels they highlight how movement skills emerge through the interaction between the individual, the environment and the task, reflecting an ecological perspective to motor development. For example, as the developing perceptuo-motor system matures from infancy this enables greater interaction with the environment, which in turn provides feedback to further enhance the motor skill (Gibson, 1979; Shumway-Cook & Woollacott, 2012). Therefore with practice and exposure the typically developing child can perfectly tailor their own motor system to meet specific demands of a task. Furthermore, the underlying mechanisms used to perform one task (e.g. walking) may provide the foundations for more complex motor tasks (e.g. jumping, running) which in turn are used for more complex interactions later on (e.g. participation in sport). These early proficiencies illustrate how strategies for the planning and organisation of movement are well on the way to maturity by the time children start school, allowing them to concentrate on the new challenges of school life.

For approximately 5% of the population (DSM-5, APA 2013) the coordination and control used to perform many of the everyday movement skills mentioned above does not develop in the typical way described above. However, it cannot be explained in terms of neurological damage, or intellectual impairment (American Psychiatric Association, APA, 2013). Previous generations have labelled these children 'clumsy' or 'lazy' (Geuze, 2007) implying that it is a lack of individual effort shaping the motor responses. Furthermore, up until the late 1980's it was thought that with development these motor difficulties would disappear (Hall, 1988).

However, in 1987 the Diagnostic and Statistical Manual (DSM) of the American Psychiatric Association recognised a specific movement disorder, which is now called Developmental Coordination Disorder.

Developmental Coordination Disorder (DCD) is an idiopathic movement disorder that affects the development of motor control and coordination in the absence of overt or acquired neurological conditions (such as cerebral palsy or stroke). The movement skills are below what would be expected given the person's age and opportunity to practice, and significantly interfere with activities of daily living, academic productivity and employment (APA, 2013). DCD affects individuals across culture, gender and socioeconomic group and is estimated to affect between 5-6% of children aged 5 to 11 years (APA, 2013). DCD constitutes a major childhood disorder which continues to adulthood (Losse, Henderson, Elliman, Hall, Knight & Jongmans, 1991; Cousins & Smyth, 2003; Kirby, Edwards, Sugden & Rosenblum, 2010). DCD, is, therefore a life-long condition, not just a developmental coordination delay which can be outgrown.

The consequences for individuals with poor movement skills are serious; research suggests they are less active than their typically developing peers and consequently less fit (Hands & Larkin, 2006). Poor movement skills have been identified as affecting children's confidence to participate in physical activity, initiating a cycle of avoidance and exclusion (Cantell, Smyth & Ahonen, 1994). Allender, Cowburn and Foster (2006) identified a major barrier to sporting involvement for children with DCD as a lack of competence in core movement skills. Unfortunately, boys who do not participate in popular and socially sanctioned activities, such as team sports, are often met with negative peer interactions, such as bullying or victimisation (Berguno, Leroux, McAinsh & Shaikh, 2004). This can increase their risk of psychosocial problems such as anxiety and depression (Piek, Barrett, Smith, Rigoli, Gasson, 2010; Pearsall-Jones, Piek, Rigoli, Martin & Levy, 2011).

1.3.1. Terminology and definition

The idea of motor coordination problems, such as those described above, contributing to a discrete disorder was first postulated in the 1930's (Orton, 1937). Since then a variety of labels has been assigned to the condition including; 'Minimal Brain Dysfunction' (Clements, 1966); 'Developmental Apraxic' (Gubbay, 1975); Sensory integrative dysfunction (Ayres, 1985), Dyspraxia (Zoia, 1999), Specific Developmental Disorder of Motor Function (SDDMF, International Classification of Diseases, 10th edition, ICD-10; WHO, 1992) and Developmental Coordination Disorder (DCD, Diagnostic and Statistical Manual of Mental Disorders 5th edition,

DSM-5; APA, 2013). This has resulted in a confusing array of titles that has changed over time, between countries and even among professionals (Cermak, Gubbay & Larkin, 2002; Peters, Barnett & Henderson, 2001). Clearly, using unified terminology has benefits for communication between researchers, health and educational professionals and parents to disseminate research, assessment and intervention programmes (Geuze, Jongmans, Schoemaker, Smits-Engelsman, 2001).

The term Dyspraxia has been adopted by many disciplines in the UK including The Dyspraxia Foundation which is a charitable organisation designed to help parents of children with movement difficulties (Chambers, Sugden, Sinani, 2005). In the UK the most commonly used terms of identification are SDDMF, Dyspraxia and DCD. However, it is only SDDMF (specified in ICD-10; WHO, 1992) and DCD (specified in DSM-5; APA, 2013) that have a specific diagnostic framework. The term DCD was proposed, and accepted, at the International Consensus meeting in Canada (1994) as the international label for the condition, and also at the Leeds consensus statement in the UK (Sugden, 2006). Additionally, a review by Geuze, et al. (2001) has identified that since 1994 most studies use DCD as their term of description for children with movement problems, therefore DCD will be the term used in this thesis, together with diagnostic criteria from the DSM (as recommended by Blank, Smits-Engelsman, Polatajko & Wilson (2012).

The DSM-5 defines the condition under four headings (three inclusive and one exclusive), briefly summarised below;

- A. The acquisition and execution of coordinated motor skills is substantially below that expected given the individual's chronological age and opportunity for skill learning and use. Difficulties are manifested as clumsiness as well as slowness and inaccuracy of performance of motor skills (e.g. catching an object, handwriting or participating in sports).
- B. The motor skills deficit in Criterion A significantly and persistently interferes with activities of daily living appropriate to chronological age and impacts academic/school productivity, prevocational and vocational activities, leisure and play.
- C. Onset of symptoms is in the early development period.
- D. The motor skills deficits are not better explained by intellectual disability or visual impairment and are not attributable to a neurological disorder affecting movement (e.g. cerebral palsy).

There have been several changes from the 4th to the 5th edition of the DSM. Those most relevant to this study include the examples of difficulties in daily activities (Criterion B.) which

have been extended to include vocational activities, recognising that DCD is a lifelong condition and still affects individual's participation in everyday activities throughout their adult life (Losse, et al., 1991; Cousins & Smyth, 2003; Kirby, et al., 2010). Criterion (C) is completely new ensuring differentiation between a developmental disorder such as DCD and acquired movement disorders such as adult apraxia. Criterion (D) ensures that the difficulties are not better explained by neurological condition and intellectual disability.

1.3.2. Applying diagnostic criteria

Until recently, there have been several issues applying the diagnostic criteria for DCD, mainly due to lack of specificity within the classifications themselves. For example, whilst both the DSM-5 and the ICD-10 state that movement difficulty must be present (DSM criterion A), neither classification system indicates how these variables should be measured. Additionally, neither system provides guidelines concerning the level of motor difficulty that would be considered 'below expected levels'. The importance of a common standardised measure to identify those with motor difficulties cannot be overestimated, as this will ensure that a representative sample takes part in studies. Subsequent research findings will therefore provide valid and meaningful information that can be generalised to the DCD population. These issues were recently addressed by Blank et al. (2012) who recommend that in order to apply the diagnostic criteria for DCD a standardised motor assessment tool is used within a diagnostic setting, and administered by a trained professional.

Even when standardised assessment tools are used, there are still inconsistencies with diagnosis due to lack of guidance as to what cut off points to use to denote impairment. A review of the literature by Geuze et al. (2001) reveals that there was little consistency in the cut-offs used to select participants for research into DCD, with the most frequent cut-off scores for motor skills ranging from the 5th (severe DCD) to the 15th (moderate DCD) percentile on the Movement Assessment Battery for Children. Blank et al. (2012) recommend that a cut-off of below the 15th percentile is acceptable for research purposes.

Assessment tools for Criteria (B, the effect on everyday activities) are also subject to intense variability across studies. In their review, Geuze et al. (2001) observe that at least one of the DSM diagnostic criteria are addressed in an implicit way, with Criterion (B) being largely ignored. The authors found only one study, from the 34 used in the review, explicitly referring to the movement difficulties interfering with normal daily activities. Recommendations by Blank et al. (2012) suggest that assessments should use age appropriate activities within the home and/or school. When applying these criteria it is essential that culturally relevant material

is used to account for differing opportunity to learn motor skills. Blank et al. (2012) suggests that the use of norm referenced tests or questionnaire (such as the M-ABC-2 checklist) may be useful in addressing this criterion. Details of all assessment tools discussed here can be found in Chapter 3.

1.3.3. Prevalence

As with many matters surrounding DCD, studies across the world investigating the prevalence of this disorder have not been consistent in their results. Estimates vary from 4% of 6-9 years old Singaporean children (Wright & Sugden, 1996), to 19% of 11 year old Greek children (Tsiotra, Flouris, Koutedakis, Faught, Nevill, Lane, Skenteris, 2006). Current UK estimates are as low as 1.8% of children aged 7-8 years (Lingam, Hunt, Golding, Jongmans, Emond, 2009); however, estimates in the DSM-5 (APA, 2013) are between 5-6% in children aged 5-11 years old.

These different rates of prevalence can be related to several issues concerning diagnosis of DCD, particularly assessment and application of the diagnostic criteria. For example, in the Lingam et al., (2009) study, where the DSM (IV) criteria were rigidly adhered to, there is room for argument about the validity of the results. Their conservative estimate of 1.8% of 7-8 year old children meeting the criteria for DCD (below 5th centile on M-ABC) belies the fact that 198 children refused motor testing. Furthermore, 42 of those refusals had evidence from writing tests or Activities of Daily Living that could indicate possible or probable DCD. Taking these issues into consideration, and Lingam et al's (2009) inclusion of 223 children with 'probable DCD (between 5th and 15th centile on M-ABC) would increase prevalence to 5.5% more in-line with DSM estimates.

The persistence of DCD into adulthood has been investigated by very few researchers, and estimates of prevalence rates from those studies vary considerably. The least favourable outcome was found by Losse et al. (1991) as 87% of the 6 year old children originally identified by teachers still had movement difficulties at 15 years old. Other estimates range from a 75% persistence rate (Geuze and Borger, 1993) to just 33% (Knuckley and Gubbay, 1983). A study by Visser, Geuze and Kalverboer (1998) also indicated that a third of their original sample caught up with their typically developing (TD) controls aged 11-14 years.

One area of consensus is that the condition is more prevalent for males than females with the male: female ratio being between 2:1 and 7:1 (Gillberg, 2003; DSM-5; APA, 2013). However, it is not clear at this stage whether this reflects a genetic predisposition or whether the nature of

presentation of difficulties is more overt for boys than girls (Cairney, Hay, Faught, Mandigo & Flouris, 2005).

1.3.4. Co-occurrence with other conditions

Whilst DCD may occur in isolation there is extensive research identifying the presence of co-morbidity between DCD and several other developmental disorders. In fact Kaplan, Wilson, Dewey and Crawford (1998) suggest that for clinically diagnosed children 'pure' DCD is the exception rather than the rule. Research shows that Attention Deficit/Hyperactivity Disorder (ADHD, Green, Baird & Sugden, 2006), Autistic Spectrum Disorder (ASD, Green Baird, Barnett, Henderson, Huber, Henderson, 2002) and Specific Language Impairment (SLI, Hill, 2001) frequently co-occur with DCD. However, ADHD and DCD have been shown to co-occur most frequently (Blank et al., 2012) with levels of co-occurrence found to be around 50% (Green, et al., 2006; Kadesjö and Gillberg, 1999).

In Sweden several longitudinal studies by Gillberg and colleagues (Gillberg & Gillberg, 1983; Gillberg, Gillberg & Groth, 1989; Hellgren, Gillberg, Gillberg & Enerskog, 1993; Rasmussen & Gillberg, 2000) have investigated the outcomes for children, originally diagnosed with DCD at 7 years old. The most recent paper, Rasmussen and Gillberg (2000), reported outcomes when the participants were around 22 years old. The authors found that outcomes were significantly worse for participants with co-occurring DCD and ADHD with 58% of this sub group more likely to have issues with one or more of the following; unemployment, problems with the law, alcohol, drugs and mental health issues compared to 13% in the control group. However, the authors argue that whilst co-occurring DCD with ADHD predicted a worse outcome than ADHD alone, young adults with DCD are particularly susceptible to poor outcomes.

1.3.5. Subtypes

Some researchers have investigated the possibility of distinct subtypes of DCD (Hoare, 1994; Dewey & Kaplan, 1994; Macnab, Miller & Polatajko, 2001). For example Green, Chambers and Sugden (2008) discuss the possibility of subtypes being defined by fine-motor versus gross motor competence, or the severity of the motor difficulty or perceptual-motor problems. However, DSM-5 does not recognise discrete subtypes within DCD, although Blank et al. (2012) argue that the existence of subtypes is likely, but at present there is little research evidence to contribute significantly to understanding the aetiology of DCD (See Visser, 2003).
Motor control difficulties associated with DCD

Criterion C of the DSM-5 requires that symptoms of DCD are evident early in development, and early signs of motor coordination problems may manifest with a marked delay in reaching childhood motor milestones such as sitting unsupported, crawling and walking. However, motor difficulties for individuals with DCD are not always apparent at this very early stage, as argued by Missiuna, Moll, King, King and Law (2007) who investigated parental perspectives on the impact of DCD. They found that whilst many of the parents noticed their children's motor development was *different* many had achieved motor milestones within the average age range. However, the parents noted something 'qualitatively different' about their children's movement; being less aware of their body in space, or lacking fluidity of movement. Even if motor difficulties are apparent before 5 years of age, DCD is typically not diagnosed at this age (Blank et al, 2012). There are several reasons for this; firstly young children with delayed motor development may catch up once given the opportunity to practice these skills. Secondly, practical issues relating to attention and understanding may affect the reliability of test results when working with children under 5 years old. However, Blank et al. (2012) recommend that if a child aged between 3-5 years has significant motor problems a diagnosis of DCD can be given provided two assessments are performed at least 3 months apart.

Once children reach school age motor coordination problems manifest with difficulties in self-care such as dressing/changing for P.E.; problems with fine motor skills such as hand writing, using scissors; gross motor skills such as running and jumping (Larkin & Hoare, 1991) and/or more complex tasks such as ball skills and team games (Cousins & Smyth, 2003). Overall, children with DCD often show reduced speed, accuracy and fluency when performing motor tasks compared to typically developing children (Henderson, Rose & Henderson, 1992; van der Meulen, Denier van de Gon, Geilen, 1991). Poor coordination can result in limited participation in team sports (Missiuna et al, 2007) and learning new motor skills has been identified as a particular issue for adolescents with DCD (Cermak, Trimble, Coryell, & Drake, 1991; Losse et al., 1991).

Whilst most of the research into DCD has, to date focused on children (Kirby, et al., 2010) it is now well established in the literature that DCD is not just a childhood condition, with motor difficulties that can be outgrown (Cousins & Smyth, 2003; Losse, et al 1991 Kirby, et al., 2010). Several studies have identified that the movement difficulties continue to impact daily life for many adults with DCD, at home, whilst in education or within the workplace, and are particularly apparent if presented with a new task to learn (Cousins & Smyth 2003). Cousins and Smyth (2003) investigated the coordination difficulties of nineteen adults aged 18-65 years who had either been diagnosed with DCD, or had reported having motor problems consistent

with DCD. In the absence of an appropriate standardised movement assessment for adults, their movement ability was compared to an age and gender matched control group. Participants were asked to perform a series of movement tasks designed to assess skills such as static and dynamic balance, obstacle avoidance, handwriting, block construction and reaction time. The authors found that the adults with DCD performed significantly worse on all measures of motor ability than the controls. They were also slower and more variable with many of the adults with DCD having problems performing a dual task and sequencing during a clap-and-catch task. However, the most revealing result suggests that the simple motor tasks used in this study were able to predict, by means of regression analysis, whether or not participants were drivers. This highlights an area of profound difficulty for individuals with DCD inhibiting independent access to many areas of daily living such as driving to work, college or attending social events.

It is clear from the extensive list of difficulties discussed above that the effects of the motor impairment are wide reaching. A recent meta-analysis summarising research findings in the DCD literature from 1997-2011 was carried out by Wilson, Ruddock, Smits-Engelsman, Polatajko and Blank (2013). The authors identified several clusters of pronounced difficulty for individuals with DCD including internal (forward) modelling, control of reaching, catching and manual interception, sensori-perceptual function, postural control and gait. Areas pertinent to this study (sensori-perceptual function, internal (forward) modelling, postural control and gait) will be discussed below using the theoretical frameworks of Information processing, Ecological systems and Internal modelling to explore these deficits. Gait will not be discussed at this stage as it will be explored in depth throughout the thesis.

1.4. Information processing for individuals with DCD

The information processing framework was one of the first to be applied to research into DCD where work focused on the role of visual perception in supporting effective motor control. For example, Hulme and colleagues (e.g. Hulme, Biggerstaff, Moran & McKinlay, 1982; Hulme, Smart & Moran, 1982) worked on the premise that if children with DCD cannot perceive the input measure of sensory information correctly this will impair the output measure of motor control as the parameters for movement will be based on misinformation. By separating their research into 3 distinct perceptual systems (visuo-perceptual; kinaesthetic-perceptual; sensory integration) they investigated whether the poor execution of movement, illustrated by individuals with DCD, was based on degraded perceptual information rather than motor control problems per-se.

Hulme, et al. (1982) investigated visual and kinaesthetic perception of children with and without DCD as they matched the length of lines presented under 2 conditions; *visual* where the child could see the line; *kinaesthetic* where the child felt a length of a rod. Once the child had seen/felt the initial stimulus it was withdrawn from sight/touch when they were asked to match the length of another line to the one they had just seen/felt. These second lines were presented under 4 conditions; 1. *Visual-visual*, where the first stimulus was presented visually, to be matched to a visually presented line; 2. *Visual-kinaesthetic*, where the first stimulus was presented visually and the child felt the rod that needed to be matched to it; 3. *Kinaesthetic-kinaesthetic*, where the child felt the first stimulus and felt the rod that needed to be matched to it; 4. *kinaesthetic-visual*, where the child felt the first stimulus but matched it to a visually presented line.

The authors found that children with DCD were significantly worse in the visual and kinaesthetic conditions than their TD peers at matching the length of the lines. Additionally, they found that motor skill correlated significantly with the visual condition for line matching but not any of the other conditions. The authors suggest that the children with DCD had difficulties in visual perception of distance and spatial relationships and that this might be an important indicator for the poor movement skills of individuals with DCD. However, group differences could be the result of a visuospatial memory deficit, rather than visual perception deficit.

Hulme, Smart and Moran (1982) subsequently addressed this issue using a similar paradigm, where participants matched the lines presented at the same time; thus removing the confound of memory. The authors found that children with DCD were significantly poorer at matching the lines, than the TD children, suggesting a perceptual deficit rather than a memory issue. Neither of the above studies investigated visual acuity as a causal element in these findings, but studies by Lord and Hulme (1987^a) and Mon-Williams, Pascal and Wann (1994) failed to find any significant acuity problems for individuals with DCD.

Work by Hulme and colleagues (e.g. Hulme, et al., 1982; Hulme, Smart & Moran, 1982) identified that perceptual problems are the result of a visual rather than a kinaesthetic deficit; however, several studies have failed to replicate these findings (Henderson, Barnett and Henderson, 1994; Hoare and Larkin, 1991). To investigate these anomalies Wilson and McKenzie (1998) conducted a meta-analysis of 50 studies to investigate whether the poor movement skills of children with DCD could be the result of information processing deficits, particularly poor integration of visual, kinaesthetic and cross-modal information. Data from 983 children with DCD and 987 controls (mean age 9 years 2 months) were analysed for this study.

The authors found several deficits in information processing skills of children with DCD; for measures of visuo-spatial processing, kinaesthetic perception and cross-modal integration. However, the largest discriminator between groups was visuospatial skill, and group differences occurred whether there was a motor component to the task (e.g. block construction and graphic copying skills), or not (e.g. length discrimination, judgement of perceptual closure). The authors argue that these findings suggest a generalised visuospatial deficit in children with DCD, which may occur at a more elementary stage, before the motor command is initiated. One final area that differentiated between groups was that of cross-modal perception between vision and proprioception and vision and touch. Wilson and McKenzie (1998) suggest that children with DCD have difficulty integrating visual, proprioceptive and tactile information.

Several studies have subsequently investigated sensory contribution to movement for individuals with DCD. For example, Mon-Williams, Wann & Pascal (1999) investigated the use of vision and proprioception for a pointing task for 32 children aged 5 to 7 years; 10 with DCD and 22 typically developing (TD) children. The experiment involved a matching task under three different conditions; *Vision* – the child pointed to a visible location on a table top; *Proprioception* – the child placed their finger on an opaque table top and attempted to match the same location with the other hand under the table, with their eyes closed; *Vision and Proprioception* – as for proprioception but with their eyes open. The proprioception condition was the hardest for both groups of children, illustrating the importance of visual information for guiding limbs. These results confirmed previous findings from a similar study with typically developing children aged 4-12 years by von Hofsten and Rösblad (1988) which the authors argue confirmed the importance of visual information for this type of motor task. However, Mon-Williams, et al., (1999) argue that the children with DCD had particular difficulty with the tasks that required integration of visual information and proprioception, lacking the advantage, illustrated by the TD children, of visual information concerning the spatial location of their limbs. They suggest that deficits making cross-modal judgements between proprioception and vision may contribute to poor motor coordination in dynamic situations for children with DCD.

This adds to findings from research by Rösblad and von Hofsten (1994) who investigated the use of vision for constructing movements in children aged 7-16 years with and without DCD. The end point target specifications were less precise than for the ones used in the Mon-Williams, et al. (1999) study as participants were asked to move small beads from one cup (9cm in diameter) to another cup the same size. Visual information from the hand and cups was manipulated using a curtain and mirrors. Findings showed that children with DCD reacted to the visual manipulations in a similar way to their TD controls. However the DCD group were

slower and less consistent whilst completing the task. The authors suggest that slower speed highlights difficulties for the DCD group in the planning of a movement. They argue that a deficit in the ability to plan and prepare for movements ahead of time can force individuals with DCD to rely on feedback information to monitor their movements. These results are supported by several studies investigating the relationship between poor anticipatory control and motor impairments (discussed in section 1.10).

1.5. Ecological systems and DCD

Some studies can be considered within the framework of the ecological systems approach whereby motor control is explored in terms of an individual's perception of the affordance of a task, carried out within the constraints of the environment. Additionally the individual must be able to control the degrees of freedom about the joints to coordinate their movements. Therefore, this approach considers the sensitivity of the whole 'system' to perceive the affordance from the environment and then self-organise the required movement. Wilson et al. (2013) included the following two studies within this framework as they examined behaviour in individuals with DCD;

Wann, et al., (1998) investigated the perceptual-action link when motor responses were measures as perceptual information was manipulated. They used the 'swinging room' paradigm, whereby participants stand in a 'room' where the walls are suspended from the ceiling. Misleading visual information was provided as the front wall could be moved backwards and forwards, creating the illusion that the participant was moving. The authors found that the participants reacted to the changing visual information by adapting their posture as if there was a threat to balance even though information from the mechanisms of the joints and muscles (proprioceptive system) and the vestibular system did not indicate sense any loss of balance. Results showed that for 4 of the 6 children with DCD, postural sway was abnormally large and equivalent to sway observed in much younger children. The DCD group also had greater postural sway, when their eyes were closed than their TD peers. The authors propose that this indicates a greater reliance on visual information for postural control in children with DCD than TD children. The sample used for this experiment was very small and not all the children with DCD reacted to a greater extent to the removal of vision than the TD children, so the results need to be interpreted with caution, but they highlight difficulties for children with DCD to self-organise their postural responses to changing environmental conditions.

Volman and Geuze (1998) investigated the rhythmic coordination in children aged 7-12 years with and without DCD. The children performed a visuo-manual coordination task which involved flexion and extension of the index fingers timed to coincide with a visual signal. Initially the children performed their finger movements either 'in-phase' (made in time with the light) or 'anti-phase' (made out of time with the light). This provided a baseline measure of stability. Following this the participants performed a similar finger task but the movement was unexpectedly perturbed. Finally a third task was performed whereby the children had to move their fingers to an increased frequency of light oscillation.

Results showed that four of the children with DCD could not perform the finger action in the anti-phase condition, even in the initial 'baseline' condition. For the remaining children there were no group differences in deviations of finger movement and the visual signal. However, the children with DCD were more variable in maintaining the rhythmic visuo-motor coordination compared to their TD peers. Additionally when the movement was perturbed the children with DCD took longer to recover and return to their baseline level of stability. Furthermore, group differences were particularly apparent when the children moved their fingers out of time with a faster light oscillation. Whilst all children switched to an 'in-time' strategy, this occurred at a significantly lower oscillation frequency for the DCD group compared to their controls. These results show that the children with DCD found it more challenging to meet the increased movement demands as the rate of movement had to increase to match the light oscillations.

1.6. Internal modelling and DCD

Analyses of the complexities involved in adaptively moving within the environment (discussed above) highlights how deficits, at any level of processing, may reduce sensitivity to environmental demands and compromise the accuracy of the motor response. In their meta-analysis, Wilson et al. (2013) propose that there is compelling evidence to suggest that individuals with DCD have difficulties with the use of feed-forward information, affecting the ability to predict the outcome of a movement (internal model). If there is a wide discrepancy between the internal model and the actual movement, this will increase the role of error management, and reduce accuracy. Some of the studies that have investigated this area with individuals with DCD are discussed below;

Firstly, Wilmut, Wann and Brown (2006) used a double-step pointing task to investigate how the eye and hand are coupled during the performance of rapid sequential hand movements. Children aged 7 years with and without DCD were asked to point to two targets as they

appeared, although in one condition the target had disappeared before the hand could reach it. Results suggest that the children with DCD relied on visual feedback for movement of their limbs to a greater extent than the TD children, demonstrated by longer foveation periods on the target location before movements were initiated. The authors argue that the children with DCD delayed their hand movements until visual information was available, which subsequently degraded accuracy once several sequential movements were required.

The study discussed above supports research by Smits-Engelsman, et al. (2003) who argue that children aged 11 years with DCD rely on visual feedback during the execution of a repetitive goal directed drawing movement more than age-matched controls, which they suggest illustrates a difficulty with feedforward or open-loop strategies, caused by a poorly developed internal representation of the action. Smits-Engelsman, et al., (2003) used two movement tasks to investigate the fine motor performance of 32 children with DCD and learning difficulties in comparison to their aged matched controls. This enables the researchers to differentiate between a discrete and a cyclic aiming movement. Surprisingly, their results did not show any group differences in speed of execution for the discrete movement task, which were in fact shorter in the DCD group than the TD group. However, in the more complex, cyclic task the children with DCD took longer and made up to 6 times more mistakes. The DCD group moved faster even when reaching the target than their TD peers, which the authors argue suggests that the DCD group failed to scale their endpoint speed to produce accurate results, thus again emphasising a deficit in predictive abilities.

In a subsequent study, Hyde & Wilson (2010) argue that rapid online control, as needed for fluent expression of motor skill, is only possible if there is a seamless integration between both forward models of movement and feed-back mechanisms. Hyde & Wilson (2010) used a double step reaching paradigm, whereby children with and without DCD (aged 7-12 years) were asked to touch a central target, then a peripheral target then back to the central target. Additionally, some trials were perturbed, at movement onset, as the central target moved to the periphery. The children with DCD were slower to initiate a movement, as would be expected, but also they found it harder to inhibit their movement to the centre when the targets moved unexpectedly to the periphery. The authors argue that this illustrates impairment for children with DCD to make rapid online adjustments that are based on a predictive (or internal) model of action.

In addition to the fine motor tasks described above, Przysucha, Taylor and Weber (2008) argue that for children with DCD anticipatory postural adjustments differ qualitatively from those of their TD peers. Przysucha, et al. (2008) compared the postural adaptations of 38 boys, aged 7 and 11 years, with and without DCD during a leaning task. Participants stood on a force

platform and were asked to lean forwards, backwards, and to the left and right whilst ground reaction forces were used to measure anterior-posterior and medio-lateral displacement in the Centre of Pressure (CoP). Findings showed that the DCD group exhibited a smaller range of excursions (swaying less from vertical) that were more frequent and less organised than their TD peers. Analysis of relative time making on-line corrections showed that the TD boys spent 78% of their movement time making on-line corrections to their Centre of Pressure using feedback control. In comparison, the participants with DCD only spent 54% of their time under feedback control. The reduced use of feedback control exhibited by the DCD group suggests a greater reliance on a less informative ballistic control, whereby once the control signal has been created it cannot easily be adjusted.

These results support the findings from Hyde & Wilson's (2010) study where once the motor command had been issued to move the hand to the centre target, this was difficult to inhibit if the target unexpectedly moved to the periphery. Przysucha, et al. (2008) suggest reduced feedback control could be due to sub-optimal processing of sensory information, as the performance of a leaning task is predominantly dependent upon proprioceptive feedback from the muscle spindles, Golgi tendon organs and joint receptors. However, causality is not easily assigned from the results presented here; is it a perceptual deficit causing the feedforward processing to accommodate this, or a feedforward deficit whereby the ballistic portion of the movement is so strong that it is difficult to adapt to, or is it a reaction time issue where reactions to perturbations take too long to assimilate?

In a study by Deconinck De Clercq, Savelsbergh, Van Coster, Oostra, Dewitte and Lenoir, (2006^b) which investigated the effect of visual occlusion on the walking patterns of children with and without DCD (discussed in Chapter 8) the authors postulate that children with DCD cannot easily shift to other sensory channels when vision is removed. They propose that there is a deficiency in utilising proprioceptive and vestibular input when visual input is degraded which particularly affects children with DCD. TD children seem more able to flexibly adapt to the different sensory modalities, effectively demonstrated by their ability to control locomotion after the removal of vision. Deconinck et al. (2006^b) argue that the problems experienced by the DCD group to fully integrate sensory information may be related to a 'noisy' internal model compared to the internal models of the control children. They argue that as the children with DCD relied more heavily on visual feedback than their peers for movement this suggests that there is a discrepancy between the forward component of the internal model, which predicts the outcome of a movement, and the expected sensory consequence of the motor command.

Therefore the frame of reference from which the individual can compare and adjust the actual movement is less accurate.

1.7. Postural control for individuals with DCD

In terms of the theoretical approaches described above there are several areas of DCD which have been investigated with a hybrid approach to research (Wilson et al 2013). A hybrid approach combines several concepts and paradigms to investigate one particular area of deficit. One such area is that of postural control. Postural control, or balance, refers to the ability to keep the Centre of Mass (COM) within the base of support. Therefore, whilst standing still the CNS must align the body segments to keep its Centre of Mass within the base of support (Winter, 1995), which in this case, are the two feet. Postural control is a fundamental skill necessary for every movement we make, and like all movement, successful postural control emerges from the interaction between the individual, the task and the environment (Shumway-Cook and Woollacott, 2012). Given this description of postural control it is clear why some researchers have adopted an ecological systems approach (Forseth & Sigmundsson, 2003). However information processing approaches are also frequently used as postural adjustments are heavily dependent upon the efficient integration of visual, vestibular and proprioceptive information (Oie, Kiemel & Jeka, 2002) Oie, Kiemel and Jeka (2002) suggest that adjustments are made between the three sources of sensory information depending on the changing demands of environmental constraints.

Given the sensory-perceptual difficulties in areas such as visual and proprioceptive integration (Mon-Williams et al., 1999, Deconinck et al., 2008), together with the internal modelling difficulties discussed earlier for individuals with DCD it is not surprising that poor balance is a common feature of DCD, with 73-87% of children with the condition having problems with these skills (Macnab, et al., 2001; Cantell, Smyth, Ahonen, 1994). In order to explore the information processing skills of children with DCD, Deconinck, De Clercq, Van Coster, Oostra, Dewitte, Savelsbergh & Lenoir (2008) investigated the control of posture during quiet standing for 10 boys aged 6-8 years with and without DCD. Four experimental conditions were used to manipulate vision (eyes open or closed) and proprioception (standing on a firm or compliant surface). There are some issues with this study, as although the mean score on the Movement Assessment Battery for Children (M-ABC, discussed in Chapter 3) for all the children in the DCD group was at the 5th percentile, they all scored above the 15th percentile on the balance assessments on the M-ABC). Notwithstanding these limitations, the study showed that boys with DCD had greater postural sway and lower postural stability across all four conditions. The

largest difference between the two groups was found when the participants stood on a firm surface with their eyes closed; the DCD group swayed more in this condition when vision was removed, but postural sway for the TD group was negligible. However, while standing on the compliant surface, the removal of vision resulted in a similar increase in sway for both groups. This behaviour can be explained as the proprioceptive sensory feedback from the compliant surface was more difficult to interpret, and therefore demanded more attention. So when vision was removed both groups had to try and coordinate a motor response to the increased attentional demands of both proprioceptive and visual information.

To unpick these findings Deconinck et al. (2008) calculated stabilization ratios to investigate the relative contributions of each sensory system in each condition. These calculations revealed a significant increase in the relative contribution of visual information for the TD group when standing on the compliant surface (proprioceptive information is less reliable). In contrast, for the boys with DCD the relative contribution of visual information did not change between conditions. Furthermore, the relative contribution of vision when standing on a firm surface was higher for the DCD than the TD group, but lower when standing on the compliant surface. Additionally, the use of proprioceptive information was found to differ between groups when visual information was manipulated; the TD boys increased their visual contribution but the DCD group didn't. Thus, the TD group relied more on proprioceptive information than the DCD group *in the absence of vision*, but the DCD group relied on visual information more than the TD group *in the presence of proprioceptive information*. The authors argue that this illustrates that children with DCD rely more on visual rather than proprioceptive information to assist in the maintenance of postural control, compared to the TD boys, who could adapt to the different sensory conditions. This supports findings from the swinging room experiments (Wann, et al., 1998) further illustrating difficulties within the DCD population to integrate visual and proprioception for the maintenance of postural control.

These findings support work by Geuze (2003) who investigated adaptive abilities of children aged 6-12 years with and without DCD to a visual and a balance manipulation. The DCD group only included children with balance difficulties which the authors argue provided a clearer understanding of control problems than a less defined group of children with DCD. Centre of Pressure (CoP) movement during stance was measured using a force plate. Measurements were taken with eyes closed and open and during two-leg and one-leg stance. Results showed little group difference whilst standing on one or two legs with eyes open, but the DCD group showed a larger postural sway compared to the controls whilst standing on one leg with eyes closed ($p = 0.053$), particularly in the lateral direction.

Geuze (2003) also investigated the effects of a perturbation on the balance skills of children with and without DCD. A ball unexpectedly hit the back of the participant just below the waist, resulting in a light perturbation. The authors found that the DCD group showed a longer duration of forceplate and EMG responses than their TD peers, but only during the first perturbation. Geuze (2003) suggests that this identifies a reduced capacity for novel perturbations for the DCD group, but fast learning reduces this effect in subsequent trials. These findings are particularly relevant to the current study as, given the unpredictability of the environment to the pedestrian (particularly with reference to the assimilation of dynamic visual and proprioceptive information from undulating ground terrain); it could be argued that almost every step taken in the real world creates a novel experience that has to be adapted to.

Taken together, the findings from studies investigating postural control illustrate only subtle group differences, which only becomes a problem to individuals with DCD in more challenging situations (such as one-leg balance and when vision is withdrawn) or in novel situations when an increase in postural sway may indicate sub-optimal balance control. These findings confirm research by Tsai, Wu, Huang, (2008) and Deconinck et al. (2010) which suggests problems for individuals with DCD with dynamic balance in challenging situations. Additionally, studies investigating gait pattern characteristics in the elderly or those with stroke can discriminate between those with and without balance problems with the application of these CoP parameters (Chou, Kaufman, Hahn & Brey, 2003, Chou, Kaufman, Walker-Rabitan, Brey, & Basford, 2004).

Whilst effective standing balance and an upright, balanced posture are essential elements for successful walking (Roncevalles, Jensen & Woollacott, 2001; Perry & Burnfield, 2010), the demands of static balance are fundamentally different to those required for a dynamic task such as walking (Winter, 1995). For an individual to balance whilst standing still, they use a closed loop system (i.e. using sensory feedback to refine movements) to keep the Centre of Mass within a fixed of support (the feet) (Nasher, 1976). However, when walking the pedestrian must contain the Centre of Mass within a *moving* base of support as the two feet move forwards. Feedforward visual information is therefore used whilst walking to prepare the motor system for future events, such as changes in terrain or avoidance of obstacles. Additionally, the pedestrian needs to make sense of dynamic visual information which needs to be coupled with coordinated motor responses.

1.8. Conclusions

In summary, effective movement control is heavily dependent upon sensory input (Hulme & Snowling, 2009), particularly visual and proprioceptive information which is used to interpret environmental constraints, and elicit skilled actions. Visual input is used to provide information concerning the environment and the individual's position within it, and proprioception provides internal reference to position and movement of the body (Gibson, 1966). When all these systems integrate efficiently with effective motor control mechanisms, the individual can easily adapt to environmental constraints.

It is clear from the evidence discussed in this chapter that sensory-motor deficits for individuals with DCD affect the efficiency of adaptive interaction with the environment. The theoretical approaches previously discussed suggest that motor control is an emergent property resulting from interaction between the biological system and perception-action couplings. However voluntary movement requires input from several systems (motor, perceptual, biological, and cognitive) and deficits in any system may reduce sensitivity to changing environmental demands and subsequent motor responses may be less accurate in their execution. Given that individuals with DCD are known to have problems with sensori-perceptual function (Wilson & McKenzie, 1998), perception-action couplings (Wann, Mon-Williams & Rushton, 1998) and internal modelling (Smits-Engelsman, Wilson, Westenberg & Duysens, 2003) it is unsurprising that the motor skills of individuals with DCD are reduced in speed and accuracy when compared to their typically developing peers (Henderson, et al., 1992; van der Meulen, et al., 1991) possibly affecting the efficiency with which individuals with DCD interact with the environment. One area of DCD research that has received little attention is that of gait. However, competence in walking must be considered a core skill necessary for many activities of daily living, and although a very mundane skill it is not a simple task; walking involves the ability to correctly interpret different environmental conditions (using sensory information) and to produce simultaneous, coordinated motor responses. It could be argued that for those with DCD a reduced ability to process relevant perceptual information from the environment may negatively affect the efficiency of the walking task. Given the findings from research discussed above identifying difficulties in these specific areas, together with findings from Wilson, et al's (2013) meta-analysis suggesting that gait is one of the areas of pronounced difficulty for individuals with DCD, this is an area of much needed research. Furthermore, the specific demands of the walking task, whereby the sensitivity of an individual to environmental information relative to their own actions can be exacerbated by the repetitive nature of walking (any error in foot placement must be corrected almost immediately by the following foot to

avoid further error), these additional constraints may disproportionately affect the walking patterns of individuals with DCD compared to their typically developing peers

Given the wide range of deficits for populations with DCD (motor, perceptual, biological, and cognitive) that are essential for proficient voluntary movement, it is important that research investigating the movement difficulties for this population is conducted in a realistic environment. This will ensure that both perceptual and behavioural adaptations can be measured, reiterating Gibson's (1979) argument that in order for research to be ecologically valid it must be sensitive to the symbiotic visuo-motor relationship. However, as discussed earlier, there are limitations to using a singular theoretical approach to describe motor proficiency, as one theory has not yet been able to explain all the disparate elements (motor, perceptual, cognitive, biological), used to successfully negotiate the environment. Therefore this thesis will adopt a hybrid approach integrating the principles of information processing (Hulme et al., 1982), ecological systems (Gibson, 1979), Newell's constraints model (1986) and internal modelling (Wolpert et al., 2003) which will provide an overarching framework to acknowledge the importance of input from several systems needed for goal directed movement. The series of studies discussed in this thesis will investigate the walking skills of individuals with and without DCD. Experimental chapters 4 and 5 will explore walking patterns on a level and uncluttered terrain. The studies reported in Chapters 6 and 7 further develop these findings by exploring the effects of perceptual manipulations on the walking patterns of individuals with and without DCD. However, in order to fully understand atypical gait patterns, a thorough understanding of typical gait is needed to provide a baseline comparison. Therefore a description of typical gait patterns is provided in Chapter 2.

Chapter 2: Typical walking, description, measurement and development

2.1. Introduction

Human bipedal walking uses a series of repetitious movements to progress the legs forwards whilst providing both support and propulsion for the whole body. Gait patterns for most humans are symmetrical (Raibert, 1986), alternating one leg half a pace behind the other. For the typical population walking is coordinated, efficient and affords a safe and independent mode of transport to explore the environment. Competence in walking is a core skill necessary for many activities of daily living, and a major contributor to quality of life (Patla & Shumway-Cook, 1999). However, although walking is a mundane skill it is not a simple task. In fact Winter (1991) argues that walking is one of the most complex and totally integrated movement tasks humans have to master, but once learnt, for the majority of individuals, it becomes almost automatic with little need for conscious thought.

It is important to understand the mechanisms behind typical gait to provide a standard against which atypical gait can be measured. Therefore this chapter will discuss key elements in the description, measurement and development of typical walking. Beginning with a description of the gait cycle, this chapter will continue with an overview of locomotor ability of typical adults, children. Additionally, a review of the literature considering walking skills of individuals with DCD will be discussed. The chapter will then consider mechanisms and sensory information used to control and support locomotion whilst negotiating a complex and dynamic environment. Finally, an outline of methods of gait measurement will be outlined.

2.2. Description of walking

Whilst walking the body divides into two separate units; passenger and locomotion; the passenger unit comprises the head, neck, trunk and arms and is carried along by the movement of the lower limbs. The passenger unit is not inert, however, as it has to maintain its postural stability during self-advancement. The locomotor unit comprises the pelvis and the two legs, with the pelvis serving as a link between the passenger and the locomotor unit. The locomotor unit comprises 11 different joints (lumbosacral; hip; knee; ankle; subtalar; and metatarsophalangeal), controlled by 57 muscles (from gluteus maximus to the 5 groups of muscles called the intrinsic muscles of the feet), with 5 bony segments (pelvis; thigh; shank; foot and toes) acting as levers. The locomotor unit propels the body forward, but must also

assist in the alignment of the passenger unit as its weight pivots over the supporting limb during stance. In addition to this forward movement, the body also moves laterally as weight centres over the alternating supporting leg during swing. The whole trunk also moves vertically as it progresses through the gait cycle, rising to its highest point as the leg swings forward (swing) and falling to its lowest point whilst both feet are on the ground (double support). Perry & Burnfield, (2010) argue that reducing the amount of sway (both vertical and lateral) is considered an important factor in reducing muscular effort, and energy, whilst walking.

To walk efficiently, all the different muscles, joints and segments from the upper and lower body must be seamlessly coordinated to propel the whole body forwards effectively. However, there are several anatomical constraints to be considered that can affect the successful completion of this task. Firstly, each body segment is being ‘pulled’ towards the ground by gravity and will fall unless it can balance on its support. Secondly, the top heavy passenger unit (up to 70% of total body weight, Winter, 1995) rests upon a multi-segmented system (thigh, shin, foot) designed for mobility rather than stability (long, narrow and segmented), which is not an ideal arrangement to maintain balance whilst walking. These constraints highlight the delicate interplay between the passenger and the locomotor units to adapt posture and balance whilst remaining upright and propelling the body forwards (Patla, Prentice, Robinson & Neufeld 1991) during locomotion. Analysis of the biomechanical processes involved illustrates the complexity and sequential coordination necessary for efficient walking and will be discussed below.

2.3. The typical, mature gait cycle

A typical gait cycle lasts from when one foot strikes the ground until that foot strikes the ground again. As demonstrated in Figure 2.1, there are two phases of double support and two longer phases of single support in each gait cycle. However, with only 20% of a gait cycle spent with both feet on the ground (Whittle, 2004), walking presents an inherently unbalanced system.

Each gait cycle is divided into 2 periods; stance (weight bearing) and swing (self-advancement). For typically developing, mature walkers stance accounts for 60% and swing accounts for 40% (Whittle, 1991), but these can vary as speed of walking changes; swing phase becoming longer, stance and double support shorter, as speed increases (Murray, 1967). These variations can cause problems for measurement as individual differences in walking speed may affect these variables, but taking measurements as a percentage of total gait cycle allows easy comparisons between individuals (Woodruff, Bothwell-Myers, Tingley, Albert 2002).

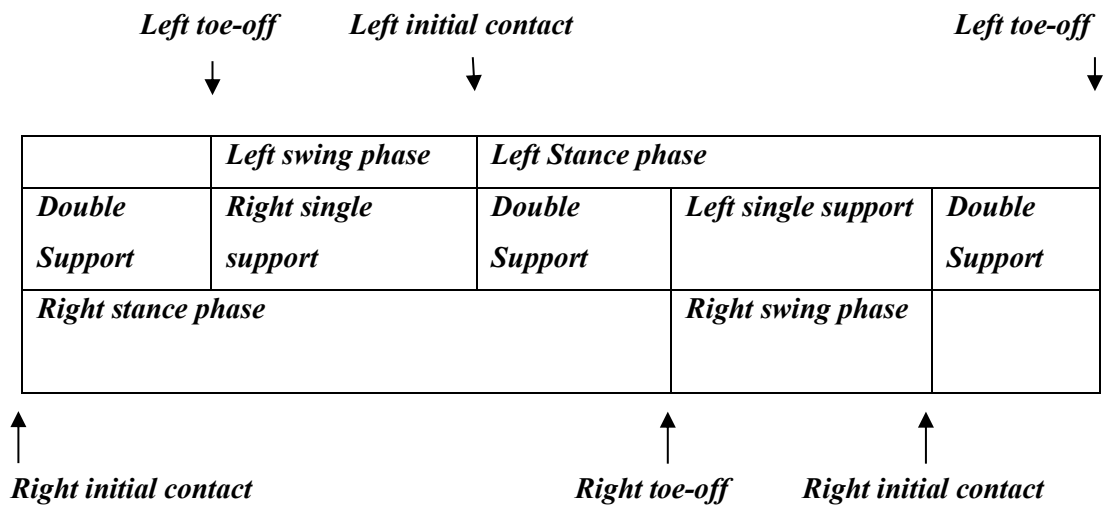


Figure 2.1. Single and double support phases during a typical gait cycle. (Whittle, 1991, p61)

Patla, et al. (1991) identified three main requirements that need to be met for human bipedal gait (using two legs alternately to support and propel the body forward) to be successful; 1)

Progression using a rhythmic pattern of leg and trunk movements to move the body towards and end goal; 2) **Dynamic stability**; supporting the body against gravitational forces and keeping it balanced; 3) **Adaptation** to changing environmental demands; avoiding obstacles, negotiate irregular terrains, changing direction. Furthermore, these requirements need to be met in the most energy efficient manner and with minimal stress to the locomotor system to minimise long-term damage to the muscular-skeletal system (Patla, 1997).

However, analysis of the mechanical processes involved illustrates the complexity and sequential coordination between the passenger and locomotor units. These patterns change to meet the functional demands of the four different phases of the gait cycle; **Heel-Strike, Opposite Heel-Strike, Toe-off** and **Opposite Toe-Off**, marking the transition between the two main periods of stance (Heel-Strike, Opposite Heel-Strike) and swing (Toe-Off, Opposite Toe-Off; Whittle, 2012; Perry & Burnfield, 2010). During the stance period of gait the body must be supported against gravity as body weight moves laterally from one foot to the other and forwards over the supporting foot (**progression** and **dynamic stability**). Additionally as this weight moves the base of support changes from the heel, through the foot to the toes. Therefore, even during stance, there is no point during the gait cycle that is stable. Furthermore, the system must be flexible so that it can **adapt** to changing ground terrains, speed and direction. During swing, the swing leg advances forwards (**progression**) ‘pulling’ the body behind it. The swing

limb must then find a safe foot hold to prepare for weight acceptance (*dynamic stability*).

Again, the system must be flexible enough to ensure foot clearance of the floor, or any obstacles during swing (*adaptation*).

The functional movements of one leg as it progresses through each phase of a typical gait cycle (the contralateral leg repeats these movements half a pace behind) will be described in detail below. Please see Figures 2.2. and 2.3. to explain terminology used in these descriptions. (All descriptions are from Perry & Burnfield, 2010; Whittle, 2012).

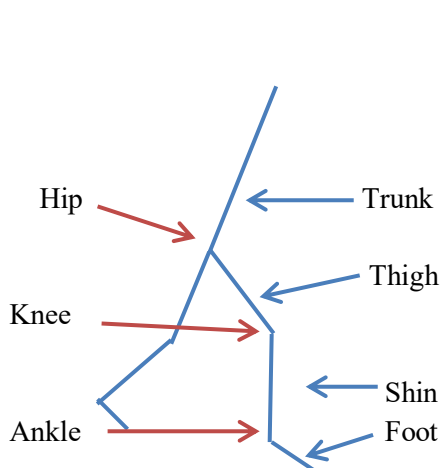


Figure 2.2 Visual illustration of joint and segment terminology

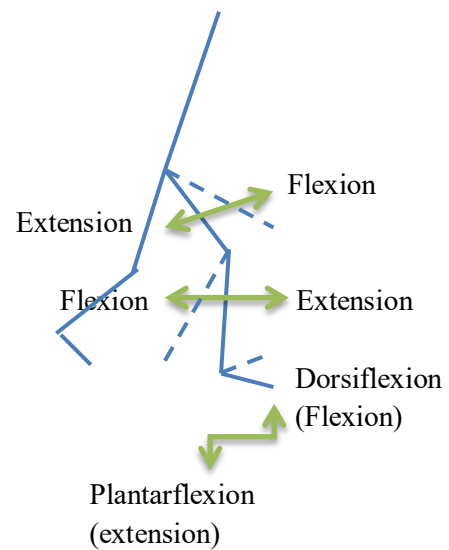


Figure 2.3 Directional illustration of flexion (and extension) about the joints. Dotted lines indicate flexion

2.3.1 Heel-Strike

Objectives; Weight acceptance; Impact deceleration; Shock absorption.

Gait period: Stance

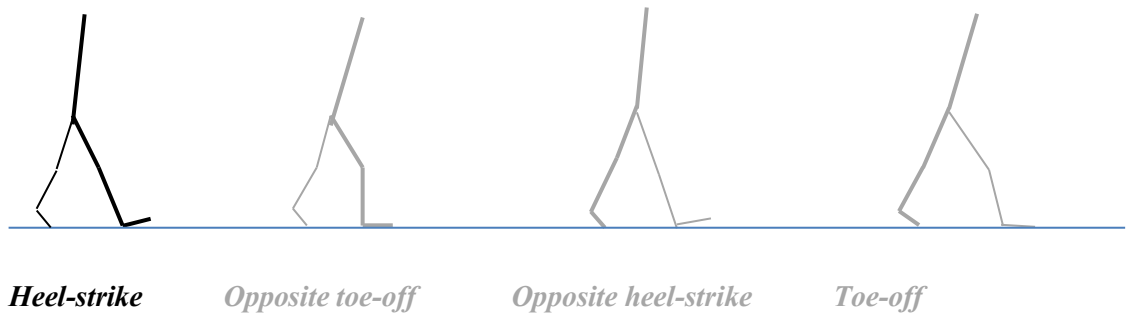


Figure 2.4. Configuration of the lower limbs at four gait events; reference limb and event is in bold.

Heel-strike (Figure 2.4) initiates the first phase of stance. There is a distinct impact as the heel makes contact with the ground ready for the transfer of weight from the trailing (contralateral) limb to the lead (reference) limb. As soon as the heel has made contact it begins to ‘roll’ the foot forward onto the ground using the heel rocker as a pivot. This pivotal action serves to transfer some of the downward force of weight falling onto the foot into forward momentum. The trunk, which is at its lowest point in the gait cycle, is behind the leading/reference foot at heel-strike, but moves laterally as its weight is transferred from one leg to the other. There is flexion about the hip (i.e. the trunk and thigh move closer together), but it begins to extend almost immediately as the trunk moves forwards. The knee enters Heel-strike almost fully extended (i.e. almost straight), but flexion about the knee begins almost immediately to act as a shock absorber during the abrupt weight transfer. The ankle is usually at a neutral position (approximately 90°).

2.3.2. Opposite Toe-Off

Objectives; Progression over the stationary foot; Limb and trunk stability.

Gait period: Stance

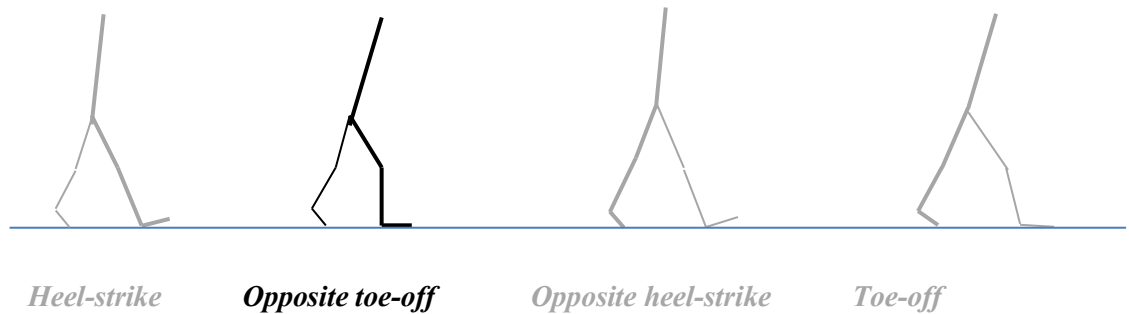


Figure 2.5. Configuration of the lower limbs at four gait events; reference limb and event is in bold.

The next phase in the gait cycle is ***opposite toe-off*** (Figure 2.5) which signals a phase of preparation as the reference limb prepares to support the weight of the whole body as the contralateral leg prepares to swing forward. The trunk begins to gain in height, as it prepares to ‘vault’ over the supporting limb, but loses speed as forward kinetic energy (energy created through the motion of the limb) is converted into gravitational potential energy (stored energy; Cavagna, Heglund & Taylor 1997). There is flexion about the hip and knee and extension about the ankle (Plantarflexion, i.e. shin and the foot move away from each other) lowering the forefoot flat onto the ground; however as soon as this movement is achieved there is flexion about the ankle (dorsiflexion) as the shin moves forwards over the stationary foot.

2.3.3. Opposite Heel-Strike

Objectives; Progression of the body beyond the supporting foot; Limb and trunk stability.

Gait period; Stance

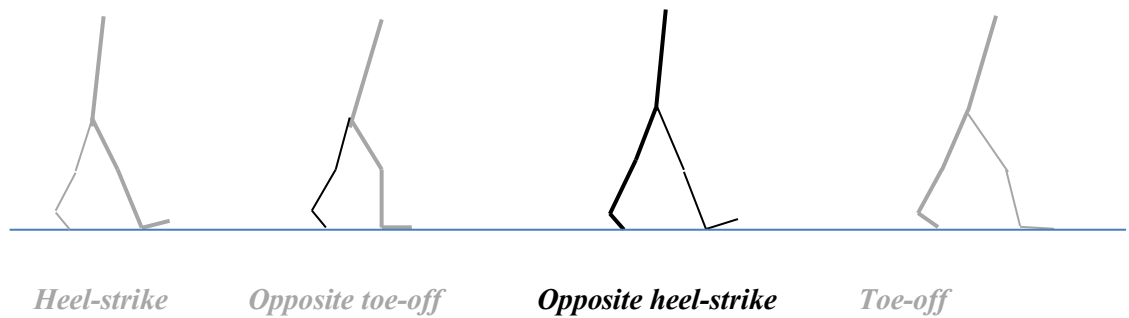


Figure 2.6. Configuration of the lower limbs at four gait events; reference limb and event is in bold.

The third phase of **opposite heel-strike** (Figure 2.6) initiates the second period of double support as the contralateral foot makes contact with the ground. The reference limb responds to this weight transfer with maximum extension about the hip (i.e. the trunk and thigh move as far apart as possible) and increased flexion (plantarflexion) about the ankle (i.e. shin and foot move closer together) and knee (i.e. the thigh and shin move closer together). The forward fall of the body weight onto the contralateral foot at Opposite Heel Strike is a major force used to advance the stance (reference) limb. It is during this phase that the generation of power at the ankle is at its greatest (Winter, 1983) although there is some controversy as to what this power is used for. Perry (1974) argues that it is used to accelerate the leg; Winter (1983) suggests it is used to accelerate the whole body and Whittle (2012) argues that it is probably a combination of the two.

2.3.4. Toe-Off

Objectives; Foot clearance for the swing leg; accelerate progression.

Gait period; Swing

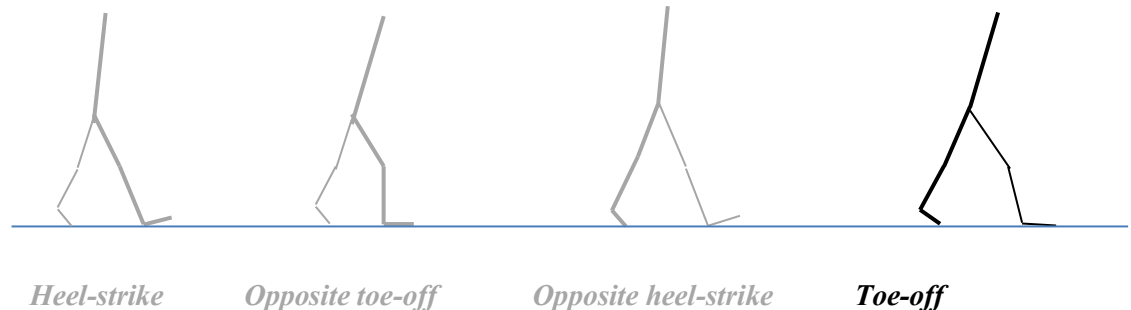


Figure 2.7. Configuration of the lower limbs at four gait events; reference limb and event is in bold.

Finally, the reference limb pushes off from the ground at **toe-off** (Figure 2.7) to begin the second phase of single support. During toe-off there is flexion about the hip (i.e. the trunk and thigh move closer together) to advance the limb, and flexion about the knee (i.e. the thigh and shin move closer together) ensures the foot lifts off the floor. However, much of the flexion about the knee is the result of hip flexion (Whittle, 2012); as the hip flexes inertia about the shin means that it is ‘left behind’ which in turn causes flexion about the knee. Flexion about the ankle reaches its maximum, ensuring the toes clear the floor as they swing forwards.

2.4. Angular kinematics of mature gait

As described above, human walking involves complex interactive control within and between the multiple joints and segments in the legs. There is much evidence to suggest that gait patterns are influenced by the range of motion and muscular power at the leg joints (DeVita and Hortobagyi, 2000; Nigg, Fisher & Ronsky, 1994). Therefore in order to provide a thorough description of the mechanisms of human gait the following section will describe the muscle control and the angular kinematics at the hip, knee and ankle needed to coordinate the multi-segmented leg to walk.

2.4.1. Muscle control

Selective muscle control is needed to move any joint in a particular direction and to combine the simultaneous flexion at one joint (e.g. knee) with the extension at another (e.g. hip) necessary for walking. Additionally, this complex multi-segmented system requires that the two legs work

in a coordinated way. These rhythmic patterns underlying locomotion (discussed in Chapter 1.) are thought to be controlled by the central pattern networks within the spinal cord (Grillner, 1973). However, the muscle groups in each leg are organised in an asynchronous manner to meet the functional requirements of stance and swing. For example, the acceptance of weight immediately after Heel-strike requires muscle activity in the ‘accepting’ leg to control extension at the hip and knee. This is then combined with flexion about the ankle as the foot is placed flat on the floor. The contralateral leg then enters Toe-off which requires flexion at the hip, knee and ankle, to ensure the leg is lifted from the ground. The selection, timing and power of muscle action is organised to control the path of the limb segment within a specific environmental context, for example walking up a steep incline will require different muscle activation to that required for walking along a level ground.

2.4.2. Angular displacements

During locomotion movements about the joints can occur in three directions (anterior-posterior; lateral; vertical). However, the largest movements occur in the anterior-posterior direction and these will be described below. Additionally, for clarity, descriptions of angular displacements of joint motion will indicate the motion of one attached segment. Typical angular displacements will now be discussed for each joint to provide a reference for later discussion;

2.4.2.1. The hip

Perry & Burnfield (2010) suggest it is more appropriate to describe the hip joints motion by the path of the thigh). There is flexion about the hip during the swing phase of the gait cycle (**Flexion** causes a reduction in the angle of the limb segments about the joint), reaching its maximum flexion (approx. 150° from vertical) during mid-swing. It extends during stance (**Extension** causes an increase in the angle of the limb segments about the joint), reaching peak extension (approx. 200° from vertical) just before Toe-off. Thus there is flexion and extension about the hip once during a complete gait cycle.

Flexion (— — — →) about the hip causes the thigh incline upwards, reducing the hip angle, extension (.....) about the hip causes the thigh to incline downwards, increasing the hip angle; see Figure 2.8 and 2.9 for illustration.

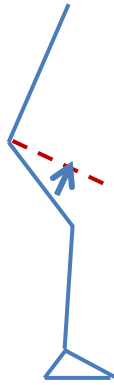


**Figure 2.8 Flexion about the hip;
incline of thigh upwards.**

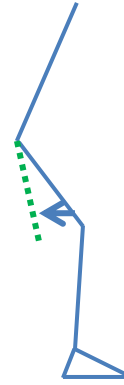


**Figure 2.9 Extension about the hip;
Incline of thigh downwards.**

2.4.2.2. The knee

There is flexion and extension twice about the knee during the gait cycle. Full extension is reached just before Heel-strike then the knee flexes as weight is transferred in stance, extending during the latter part of stance as body weight vaults over the supporting leg, and then reaches its maximum flexion early in swing phase.

Flexion (- - -) about the knee causes the shin to incline backwards, reducing the knee angle, extension (.....) about the knee causes the shin to incline forwards, increasing the knee angle; see Figure 2.10 and 2.11 for illustration.

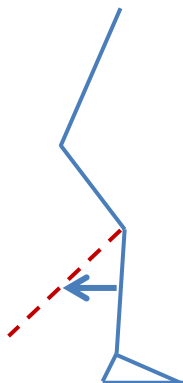


**Figure 2.10. Flexion about the knee;
knee; incline of shin backwards**

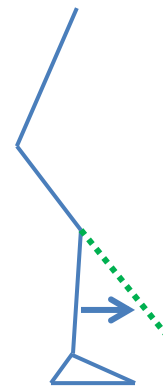


**Figure 2.11. Extension about the
incline of shin forwards**

2.4.2.3. The ankle

Motion about the ankle changes direction four times in a gait cycle. It is approximately neutral (90°) at Heel-strike, then extension (plantarflexion) brings the foot to the ground, at mid-stance the shin 'rolls' forwards over the foot, causing flexion at the ankle (dorsiflexion). Extension occurs again at Toe-off, but there is flexion about the ankle during swing to ensure that the foot clears the ground, and then the ankle resumes its neutral position until Heel-strike. The ankle plantar-flexor muscles are important for gait as they make it possible for the body to extend forwards beyond the point of support (Sutherland, Cooper & Daniel, 1977).

Flexion, or dorsiflexion (- - -) about the ankle causes the foot to incline upwards, reducing the ankle angle, extension about the ankle, or plantarflexion (.....) causes the foot to incline downwards (and backwards), increasing the ankle angle; see Figures 2.12 and 2.13 for illustration.



Figure 2.12 Flexion about the ankle (Dorsiflexion); incline of foot upwards



Figure 2.13 Extension about the ankle (Plantarflexion); incline of foot downwards

As illustrated in Figures 2.8-2.13 flexion about the hip and ankle (reduction in joint angle) occurs through an increase in segment angle (i.e. the limb inclines upwards), but as the knee joint is hinged in the opposite direction flexion about the knee occurs with a decrease in segment angle (i.e. the shin inclines backwards).

2.4.3. Strategy

Human bipedal walking uses either a hip strategy (pulling the leg forward from the hip) or an ankle strategy (pushing the limb forwards using ankle plantar flexion) to move the leg forward at Toe-off. A 'choice' of strategy implies there is 'communication' between the propulsive push at the ankle and the 'pull' at the hip. Whilst both strategies are 'acceptable' for typical walking (Mueller, Sinacore, Hoogstrate & Daly, 1994), an ankle strategy is upto 4 times more energy efficient than hip strategy (Kuo, 2002). Thus using the ankle to propel the leg forward is the most energy efficient way to walk, and the preferred walking strategy for typical adult walkers (Mueller et al., 1994). However, DeVita and Hortobagyi (2000) argue that typically developing older adults adopt the less efficient hip strategy to walk, reflecting lower muscular strength at the ankles compared to typically developing young adults. Given the lower muscular strength identified by Raynor (2001) for individuals with DCD, this is an area worthy of further investigation. If muscle strength is reduced at the ankle for individuals with DCD, as for the older population in DeVita and Hortobagyi's (2000) study, then differences in angular rotation about the joints may be apparent when comparing individuals with DCD to typically developing walkers.

2.5. Control mechanisms for gait

Walking is controlled through a complex pattern of nerve signals which are sent to the muscles which then move the limbs and joints. This task is assisted by specialised neural networks designed to produce the cyclical motor patterns needed for activities such as walking (Duysens & Van de Crommert, 1998). It is thought that these central pattern networks within the spinal cord are responsible for the rhythmic patterns underlying locomotion (Grillner, 1973), and although much of the research investigating these control mechanisms has been conducted on animals there is evidence to suggest that human locomotion is organised in a comparable way to cats (Duysens & Van de Crommert, 1998). The rhythmic patterns generated within the spinal cord are controlled by 'higher levels' in the brain such as the brainstem, cerebellum and the basal ganglia. These stereotypical movement patterns are supported by feedforward internal models which can provide both predictive and reactive control strategies. As discussed in Chapter 1, Wolpert, et al. (2003) proposes that the feedforward model use available perceptual information together with the appropriate motor programme to predict the sensory outcome of a motor command. If the planned outcome of the movement is not matched by the actual sensory outcome of a movement then an error signal is created. This enables the existing model to account for any discrepancies between the planned and the actual movement and a gradual refinement of the movement occurs to achieve optimum balance between the predicted and the

actual movement. Thus the mobile pedestrian uses feedforward internal models to predict the sensory outcome of each step, and then real-time sensory feedback is used to update the system. This is particularly important given the continuous nature of the walking task as any errors made in foot placement must be corrected almost immediately by the following foot.

The balance of feedforward to feedback information is one of the key principles for effective walking in animals (Donelan & Pearson, 2004) allowing the pedestrian to interpret and respond to dynamic feedback information with appropriate feedforward control. Too much emphasis on feedback information (whilst functional for negotiating unexpected disturbances in the pathway, Kuo, 2003), fails to allow the pedestrian to prepare for future steps and subsequently produces an inefficient walking strategy unable to modify movement to adapt to environmental constraints (such as walking on icy ground). Similarly, too much reliance on feedforward information produces a rhythmical gait which cannot respond to unexpected disturbances in the environment. Therefore, it is not surprising that Kuo (2002) argues that this combined strategy works more efficiently for movement control than either strategy alone. Furthermore O'Connor and Kuo (2005) argue that when feedforward and feedback information is appropriately balanced step-to-step variability is minimised.

As identified by Perry & Burnfield (2010) and Patla, et al., (1991) an essential element to successful walking is the ability to maintain an upright, balanced posture. The Central Nervous System (CNS) must control the biomechanics of a multi-segmented body whilst simultaneously adapting to fluctuating sensory information (discussed in detail below) as it moves around the environment. Successful interpretation and integration of this sensory information ensures that the whole body remains balanced and at the appropriate orientation to the environment. However, the constraints to postural balance control vary depending upon the demands of the task. For example, in order to maintain balance whilst standing still (static balance), when sensory information and biomechanical demands are stable, the CNS must align the body segments to keep the body's Centre of Mass (CoM) within the base of support, in this case the feet (Winter, 1995). In contrast, to maintain balance in a dynamic situation, such as walking, the CNS has to align the body segments to ensure that the Centre of Mass is kept within a moving base of support (Marigold & Patla 2002), as each alternating stance leg accepts the body's weight as it progresses forwards. The CNS must therefore be able to integrate and interpret dynamic sensory information together with the biomechanical demands of moving each body segment without affecting stability. Whilst the demands for static balance are different to those required in a dynamic situation such as walking (Winter, 1995), postural control is a fundamental skill necessary for every movement we make (Shumway-Cook and Woollacott,

2012). Additionally, Roncevalles, Jensen, Woollacott (2001) argue that effective standing balance is a prerequisite to locomotion, and therefore atypical postural control may affect walking performance (Deconinck et al, 2008).

Additionally, as the limbs move to propel the body forwards whilst walking it must be able to 'counteract' the muscular forces and torques caused by segmental action in order to maintain postural control. For example, as one leg is lifted to swing forwards, this action creates torque that the body must counteract in order to maintain postural control. This is an area of particular relevance to the study discussed in Chapter 6 as inefficient postural control whilst walking not only exposes the body to loss of balance but also wastes valuable energy resources counteracting unexpected perturbations to the system. In the typical population, both children (Assaiante, Woollacott, Amblard, 2000) and adults (Cordo & Nasher, 1982) have the ability to anticipate postural disturbance and counteract the mechanical effects that the movement may have on balance. Furthermore, Cordo & Nasher (1982) invited adults to push or pull a handle whilst standing. The authors found that postural muscles of the legs and trunk were activated before the biceps of the arm, were moved, thus counteracting the destabilising effects of the movement.

As discussed earlier, information needed to regulate postural control includes sensory input from the visual, proprioceptive and the vestibular systems (discussed in detail below). Given that two of these systems are housed within the head it is essential that it is held as stable as possible as we negotiate the environment (Berthoz & Pozzo, 1994) to provide a stable frame of reference. Assaiante and Amblard (1995) suggest that in response to balance perturbations whilst walking, the human locomotor system will minimise head movements to accurately interpret sensory feedback information used for balance control. In adults head stabilisation is said to be *articulated*, i.e. the head is stabilised at the neck separately from the trunk. The articulated mode of head stabilisation occurs developmentally as sensitivity to the orientation of the head about the trunk increases, together with increased ability to control the degrees of freedom about the neck and head (Lund & Broberg, 1983). Assaiante and Amblard (1995) argue that this model predicts that any impairment in sensorimotor or biomechanical systems may prevent or postpone development of mature, articulated head stabilisation.

In addition to the assimilation of sensory information, postural stability relies on appropriate motor responses to keep the Centre of Gravity within the base of support. These motor responses are primarily seen at the ankle or hip (Nasher, 1997; Chenn, Hsu, Chen, Chen, 2007) and are used to maintain stability during stance. Ankle strategies are most frequently used when adapting to a small external perturbation whilst standing on firm ground. Alternatively, hip

strategies are used during larger and faster perturbations and when the ground is compliant (Nasher, 1997). Typical individuals use a combination of these two strategies to maintain postural stability (Nasher, 1997; Shumway-Cook & Woollacott, 2012).

2.6. Typical walking in adults

Although the description of bipedal gait above is based on typical adult gait, little research has been done to investigate the typical walking patterns of adults in their ‘middle’ years, although there is substantial research investigating the walking patterns of older adults. This is mainly because the increased risk of falling and injury represent a serious problem for older walkers, being the 7th leading cause of death in people over 75 years (Ochs, Newberry, Lenhardt, Harkins 1985). Therefore there is a need to investigate the mechanisms underlying these more frequent falls to inform practice.

There is plenty of evidence to suggest that gait patterns change as humans’ age, with the most consistent findings from research indicating that older adults (over 70 years) walk more slowly than young adults under 65 years (Lord, Lloyd & Li, 1996; Oberg, Karsznia & Oberg, 1993). This slower walking pace may result from a shorter step length (Elble, Thomas, Higgins & Colliver, 1991; Lord, et al., 1996; Oberg, et al., 1993) and increased time spent in double support (Lord, et al., 1996; Ferrandez, Pailhous & Durup, 1990; Winter, Patla, Frank, Walt, 1990). Some researchers hypothesise that reduced speed is a compensatory measure to produce a ‘safer’ walking pattern to assist with balance constraints (Winter, et al., 1990; Woollacott & Tang, 1997). Winter, et al. (1990) investigated the walking patterns of 15 healthy older adults aged from 62-78 years. Walking performance was compared to a database of 12 young adults aged 21-28 years. The authors found the older participants walked with a significantly shorter step length, an increased double support period and lower push-off strength. Winter, et al. (1990) argue that the reduced stride length may be a conscious effort to increase stability and the reduced ankle flexor power at push-off is the result of this adaptation.

..

In contrast to the above arguments, DeVita and Hortobagyi (2000) and Nigg, et al., (1994) argue that the reduced speed of elderly gait is associated with reduced muscular strength and range of motion, particularly at the ankle. DeVita and Hortobagyi (2000) used a force platform to investigate the effects of age (young = 22 years; old = 69 years) on hip, knee and ankle torque and power, whilst walking at a self-selected speed. They found that there were group differences in contributions of the joint muscles at the hip, knee and ankle with the older group using hip extensors more, but knee extensors and ankle plantar flexors less than the younger group. This

disparity in muscle activity caused group differences in angular rotation about the joints; the older participants were more flexed about the hip (i.e. hip angle was smaller) than the younger age group, which the authors argue was due to a greater trunk inclination towards the ground. Additionally the older adults had reduced knee flexion (knee angle was larger) and ankle plantarflexion (ankle angle was smaller) during late stance compared to young adults. The authors argue that this illustrates an adaptive response at the hip to compensate for reduced ankle plantar flexion. Additionally, Nigg, et al. (1994) argue that reduced muscle strength, particularly at the knee and ankle joint, and a need for increased stability are the major constraints to walking for the older population.

2.7. Typical walking in children.

The development of walking skill follows a very predictable pattern for typically developing infants, which Shumway-Cook and Woollacott (2012) argue is the result of three sequentially emerging mechanisms; stepping pattern followed by balance control then the ability to adapt to the environment. These routes to walking are well documented, but the focus here will concentrate on the development of walking patterns beginning with a seminal study by Sutherland, Olshen, Cooper, Woo (1980) who investigated the development of gait for 186 children aged 1-7 years old from America. The children walked along a 21m walkway whilst wearing markers to identify joint positions for the hips, pelvis legs and feet. The walkway had a 2.7m lead in before the data collection area (3.4m) and a lead out of more than 4m to ensure that normal walking speed was reached and maintained during data collection. Data were collected using a motion-recording system comprising 4 motion-picture cameras and an analyser. At least 3 walks were completed for each participant and data from the 3 walks were averaged. The trial which most resembled average measurements was selected for analysis.

There are a few issues with this method of data collection particularly as certain trials were selected for analysis based on previously defined 'average' measurements, but no information is given as to how this average was determined. However there are many positive contributions to the literature from this study. It is a key work investigating the walking patterns of new walkers to age 7 years, resulting in a substantial database to use as a reference for subsequent studies in both typical and atypical populations. It describes the development, across a large sample, of a range of measures including stride length, cadence, speed and single stance together with angular rotations of the joints (hips, knees, ankles) and segments (thigh, shin, foot) of the lower limbs. From this research Sutherland et al., (1980) argue that there are 5 determinants of mature

gait; duration of single-limb stance, stride length, ratio of pelvic span to step width, cadence and walking speed. Please see Table 2.1. for definitions:

Table 2.1. Definitions for Sutherland et al.'s (1980) 5 determinants of mature gait.

Measure	Definition
Single limb stance	Amount of time (or %) during one gait cycle spent on one leg.
Stride length (m)	Distance between sequential points of heel strike of one foot, measured in meters.
Step width ratio	Step width (ankle to ankle) as a ratio to hip width
Cadence (steps/min)	Steps per minute
Speed (m/s)	Meters per second

These five characteristics can be used to differentiate the gait of young children from that of adults (Sutherland et al., 1980). For example, single limb stance, stride length and walking speed are lower in children under 7 years than adults. Cadence and step width are both higher. Todd, Lamoreux, Skinner, Johanson, St Helen, Moran and Ashley (1989) detailed the relationships between height of children and their general gait parameters. They found that cycle time increases with age but is still around 0.87m/s at age 7 years, which is considerably below the typical values for men (1.11m/s) and women (1.05m/s). The authors explain that the shorter cycle time can be explained by the shorter stride length of children compared to adults. Since children are shorter than adults it is not unreasonable that they walk with shorter strides and at a slower speed. Sutherland, et al (1988) showed that stride length is closely related to height and that that the ratio of stride length to stature is similar to that found in adults.

The developmental growth in stride length which increases linearly from the age of 1-7 years has a direct impact on the number of steps per minute (cadence) which decrease, and speed which increases as the amount of ground covered per step increases. Thus adult walking speed, cadence and stride length cannot be achieved until adequate growth occurs and stride length increases. Please see Table 2.2 for values;

Table 2.2. Typical values for the five characteristics of gait at 1year, 7years (Sutherland et al., 1988) and adults (Whittle, 2012)

Measure	Child 1 year	Child 7 year	Adult 18-49 years
Single leg stance % of gait cycle	64%	76%	78%
Walking speed meters/second	0.32-0.96m/s	0.80-1.48m/s	0.94-1.82m/s
Cadence steps/minute	127 -223s/m	115-172s/m	91-138s/m
Stride length Meters	0.29-0.58m	0.69-1.22m	1.06-1.85m
Step width ratio Ankle width: hip width	7:1 (3.5:1 by 3.5 yrs.)	3:1	<3:1

Using the data from their 1980 study, Sutherland et al., considered which variables best differentiated immature walking from mature walking. They proposed that, in order of importance, stride length is by far the best discriminator. However as stride length is closely related to height this variable was removed from the analysis. The next most important variable was speed, followed by step width ratio then duration of single-limb stance and finally cadence. Variables with the least discriminating power were the angles of the ankle at heel-strike and the presence or absence of a heel-strike.

Of the 5 measures of gait difference identified by Sutherland et al. (1980) the only measure that matures after 7 years of age in typically developing (TD) children is the ratio of pelvic span to step width, (typically maturing after 10 years) which is relatively wider in children than adults. This may be because step width is used to assist in postural stability and many of the mechanics underlying balance and postural control mature after the age of 7 (Assaiante, 1998). Single leg stance is mature by age 7. The interrelated measures of speed, cadence and stride length are all dependent upon growth.

Sutherland et al. (1980) argue that step length (and not higher cadence) is a major contributor to children's walking speed. However, what if the shorter step length was the result of kinematic deviance rather than biomechanical constraints? For example less flexion about the hip, and/or less extension about the knee during swing would reduce step length. Sutherland et al. (1980) investigated this issue by calculating the average angle at the hip and knee at Heel-strike. They

found that hip angle for children aged 2 and 7 years and adults was identical, and knee angles of children aged 2 and 7 years differed by only 3°, with 7 year old children having almost identical knee angles to adults. The findings from this study support those from Foley, Quanbury and Steinke (1979) who also found that the joint angle range for children aged 6-13 years was identical to adult values.

From the evidence presented here, it appears that there are similarities between the gait patterns of the elderly and the ‘immature’ patterns exhibited by the very young. For example, both groups spend longer in double support, (Bril & Breniere, 1993; Winter et al. 1990; Sutherland et al 1980),) and have a greater co-activation of agonist and antagonist muscles whilst walking than typically developing adults (Forssberg, 1985). All these adaptations are hypothesised by the authors to be an adaptive response to poor balance (Winter, et al. 1990; Woollacott & Tang, 1997;). Even though the aetiology of the balance constraints may differ between the two populations, with young walkers lacking experience and exposure, but older adults perhaps lacking muscular strength (Winter, et al., 1990) or have a fear of falling (Maki, 1997), highlight that the strategies used to accommodate balance constraints are similar, and may signpost a strategy used by other populations with balance difficulties such as those with DCD. However, differences between the gait patterns of the elderly and the young are apparent when analysing the angular kinematics for both populations, with angular rotations of the lower limbs reaching adults levels by the age of 3 years (Sutherland, et al., 1980) contrasting with the smaller range of motion exhibited by older walkers, attributed to reduced muscle strength (DeVita & Hortobagyi, 2000; Nigg, Fisher & Ronsky, 1994). These differences may further support the hypothesis that muscle strength is a major factor required for efficient walking patterns.

2.8. Walking patterns for individuals with DCD

Walking is a fundamental skill necessary for many activities of daily living; however, it is a skill that individuals with movement difficulties may struggle with. For example, individuals with Developmental Coordination Disorder (DCD) are often reported to be awkward in their gait, and frequently appear to stumble and walk into things (Parker & Larkin, 2003). In addition, walking is often the only independent method of transport available to many adults with DCD given that riding a bicycle and driving is often prohibitive (Cousins & Smyth, 2003). Therefore, the importance of understanding the mechanisms that underlie deviant walking skills for individuals with DCD cannot be underestimated.

Given the complexities of human bipedal walking, it is surprising that there is little retrospective evidence to suggest that infants with movement difficulties, later diagnosed as DCD, acquire these skills any later than typically developing children (Whitall & Clark, 2012). Developmental delays are only apparent if the children also have low birth weight (Holsti, Grunau & Whitfield 2002). However, qualitative studies have documented differences once children with DCD start to walk. For example Parker & Larkin (2003) noted that children with DCD have poor head control, excessive hip rotation, shorter step length, wider base of support and pronounced asymmetry. These differences may reflect the increasing environmental and task demands, as the children begin to move around their environment and need to be able to assimilate optic flow and coordinate dynamic visuo-motor information.

As discussed earlier, there is a paucity of research investigating the walking patterns of children with DCD. An early study by Woodruff, et al., (2002) investigated the possibility of classifying the walking patterns of children with DCD and to compare performance to norms established in the San Diego database (Sutherland, et al., 1980), as described earlier. Woodruff et al. (2002) used an Optical Motion Capture System (OMCS) to assess the spatio-temporal measurements of 7 children with DCD aged 6-7 years. The mean values of this data, together with the standard deviations were combined with Hotelling's T^2 statistic to produce a one-dimensional index of walking performance. The authors found there were no differences in means across four foot measurements (percentage gait cycle spent in single stance; percentage gait cycle at toe-off; percentage gait cycle at opposite-toe-off and step length as a percentage of gait cycle) between children with DCD aged 6-7 and TD children aged 3-7 years. However, group differences in variability were apparent with the DCD children showing a greater variability (standard deviation) about the means than their TD peers.

These results, when combined within the walking index, suggest that the children with DCD had more '*abnormal*' walking patterns than the comparable population of typically developing 3-7 year olds. This was illustrated by group differences in step time, foot toe-off and single stance. The authors argue that reduced standard deviation about the mean for the TD group highlights, that although the walking patterns of the TD children were not adult-like in their execution, they show a typical pattern of gait development. However, for the children with DCD, the larger standard deviations illustrated a much less systematic departure from normal walking patterns. Whilst this study has its limitations in terms of sample size and limited age range the results have been replicated in other studies (Cherng, Liang, Chen, Chen, 2009; Deconinck, et al., 2010) where the authors failed to find any mean differences in level walking patterns between children with DCD and age-matched controls.

Further investigations were carried out by Deconinck, De Clercq, Savelsbergh, Van Coster, Oostra, Dewitte and Lenoir, (2006^a) who explored the walking patterns for 20 children (mean age 7.4 years) with and without DCD. An OMCS was used to record movements whilst the children walked on a motor-driven treadmill. The authors found significant differences in mean outcome measures for several gait variables, such as shorter steps with an increased frequency for the children with DCD compared to their TD peers. However, when their gait cycles were scaled to duration the time spent in each phase of the gait cycle (double support; single support; swing) was similar to the TD children. These results suggest that the rhythmic locomotor pattern is within a typical range for both groups of participants although shorter in space and time for the children with DCD. Additionally, the children with DCD adopted a greater trunk inclination towards the ground than their TD peers whilst walking. The authors propose these are compensatory measures for deficits in neuromuscular and balance control, producing a safer walking pattern whilst finding an optimum compromise between balance control and forward propulsion.

In addition to the findings discussed above, Deconinck et al. (2006^a) calculated the mean index of walking performance as used in the Woodruff et al (2002) study. Their findings show that the walking index was significantly larger (worse) for the DCD group compared to the TD group; falling within the abnormal range. The results of this calculation reflect the increased variability in walking patterns (standard deviation from mean) for the DCD group compared to their TD peers, reiterating the findings from Woodruff et al. (2002).

Inconsistencies between these studies may be partly explained by differing methods used to collect data and highlight the importance of ecological validity when designing a study to assess walking style within the DCD population. This will ensure that findings are valid and not a measure of adaptive walking patterns selected to cope with difficult or unusual environmental conditions. Deconinck et al. (2006^a) investigated walking style by assessing walking on a treadmill. However, this approach is limited by a lack of environmental validity as this is not a natural medium for walking.

Studies comparing treadmill to over ground walking illustrate that the treadmill itself may influence walking patterns (Savelberg, Vorstenbosch, Kamman, van de Weijer and Schambardt, 1998), and visual flow (Konczak, 1994). This is particularly relevant whilst testing populations with DCD as it is well documented that children with DCD rely more heavily on visual information than their TD peers for the organisation of movement (Wann et al 1998; Deconinck, et al, 2006^b). These constraints may have affected individuals with DCD more than the TD population and highlights that even though the DCD group in Deconinck' et al's (2006^a) study

had higher mean on the M-ABC (7.3) than in Deconinck et al's (2006^b) study (i.e. fewer movement difficulties), they still had greater adaptations to walking on the treadmill compared to level walking. Differing inclusion criteria used for children with DCD may also contribute to inconsistencies in findings, with some studies using participants with higher movement ability (Deconinck et al 2006^a; Woodruff et al., 2002) than others (Deconinck et al. 2006^b).

Different measures chosen to describe the walking patterns may also have an effect on the results with mean values identifying very little difference between children with and without DCD. For example, most of the previous studies investigating the walking patterns of children with and without DCD have considered spatio-temporal variables such as stride length, step width, time spent in double support and speed. Another way to consider movement is by looking at the variability, or consistency of movement; when a movement is repeated, such as walking, it needs to be consistent. Measurement of variability can add to the description of the walking pattern, possibly indicating difficulties with the underlying mechanisms controlling movement. It could be argued that once variability entered the equation (as in the walking index, Woodruff et al., 2002) a different picture emerged for the walking patterns of individuals with DCD, with the DCD groups showing significantly greater variability in their walking patterns compared to their TD peers.

In terms of the impact of increased variability whilst walking, Maki (1997) identified that variability in step length, speed and time spent in double support seems to be positively associated with falling in older adults. The authors hypothesise that variability in these parameters destabilise the trunk, even when they widen and lower the base of support (procedures normally associated with increased stability), thus increasing the likelihood of falling. Additionally, increased variability may show that a motor task is less well automatised and requires a greater level of attention for successful execution of the movement (Shumway-Cook & Woollacott, 2002). Given the attentional demands needed to assimilate and interpret the sensory constraints of a complex and dynamic environment, this is an important consideration when investigating the walking patterns of individuals with DCD.

In order to investigate this further, Rosengren, Deconinck, DiBerardino III, Polk, Spencer-Smith, De Clercq and Lenoir (2009) used Elliptical Fourier Analysis (EFA) to investigate the complexity and variability of walking patterns for 10 children (mean age 7.4 years) with and without DCD. The phase portraits of the lower limb segments (thigh and shin) were used to assess the complexity of movement. This was achieved by calculating the number of harmonics (either 500 or 10) required to produce an accurate fit of the data; complex movement patterns require a greater number of harmonics. The authors found group differences in the phase

portraits, illustrating that the children with DCD had a greater complexity and variability of movement about the shin and thigh compared to their TD peers. Rosengren et al. (2009) argue that these differences could relate to problems for the children with DCD controlling their lower limbs compared to their TD peers, and might be an adaptive response to compensate for balance difficulties experienced by many children with DCD (Geuze, 2003; Geuze, 2005; Deconinck et al., 2010).

Causality is difficult to assess from the data discussed above; is it the balance difficulty causing greater variability and complexity *or* the greater complexity and variability causing the balance difficulties? Additionally, they identified that for the DCD group complexity and variability about the shin was significantly greater than at the thigh (although this was primarily the case during stance only). The authors suggest these group effects could be the result of differences in ankle control, although they comment that further research is needed to confirm this. There are some issues concerning this study such as small sample, narrow age range and treadmill walking, so the results must be interpreted with care. However, they do reiterate previous research where variability in motor performance for children with DCD was greater than their TD peers; For example, finger tapping (Volman & Geuze, 1998); ball catching (Estil, Ingvaldsen & Whiting); hand-foot coordination (Volman, Laroy & Jongmans, 2006) and walking, (Woodruff et al., 2002).

2.8.1. Angular kinematics for individuals with DCD.

Only two studies, to date, have investigated the joint/segment angles during walking for individuals with DCD, and both have concentrated on children under 10 years. Firstly, the study by, Rosengren, et al. (2009) discussed above, and the study by Deconinck et al. (2006^a) described on p54. Deconinck et al. (2006^a) also analysed the angular measurements of the trunk and lower limbs. They found that the children reduced their hip angle throughout the gait cycle (manifesting as greater forward inclination of the trunk). This, together with a greater flexion at the knee, was argued by the authors to be an attempt by the children with DCD to lower their centre of mass to assist with balance requirements, reiterating research with older adults (Menz, Lord, St George & Fitzpatrick, 2004). Additionally, the children with DCD had decreased extension at the ankle (plantarflexion) at toe-off and the authors argue this could be due to a lack of neuromuscular strength to propel the body forward at this key point in the gait cycle.

However, it is not clear from this study whether group differences were the result of balance/neuromuscular difficulties for individuals with DCD, exacerbated whilst walking on a treadmill, or whether they are mechanisms employed generally in more natural walking

conditions. However, given the findings from the study discussed in Chapter 4 which showed that the spatio-temporal measures were not different between groups, whilst walking along a level surface, but the step-to-step variability of those movements was significantly different, it could be hypothesised that mechanistic constraints, such as decreased extension about the ankle, may affect walking patterns for individuals with DCD even within very predictable, stable environments.

2.8.2. Muscular strength for individuals with DCD.

There have been limited investigations exploring muscular strength in individuals with DCD. One study by Raynor (2001) used a knee flexion and extension task to investigate the strength, power and muscle co-activation levels in 20 children, aged 6-10 years, with and without DCD. EMG recordings were used to measure muscle activity at the knee under three conditions; isometric (muscle strength whilst in a static position) knee flexion; isometric knee extension and isokinetic (muscle strength in a dynamic situation) knee flexion and extension. Additionally the isokinetic conditions were measured at three different speeds (120, 165 and 210 degrees/second) whilst the children “kicked their legs out” to 180° and “pulled” them back to 90°. The authors found that the children with DCD were less powerful than their TD peers for both the knee extension and flexion tasks and the difference became more apparent as velocity increased. Additionally, Raynor (2001) used a muscle co-activation ratio to investigate muscular organisation; lower levels of co-activation indicating an effective use of muscular activation to produce maximum force. She found that the children with DCD had increased levels of muscle co-activation compared to their peers, and hypothesised that this is due to a less well developed muscular organisation system.

2.9. Perceptual interpretation of the environment

How does the human body incorporate the demands of progression and stability whilst adapting to complex and often unpredictable environment? Sensory information provides a vital contribution to this process, and in particular the integration of vestibular, proprioceptive and visual information which have been identified as essential elements for the effective control of motor skills (Peterka, 2002; Sugden and Chambers, 2005; Hulme & Snowling, 2009).

2.9.1. Maturation of the sensory systems

Effective motor skills for typically developing infants evolve gradually over several years, and are heavily reliant upon visuo-perceptual input (Hulme & Snowling, 2009) however maturation

of these sensory systems occurs at different times. Therefore, whilst many of the processes needed for successful locomotion are mature by age 7 years (Sutherland et al, 1980), there are several mechanisms important for perceiving environmental change (therefore essential for safe, balanced locomotion) that mature later in childhood. The three sensory systems relevant to walking will now be discussed individually.

2.9.2. Proprioceptive processing

Proprioceptive information is used to identify the position of body segments in relation to each other. There are four sensory receptors that provide information on movement sensation; muscle, tendon, joint and cutaneous receptors. Muscle spindles are found in all skeletal muscles to provide information change in muscle length, and therefore can finely regulate muscle stretch during movement (Shumway-Cook & Woollacott, 2012). Muscle spindle information contributes to motor control at several levels of the CNS hierarchy. Golgi tendon organs are found in the tendons that attach muscles to bones, they are sensitive to changes in tension (stretch or contraction) of the muscles. There are several receptors within the joints including Raffini-type endings and Pacinian corpuscles; joint receptor information is used to signal extreme ranges of motion (Burgess & Clark, 1969) which is thought to protect the joint from injury (Abernathy, Kippers, Mackinnon, Neal & Hanrahan, 1996). Finally, there are many cutaneous receptors in the skin. Some are found at a deep level such as Pacinian corpuscles, and detect mechanical stimuli. Other receptors such as Raffini endings and Merkel's receptor are nearer the surface and monitor light pressure.

The importance of proprioceptive information to support motor control and posture is illustrated in the case of IW who has a sensory neuropathy (Cole & Cole, 1995). As a result of a viral infection IW lost all proprioceptive sensation from his feet to his neck. Eventually he realised that if he looked at a limb and 'thought' the movement, it became possible to move, using vision to provide the feedback necessary for movement control. After intense training over a period of 2 years he re-learned how to walk. IW adapted his gait by reducing the degrees of freedom about the knee and increasing his base of support which the authors propose is a strategy to assist with stability, in the absence of sufficient proprioceptive feedback. Additionally, compared to typical controls, the gait pattern of IW was slower, with a shorter cycle length, longer cycle duration and a lower cadence (Lajoie, Teasdale, Cole, et al., 1996). Furthermore, Klint, Nielsen, Cole, Sinkjaer and Grey, (2008) investigated sensory feedback of typical adults (mean 26 years) and IW whilst walking on a platform mimicking an uneven support surface. EMG activation was assessed as the participants traversed the platform at various inclines. For typical participants EMG activity increased when the platform inclined and decreased when it

declined compared to level walking. For IW, however, there were no changes in muscle activity for any platform incline. The authors argue that these results demonstrate the importance of proprioceptive feedback to accommodate the small underfoot irregularities experienced during real-life locomotion.

2.9.2.1. Development of Proprioceptive processing

¹Due to their key role in the body's reflex system the proprioceptive receptors are functional at birth. The main development of muscle spindles, Golgi tendon organs, joint and cutaneous receptors occurs 3-5 months before birth and may function reflexively from that point on. However, whilst the mechanisms are in place well before birth, the sensitivity of the proprioceptive system is thought to improve during childhood and may even continue throughout adolescence (Visser & Geuze, 2000).

Visser & Geuze (2000) used the Kinaesthetic Sensitivity test (KST), developed by Laszlo and Bairstow (1985), to examine the kinaesthetic/proprioceptive acuity of adolescent boys aged 11¹/₂-16¹/₂ years, divided into two groups (11¹/₂-14 years; 14-16¹/₂ years). The findings from this study were enhanced with normative data for 5-12 year old children provided in the manual of the KST. Kinaesthetic acuity of the left and right arm was tested as the children were asked to judge which arm went higher as the arms were pulled up and down a covered slope. The authors found that there was a fairly continuous development of kinaesthetic acuity from the age of 5 to 16¹/₂ years. However the scores for the adolescent age group (11¹/₂-14 years) varied considerably which the authors argue could be due to the physical changes occurring during the growth spurt.

The Kinaesthetic Sensitivity Test (KST) has received criticism as it only assesses the acuity of the limb position sense, but not passive or active motion sense, two important areas of kinaesthesia. The KST has also been criticised for psychometric shortcomings (Lord & Hulme, 1987^b), poor accuracy (Doyle, Elliott, Connolly, 1986) and ecological validity (Elliott, Connolly, Doyle, 1986), thus findings from this study must be viewed with caution. Whilst the task used by Visser & Geuze (2000) involves an arm movement, the proprioceptive processing used by the CNS to form a mental model of where the arm is in space is the same for the leg. Thus, findings from Visser & Geuze's (2000) study suggest that there is a developmental progression in kinaesthetic acuity which could affect the sensitivity of children and adolescents

¹ The term proprioception is used throughout this thesis to describe the awareness of the position and movement of the parts of the body through sensory information sent from the muscles and joints. However, occasionally the term kinaesthesia is used particularly when it forms part of an assessment tool title.

to describe the spatial and relational arrangement of the legs with reference to their environment, which could subsequently affect efficient environmental navigation.

2.9.3. Vestibular processing

The vestibular system is located in the vestibule of the inner ear and is comprised of two main components; the *semi-circular canals* and the *otolith organs*. When the head moves small hairs in the otolith organs and semi-circular canals sway and detect movement of the head. The three semi-circular canals are each positioned at right angles to the other two to detect rotational movements of the head in any direction. Thus the vestibular system can be likened to a gyroscope that assists with orientation, sensing changes in linear and angular speed together with the directional pull of gravity. The outputs of vestibular information enter the brain via the pons, ascending up through the medulla, reticular formation, cerebellum, basal ganglia and the thalamus to the cerebral cortex. Additionally, vestibular information is sent to the oculomotor complex where the vestibulo-ocular reflex, which rotates the eyes in the opposite direction to head movement, is used to stabilise visual images on the retina during head movements (Tanguy, Quark, Etard, Gauthier & Denise, 2008). This provides a stable frame of reference to assist with the maintenance of postural stability whilst walking.

Vestibular information is important for many dynamic motor activities including walking, particularly when walking over obstacles or an irregular terrain. Nasher (1997) argues that it is the most important and reliable sensor for postural control. Two studies by Chou and colleagues investigated strategies used to maintain balance whilst traversing an obstacle of varying heights for young (Chou, et al., Kaufman, Brey, Drafanich, 2001) and older (Chou, Kaufman, Hahn and Brey, 2003) adults. Their findings show that for young adults the medio-lateral movements of the Centre of Mass were not significantly different as the height of the obstacle increased. The authors argue this is a successful strategy to control balance, keeping the body mass within the base of support, avoiding imbalance. However, older adults with balance/vestibular impairments (Chou, et al., 2003) had significantly greater lateral movement of the Centre of Mass when traversing higher obstacles compared to non-balance impaired elderly controls. This behaviour may illustrate that modulations of the vestibular inputs to detect changes in angular and linear velocities during motion appear to be less efficient for individuals with vestibular impairments.

2.9.3.1 Development of vestibular processing

The vestibular system is fully developed structurally well before birth, but there is research to suggest that vestibular processing is subject to developmental changes over time. Assaiante & Amblard (1995, 1993) investigated the changes in strategies used to control balance with age.

Based on the premise that stabilisation of the head is a vital contributor to stable vestibular information they investigated changes in control of the head, arms, and trunk (HAT) body segments from early walkers up to 10 years.

Assaiante & Amblard (1995, 1993) suggest that balance and locomotion can be organised into one of two stable reference frames. Firstly, the support surface on which the subject walks and secondly, gravitational pull. Also, the head can be stabilised in two different ways either *en bloc* where the head and the trunk move together or *articulated* where the head moves freely. They argue that when using the support surface as reference, the children organised balance responses from the feet up towards the head (ascending temporal organisation of balance control), using mainly proprioceptive cues from the feet (based on EMG activity from the tibia anterior muscle). In contrast when the children stabilised the head using visual and vestibular information balance was organised from the head down towards the feet (descending temporal organisation of balance control), this changed developmentally. The authors found that from the acquisition of stance until about 6 years children organise locomotion from the bottom up using the support system as a reference and controlling head movements *en bloc* to reduce the degrees of freedom to be controlled. During this period children learn to stabilise the hips then shoulders and finally the head. At about 7 years, with mastery of control of the head, the head control changes to an articulated mode and top down organisation of balance during locomotion becomes dominant. Thus the increased use of stabilisation at the hip and neck ensures that head movements are relatively independent from perturbations to the legs or trunk providing a stable frame of reference to interpret vital sensory information.

2.9.4. Visual processing

Vision provides information about the surrounding environment, both near and distant. This allows the individual to not only regulate movement based on feedback control, but also to use feed-forward information from distant visual sampling to plan and adapt movement strategies (Patla, 1998). Additionally, the visual system provides information as we progress through the environment both globally as a whole ‘body’ and as a series of inter-related body segments. As such it is perfectly suited to assist in locomotion.

Light enters the eye through the cornea, but visual processing begins in the receptive surface at the back of the eye; the retina. There are two types of receptors in the retina, rods and cones, but they are not evenly distributed. Cones are highly concentrated at the fovea, to maximise visual acuity. Being able to move the eyes independently of the head and the head independently of the body allows humans to scan the environment without having to move the whole body. Visual

information from the retina travels along the optic nerve of each eye to the Lateral Geniculate Nucleus, at either side of, and forming part of, the thalamus. From there fibres forming the optic radiations project to the primary visual cortex. Parallel processing continues as visual information travels along the dorsal stream to the posterior parietal region where it is used to support movement and along the ventral stream to the inferotemporal cortex where it is used to recognise objects and faces. Milner and Goodale (1995, 2006) argue that these pathways provide two important visual functions relating to perception and action; supporting perceptual theories such as The Dynamical Systems Approach, discussed in chapter 1, which emphasises the relationship between vision and motion with the environment.

As people walk about the environment they fixate on task-relevant objects (object fixation) such as an obstacle in the path, but we also travel fixate, where gaze is anchored 2-3 steps in front of the body (Patla and Vickers, 1997, Land, 2006) allowing optic flow to be processed. Optic flow is a term introduced by Gibson (1950, 1966) to describe how, as an individual moves about the environment the fluctuating patterns of light can help to define the characteristics of objects and surfaces. This information from the optic array can help specify the layout of shapes and objects in relation to the observer, together with defining the observer's movements with respect to the world. Gibson (1950, 1966) argued for the importance of optic flow for affordance perception, as discussed in chapter 1, to inform possibilities for action within the environment.

Patla and Vickers (1997) argue that travel fixations account for 60% of all fixations during locomotion, with object fixations being used to solve complex locomotor problems such as obstacle negotiation and changing direction. It would make sense that as a task increases in difficulty vision becomes more active and there is an increase in the fixations to task relevant information, which in a challenging environment could be argued to be a solid foot hold. Patla and Vickers (2003) confirmed the dominant use of travel fixations in more challenging locomotive situation; whilst stepping on irregularly placed stepping stones. They argue that this indicates the use of visual information obtained from travel fixations is used for planning and control of future steps, and is as task relevant as the need for object fixations to a secure foothold incurred through irregular stepping surfaces.

2.9.4.1. Development of visual processing

In contrast to the previous two sensory systems the visual system undergoes significant maturity after birth, being the last sensory system to develop (Gottlieb, 1971). Abernathy, et al. (2005) argues that visual acuity matures at a rate to support the movement requirements of each developmental stage. Furthermore, the development of perception of affordances to negotiate stationary and moving objects in the travel path develops in accordance with the dynamical

systems theory; refining the ‘fit’ between the perceiver and the environment with age and experience. For example, perceivers first learn to scale their actions to accommodate the static properties (height, angle, size) of objects. Studies investigating the typical development of this skill have shown that children aged 6-10 years can make accurate judgements concerning scalability of barriers at different heights in relation to their own characteristics (Pufall & Dunbar, 1992). Additionally, children aged 8-10 years can tailor their movements (like adults) to walk through stationary apertures of varying sizes (Wilmot & Barnett, 2011).

However, the visual skills needed to negotiate safely around moving objects may not be fully mature until adulthood (Wann, Poulter & Purcell, 2011). For example, as an object moves closer the image on the retina becomes larger, almost all locomotor animals use the process of change in optical size (or looming) to negotiate their environment (Field & Wann, 2005). Given the importance of sensitivity to looming, particularly to judge time-to-contact with moving objects (such as a moving car when crossing the road), it is clear that any deficit in this skill can have serious consequences. In fact, Toroyan and Peden (2007) argue that children’s visual limitations are a key factor in the high death rate of pedestrians under 15 years old.

2.9.5. Integration of sensory input whilst walking

In order to move the multi-segmented body smoothly and adaptively within a dynamic environment integration of visual, proprioceptive and vestibular information is clearly important to sense where the body is in space with respect to the environment and gravity, and whether or not it is moving (as proposed by Bernstein, 1967). Multi-sensory information can only work effectively if it can easily be differentiated, but also simultaneously integrated (Brill & Ledebt, 1998). The CNS reweights (changes the emphasis of) visual, vestibular and proprioceptive information dependent upon the specific demands of the task and environmental conditions (Peterka, 2002; Oie, et al., 2002; Bair, Kiemal, Jeka, Clark, 2007), supporting the ecological approach to motor control. Peterka (2002) argues that sensory integration is processed in a linear fashion when conditions are stable, but when sensory stimulus changes, as in walking, then nonlinearities occur. For example if proprioceptive perturbations increase whilst walking along an irregular terrain, there will be increased utilisation of vestibular and/or visual cues (Peterka, 2002). Thus the CNS can ‘download’ reliable sensory information whilst ‘down-weighting’ less reliable proprioceptive information from the feet.

Usually, sensory information from the different modalities provides an accurate picture for the CNS to interpret, however occasionally sensory information may provide contradictory information for the brain to interpret. In order to resolve this conflict there is a hierarchy of

sensory input with visual information being dominant over the other two. This is demonstrated by the 'swinging room' experiments by Lee and Aronson (1974) using the same paradigm as that used by Wann et al (1998), described in section 1.5. using adult participants. However, reactions were similar as the adults reacted to the changing visual information by adapting their posture as if there was a threat to balance even though information from the mechanisms of the joints and muscles (proprioceptive system) and the vestibular system did not indicate sense any loss of balance. Given the importance of information from the vestibular and the visual systems for navigational purposes (both systems are located in the head) there is little surprise that head stabilisation is a critical issue for successful interaction with the environment (Assaiante & Amblard, 1993; Berthoz, and Pozzo, 1994). If the head were not stable during movement sensory information would have to be disentangled from noise created by head movement. Berthoz, and Pozzo, (1998) explain that the head is stabilised during walking to ensure visual information is accurate and facilitates the integration of vestibular information through the vestibular-ocular reflex (Pozzo, Berthoz & Lefort, 1990). Berthoz and Pozzo (1994) argue that to protect gaze stability, head stabilisation is independent of the movement of the trunk and requires input from the vestibular system as patients with vestibular deficits (bilateral labyrinthine lesions) cannot stabilise their heads in this fashion. Additionally, Assaiante, et al., (2011) claim that for typical adults the head is "perfectly stabilised in space during locomotor tasks" (p. 236) creating a frame of reference for the organisation of movement for the whole body.

2.9.5.1. Development of sensory integration

As discussed above, integration of sensory information is essential to effectively negotiate a dynamic environment. However, there is evidence to suggest that the maturity of the sensory systems doesn't happen at the same rate. This, according to the dynamical systems approach, can act as a rate limiter as slower maturing systems become a constraint to movement. Several studies have considered the effect of development on sensory integration for effective postural control. Given, postural control is a prerequisite for walking (Roncevalles, et al., 2001) the development of the ability to integrate sensory information for controlling posture (Shumway-Cook and Woollacott, 1985; Forssberg and Nashner 1982) is of interest to this study. However, it must be noted that sensory integration for walking is a different task to that required for postural control, given that walking involves movement within the environment, rather than stationary postural control. Notwithstanding these limitations findings from studies investigating postural control can inform research about the maturity of sensory integration.

The contribution of visual information to postural control is by far the most studied and typically uses one of two paradigms; Firstly, Lee and Aronson's (1974) moving room paradigm (discussed above) has been used on several occasions to demonstrate a developmental progression in the use of visual flow to control postural balance. Foster, Sveistrup & Woollacott (1996) investigated sway responses to changes in visual flow for children aged 5 months to 10 years and compared the results to those of adults under similar experimental conditions. Sway responses were recorded from a video camera positioned in a one-way mirror and muscle responses were gathered using EMG. The authors found that children as young as 5 months, with no experience of independent locomotion, swayed in response to the room movements even though vestibular and proprioceptive inputs remained stable. Additionally, the magnitude of sway decreased with age. The authors argue that the large sway responses in the younger groups indicate an inability to switch from the unreliable source of visual information to the more reliable proprioceptive or vestibular information, and suggest that the ability to resolve this conflict develops with age and experience.

Secondly, the contribution of vision to postural control has been investigated whilst eyes are closed and comparing performance to eyes open (Forssberg & Nashner, 1982; Shumway-Cook and Woollacott, 1985). Shumway-Cook and Woollacott (1985) used a moveable platform to investigate the underlying mechanisms of balance in typical children aged 5-10 years (divided into 3 groups; 15-31 months; 4-6 years; 7-10 years). A movable platform was used to displace movement either in an anterior-posterior direction or extension/flexion at the ankle. Additionally there were two visual conditions as participants were asked to perform the tasks with eyes open and closed. EMG was used to gather amplitude and latency of muscle responses and cinematography recorded amplitude of sway.

The results of ankle perturbations under the two visual conditions demonstrated that there was a developmental progression in the use of visual and proprioceptive information; children aged 4-6 years depended mainly on visual information to control posture, demonstrated by increased postural sway when vision was removed, but this shifted to a mature mode between 7-10 years using a combination of visual information and proprioceptive input from the ankle joints. However Sparto, Redfern, Jasko, Casselbrant, Mandel, & Furman, (2006) suggest these mature strategies for postural control may occur later in development. They argue that whilst children aged 7-12 years and adults adopt similar strategies to use dynamic visual cues to assist with postural control, but whilst standing on a fixed platform the children responded with a greater sway. This suggests that they did not use proprioceptive cues to stabilise posture to the same extent as the adults.

Cuisinier, Olivier, Vaugoyeau, Nougier & Assaiante (2011) investigated the development of postural control strategies for children aged 7-11 years together with adults. They measured postural performance using a force platform as participants stood in a semi-tandem position with the right foot in front of the left. Participants were asked to stand as still as possible in two 'proprioceptive' conditions (with and without vibration at the ankles) while visual information remained available for both conditions. Results revealed that during the ankle perturbation all the children increased their sway speed, but the adults did not. There was a linear reduction (improvement) in postural sway between the ages of 7-10 years, but no change for 10-11 year old children. The authors suggest that reweighting (change in the hierarchy of sensory information to the CNS) visual and proprioceptive information is still maturing between 7 and 11 years. Furthermore they suggest that the predominant use of vision used to resolve sensory conflict by adults (Lee & Aronson, 1974) could not fully compensate for the alteration of proprioceptive information in the children. But, importantly they argue that there is still improvement in these strategies until adulthood, reiterating the findings of Sparto, et al. (2006) that children do not reach adult-like levels of visual and proprioceptive integration before the age of 12 years.

These underlying mechanisms may affect the efficiency with which immature walkers negotiate their environment, and, therefore postural adaptations may differ to those of mature walkers. This may be particularly relevant when investigating individuals with DCD who do not follow typical developmental progression, and have deficits in the integration of sensory information (Deconinck et al 2006^b; Deconinck et al, 2007; Wilson & McKenzie, 1998; Geuze, 2003). Additionally, given the motor control theories reviewed in Chapter 1 and the importance of both predictive (feedforward) and reactive (feedback) control strategies (internal modelling) for successful walking patterns, it is easy to see that any deficits in sensory processing could affect the accuracy of stepping behaviour (Information processing theory) and subsequently degrade the individual's ability to perceive environmental constraints for the walking task (Ecological theory). The studies reported in Chapters 6 and 7 discuss the difficulties of integrating visual, proprioceptive and vestibular information for children with DCD (Deconinck et al 2006^b; Deconinck et al, 2007; Wilson & McKenzie, 1998; Geuze, 2003). These deficits may negatively affect the balance between feedback and feedforward information for individuals with DCD and may affect the flexibility of the lower limbs to adapt to changing environmental constraints.

2.10. Measurement of gait.

2.10.1. The nature of the walking task

Walking is a very common human activity and one that has been analysed extensively. The methods used to gather data vary considerably between studies and each measurement technique differs in cost, ease of use and completeness of data produced. However, the one consistent factor in all walking studies is the need for a long enough uncluttered walkway to capture the minimum number of strides necessary for analysis. The ideal length of the walkway has yet to be verified, although Whittle (2012) suggests that for fit young adults an 8m walkway is sufficient but 10-12m is preferable to allow faster walkers to 'get into their pace'. Typically, data collection using a level, uncluttered walkway follows one of two options. Option 1; participants walk along the complete length of the walkway then stop, turn and repeat the walk again. Option 2; participants walk continuously for a specific length of time (e.g. 2 minutes) up and down the pathway. The data collection area for both options is positioned towards the middle of the walkway to ensure that participants are walking at normal speed and not accelerating/decelerating from a starting/stopping position (as in option 1), or recovering from a turn (as in option 2).

Data collection areas also vary in length from approximately 3m (Sutherland et al., 1980) to 6m long (Perry & Burnfield, 2012) enabling data to be collected from a minimum of 2 strides per walk (Sutherland et al., 1980). There are advantages and disadvantages to both methods of data collection, for example option 1 will require a longer walkway to allow the participants to reach their normal walking speed before they reach the data collection area and this may be difficult to accommodate within the structural confines of some buildings. Additionally, as walking is a continuous and cyclical movement, option 1 doesn't replicate real life and may interrupt the walking rhythm as the participants stop and start at the end of each walk, which will be a maximum of 10m. Option 2 allows the participants to settle into their natural rhythm as they are continuously walking for a length of time; however care must be given to tailor the time constraints to the population being investigated, and to balance the needs of data collection with boredom factors, particularly when testing small children, when walking for a long period of time.

Where space is severely limited the use of treadmills are a popular option and they have the advantage that data can be collected from a long continuous straight walk. However several studies have identified subtle differences in overground and treadmill walking particularly as there is a limited length to a treadmill which may shorten the step of participants. Additionally,

the reduction of visual flow experienced whilst walking on a treadmill (as the participant is effectively standing still whilst their legs ‘do the walking’) may affect walking patterns (Konczak, 1994).

Savelberg, et al. (1998) demonstrated that there were significant differences in kinematic patterns during treadmill and over land walking. For example intra-stride variability was greater on the treadmill compared to overground walking. Furthermore, Savelberg, et al. (1998) argue that the most important differences are related to speed changes in the treadmill belt as the participants feet decelerate at heel-strike and accelerate at toe-off manifesting in a transfer of energy to the treadmill. These difficulties can be overcome to some extent if the treadmill belt is sufficiently stiff and participants are acclimatised to treadmill walking (Riley, Paolino, Croce et al., 2008). However treadmill walking may not be suitable for certain populations, such as the elderly or those with balance difficulties as acclimatisation to the strategies needed for walking on a treadmill may take longer. Additionally, given that children with DCD rely more on vision than their TD peers for the guidance of movement (Deconinck et al., 2006^a; Wann, et al., 1998) this may not be an appropriate medium to test this population either.

Another variable that can affect the validity of results from gait analysis is walking speed. This may vary according to the requirements of the task or the population being investigated, for example when asked to walk at their preferred pace, older adults walk more slowly than younger adults (Menz, Lord & Fitzpatrick, 2003^b). Researchers usually ask participants to walk at a self-selected pace, however some researchers wish to control the speed of walking as many measurable parameters of gait (such as cadence) are affected by speed. Walking under these controlled conditions may affect walking patterns and will also reduce the ecological validity of the findings. This may highlight a further problem when gathering data whilst participants walk on a treadmill as speed is often set (similar constraints also exist when walking on a treadmill).

Zijlstra, Rutgers, Hof and Van Weerden (1995) asked typically developing adults to walk to the rhythm of a metronome. They found that there were significant differences when asked to walk at their preferred speed compared to the walk constrained by the rhythm of the metronome. The authors explain that walking patterns under normal conditions were characterised by a linear relationship between step frequency and step length, however when participants had to adjust their walking to the temporal constraints of the metronome this resulted in changes in step length to modulate the frequency of leg movements to the beat. Additionally participants with motor control problems may find walking under these conditions challenging (Whittle, 2012) and the attentional demands required to organise the motor system to an external rhythm may affect the validity of the results.

2.10.2. Measures of gait patterns

There are many different measures used to analyse human walking patterns and the investigative style and population being studied will affect which measurements are chosen. For example, gait is very obviously atypical in some populations, such as those with stroke or Parkinson's disease and data collected for *output measures* (i.e. the observable outcome of a movement command) is sufficient to identify where gait patterns deviate from the norm. Generally, the output measures are chosen to measure the five most important characteristics of typical mature gait as identified by Sutherland, et al. (1988) which comprise; duration of single-limb stance, stride length, ratio of pelvic span to step width (discussed in more detail in section 2.6.), cadence, and walking speed. However, for individuals with less overt atypical gait pattern than seen for example following a stroke, a deeper analysis is needed to describe their walking patterns. These strategies look at variability and have been useful for investigating older samples. For example Maki (1997) found that stride-to-stride variability in an individual's step length seems to be positively associated with falling in older adults.

An alternative method to describe normal gait compared to abnormal gait is through gait kinematics or the movement of the joints and segments of the body as it moves through space. This method is useful to understand how the separate units (segments, joints) work together and can signpost the underlying mechanisms behind the observable outcome of a movement. For the majority of the population the coordination of all the joints and segments is seamlessly organised and almost automatic. This allows pedestrians to focus on important aspects of the environment, such as obstacles in the pathway or changing terrain.

Small differences in the angular measurements of some joints or segments can severely impact the efficiency of gait, which may in turn affect the ability to automate the walking pattern. For example, Winter, et al. (1990) compared the walking patterns of 15 healthy older adults aged 62-78 years to 12 younger adults aged 21-18 years. Kinematic data were collected for at least 10 walking trials using a digitized motion capture system and a force plate. This system tracked the motion of reflective markers attached to the joints and segments of the legs. Together with findings of a shorter step length and longer time spent in double support, the authors identified that the ankle plantar flexors had significantly less power during push-off. Winter et al. (1990) hypothesised that this could result from reduced muscle strength in the ankle plantar flexor muscles, which may have a causal role in the shorter step of the older adults. Alternatively, the reduced push-off could be a strategy to assist with stability as the power generated at push-off is highly destabilising.

This example illustrates how differences at a joint level can explain deviant outcome measures of gait. Therefore, kinematic analysis of the joints and segments, taken at each of the four phases of the gait cycle, is a useful strategy to assess how the individual meets the specific demands of each event and can signpost possible causal effects. The study discussed in Chapter 4 uses spatio-temporal measures to describe the gait patterns of individuals with and without DCD whilst walking on level ground. These analyses are enhanced with measures of step-to-step variability and angular measurements of joints and segments. The resultant findings provide a detailed description of walking parameters for the individuals with DCD and their typically developing peers.

One final approach to be discussed is the analysis of gait symmetry, which can be defined as perfect agreement between the movements of the left and right lower limbs (Sadeghi, Allard, Prince, Labelle, 2000). Gait symmetry is a good indicator of the degree of control used in gait as it is a measure of parallels between the lower limbs for measures such as step length and time spent in swing. Additionally, symmetrical gait is regarded as the most efficient way to walk (Draper, 2000), and although often assumed for the typical population, research findings are not unified. For example, Claeys (1983) and Hamill, Bates & Knutzen (1983) found no significant differences in ground reaction force between the right and left foot. In contrast, several other researches have reported asymmetry in typical gait including Ounpuu and Winter (1986) who reported asymmetrical electromyographical activities of leg muscles for typical walkers (this issue is discussed further in Chapter 5).

In pathological gait such as for amputees with a prosthetic limb (Skinner, & Effeney, 1985) or individuals affected by a stroke (Griffin, Olney & McBride, 1995) marked differences are seen in the symmetry between affected and non-affected lower limbs whilst walking. There are several consequences to asymmetrical gait patterns for post-stroke patients such as challenges to stability and reduced activity levels. Consequently reduction of asymmetry is commonly addressed during rehabilitation (Wall & Turnbull, 1986). However, rather less is known about the symmetry of gait for populations such as those with DCD, but given the importance of symmetrical gait for efficient walking patterns and balance control this needs investigation. The study reported in Chapter 5 discusses a preliminary investigation into gait symmetry for individuals with and without DCD.

2.10.3. Instrumentation

Instrumentation designed to gather data on gait characteristics can be placed along a ‘technological spectrum’. At one end there is no use of technology at all, but this progresses

right though to increasingly more sophisticated (and expensive) data collection equipment. A brief summary of the different methods used will follow.

At the simplest (and cheapest) end of the spectrum *visual gait analysis* uses no technology at all and the researcher observes the participant's gait patterns that are visible to the human eye. Measures such as excessive extension/flexion about the knee; abnormal hip rotation; abnormal foot contact, insufficient push off, or rhythmic disturbances can be observed using this approach (Whittle, 2012). This method is very versatile and immediate and can be assessed in many environments, having the potential to produce ecologically valid information. Additionally it is not reliant upon complicated technology for data collection or interpretation. However, visual gait analysis is subjective and is highly dependent upon the skill of the observer; it is also transitory with no permanent record of the gait pattern for later analysis. Krebs, Edelstein & Fishman (1985) found visual gait analysis to be only *moderately* reliable between three observers.

Next along the technological spectrum is assessment using video recordings. This method can reduce the amount of walks required to collect data when compared to visual analysis, and it provides a permanent record of the walking patterns. It is usable in a variety of environments and also enables analysis of high-speed events not visible to the naked eye as the video tape can be slowed down during a replay. In addition to the subjective data mentioned above, video analysis (with the addition of a measured walkway and a stop watch) can also capture some objective variables such as cycle time, cadence, stride length and speed. The addition of on-screen digitisers can assist in gathering information on joint angles, although the accuracy of such measures is not high as joints cannot always be observed at an ideal angle (Whittle, 2012).

The use of instrumented walkways enables objective quantitative measurement of the timings of foot contact and the position of the foot on the ground. There are many different designs, but typically they comprise a walkway covered in an electrically conductive material such as sheet metal. Participants walk over the walkway in shoes with suitable positioned electrical contacts attached to complete the electrical circuit. This type of walkway together with its associated software, quantifies the following spatio-temporal variables; speed, cadence, step length, single and double limb support and the duration and stride width for individual steps. However, the participant is encumbered with trailing wires connecting the data from foot contact to a computer which may affect walking patterns. Alternatively, there are some walkways that contain all the necessary electrical equipment within the walkway itself to detect the position of the foot. Thus the same variables can be detected as those mentioned above but participants can walk unencumbered by wires. These walkways are moveable but need to be positioned on a flat

surface, and there is only a short area available for assessment, with the walkway typically approximately 5m long with a data collection area of between 3-4 m (e.g. GAITRite).

Kinematics of gait can be measured using optical infra-red motion capture systems which can provide a three-dimensional record of gait. This is achieved using a series of measurements viewed from more than one viewpoint and therefore requires several cameras positioned around a walkway. Participants walk along a specified walkway with a series of reflective 'markers' attached to their limbs, usually close to the joint centres and/or limb segments. Position of the markers is recorded by the cameras, and reconstructed in 3-D space. Data collection using motion capture systems produces a thorough and quantifiable description of gait, adding to those measures described above by providing data on the position and orientation of body segments along with the angular rotations of the joints and segments. Additionally, fast sampling frequencies ensure that movements are captured precisely and high resolution measurement ensures the images provide detailed optics. However, it is expensive and can only be used within a laboratory setting and a lot of data are produced that can be time consuming to analyse.

2.11. Aims and research questions for the thesis

Four main questions were explored in this thesis, as detailed below. Each question is discussed within its own chapter, where more specific hypotheses are discussed following description of relevant literature reviews.

An important element of this study was to address some of the methodological limitations of previous work in this area. Therefore implicit within this study was the use of stringent inclusion criteria to ensure that all participants in the DCD group met DSM-5 criteria. The walking task was designed to provide a naturalistic baseline measure of walking patterns. Therefore participants walked along a level, uncluttered surface continuously for 2 minutes to ensure that data were collected in a realistic but controlled laboratory environment. Additionally, the data were analysed using '*spatio-temporal*' measures such as speed, step length, step width etc. together with variability, angular rotations and symmetry of the lower limbs. This allowed the following question to be addressed;

1. Are there differences in gait patterns between individuals with and without DCD whilst walking on level ground? (Studies reported in chapters 4 and 5).

Whilst data collected from the level walkway is an essential part of this thesis, it is not fully representative of real life. Not only do we have to process rich perceptual information to safely forge a path to our destination, this perceptual information must be integrated with the motor demands required to move the body forwards and keep it balanced, whilst simultaneously adapting to different ground terrains. It has been suggested that adjustments are made using visual, proprioceptive and vestibular information to maintain balance and postural control (Oie, et al., 2002), but it seems that individuals with DCD have difficulty readjusting movement using these sources of information (Wilson, & McKenzie, 1998), which may result in less efficient walking patterns. However, there is little research, to date, investigating how these difficulties manifest in the walking patterns of individuals with DCD. This is a vital consideration given the importance of walking to access everyday activities, and the lack of uncluttered flat terrain to walk on. Therefore this research further examined gait in individuals with and without DCD using two distinct manipulations, namely: walking on an unpredictable terrain (challenging the interpretation of proprioceptive information) and walking with reduced visual feedback (Challenging visual planning skills), therefore investigating the following questions;

2. Given any differences in gait pattern for the two groups observed in relation to Question 1, are these exacerbated when walking over an irregular terrain? (Study reported in chapter 6)

3. Does visual occlusion of the feet differentially affect gait patterns between individuals with and without DCD; (studies reported in chapter 7)

i) Whilst walking on level ground?

ii) Whilst walking on irregular terrain?

All of the previous studies investigating the walking patterns for individuals with DCD have only focused on young children (age <10 years), with each study sampling a narrow age range (typically 2-3years). However, DCD is a lifelong condition with motor deficits having a negative impact on daily living throughout adolescence and into adulthood (Cousins & Smyth, 2003). Therefore, considering walking patterns throughout childhood and into adulthood is vital given that it is an essential skill necessary for independent access to everyday activities.

Additionally, Sutherland et al., (1988) argue that gait patterns for typically developing children are mature by 7 years of age (whilst traversing a level terrain). However research with typically developing children has shown a distinct developmental trend in the maturation of the perceptual mechanisms needed to successfully negotiate the environment (Visser & Geuze, 2000; Assaiante & Amblard; 1995, 1993; Wann, Poulter & Purcell, 2011). These findings predict a differential effect on gait adaptations of children compared to teenagers and adults when negotiating more complex environments (irregular terrain, or visually occluded walking). Furthermore, constraints to visuo-perceptual development for children with DCD (Wann et al., 1998; Mon-Williams, et al., 1999; Shumway-Cook & Woollacott, 1985) predicts that adaptive walking patterns could be less efficient compared to teenagers and adults with DCD and their TD peers.

4. Are there significant age effects between individuals aged 8-32 years with and without DCD for any of the above questions? (Findings reported in chapters 4-7)

Chapter 3: Methods: Recruitment and Selection

3.1. Introduction

This thesis investigated the walking patterns of individuals aged 8-32 years with and without DCD. Gait was measured under 4 different conditions; level walking; walking on an irregular terrain; visually occluded level walking and visually occluded walking on an irregular terrain, the results of which are discussed in Chapters 4-8. The methods employed to collect the data were the same for all conditions. This chapter will discuss the participant selection process, the experimental paradigm and the methods of data processing used to explore the five research questions. Ethical approval was obtained from the University research Ethics Committee at Oxford Brookes University (Appendix I).

3.2. Participants

The same participants were used throughout and this section provides the relevant background information for these participants.

Typically developing (TD) children were recruited from primary and secondary schools in the Oxfordshire area and from the database of the Oxford Brookes Babylab (a database of children whose parents are interested in taking part in research). Recruitment comes from a variety of sources; babylab coffee mornings, internet/Facebook, and leaflets in children's centres, sports clubs. TD adults were recruited from Oxford Brookes University, the Department of Psychology Participant Panel and Oxford Brookes Digest for Research Activity. The Department of Psychology Participant Panel is a reward based system designed to encourage students to participate in current research. Researchers post details of their study and students sign-up to studies they are interested in. Students receive course credits for participation. The Oxford Brookes Digest for Research Activity is a Brookes University intranet system designed for researchers to recruit participants for their studies from staff within the university. This system is not a reward based system, but staff can sign up to participate in research they find interesting, and therefore have first-hand experience of current research.

Children and adults with DCD were recruited from a variety of sources including schools, Oxford Brookes University and the local branch of the Dyspraxia Foundation, a family support group. Participants with DCD were recruited to this study if they met the diagnostic criteria as stipulated by the DSM-5, together with recommendations from the European Academy for

Childhood Disability (EACD, Blank, Smits-Engelsman, Polatajko & Wilson, 2012). At the time of data collection DSM-IV criteria was used to select participants with DCD, however there has been a new issue of the DSM (5th edition), published in 2013. Whilst the diagnostic criteria for DCD have changed slightly (as discussed in Chapter 1) the participant selection for this thesis meet both the DSM-IV and DSM-5 specifications. Therefore, DSM-5 will be referred to in this thesis.

3.2.1. Diagnostic criteria for DCD

Recommendations from the EACD (Blank et al., 2013) suggest a multi-level approach to assessment of DCD in order to clearly describe the condition. Therefore in addition to the assessments discussed below a detailed history was gathered using parental reports to provide evidence of achievement of motor milestones during infancy, school accomplishments, together with co-occurring conditions, medical diseases, or neurological damage.

The Diagnostic and Statistical Manual of Mental Disorders 5th edition (DSM-5) uses four criteria to diagnose DCD as listed in Table 3.1.

Table 3.1 DSM-5 Diagnostic criteria for DCD (APA, 2013)

Criterion	Description
A	The acquisition and execution of coordinated motor skills is substantially below that expected given the individual's chronological age and opportunity for skill learning and use. Difficulties are manifested as clumsiness (e.g. dropping or bumping into objects) as well as slowness and inaccuracy of performance of motor skills (e.g. catching an object, using scissors or cutlery, handwriting, riding a bike, or participating in sports).
B	The motor skills deficit in Criterion A significantly and persistently interferes with activities of daily living appropriate to chronological age (e.g. self-care and self-maintenance) and impacts academic/school productivity, prevocational and vocational activities, leisure and play.
C	Onset of symptoms is in the early development period.
D	The motor skills deficit are not better explained by intellectual disability (intellectual developmental disorder) or visual impairment and are not attributable to a neurological disorder affecting movement (e.g. cerebral palsy muscular dystrophy, degenerative disorder).

In order to ensure the DSM-5 diagnostic criteria for DCD were met, a range of different assessments were used, a summary of which is now discussed; **Criterion (A)** was assessed using The Movement Assessment Battery for Children-2 test component (M-ABC-2) (Henderson, Sugden & Barnett, 2007) for children aged 8-16 years and both the M-ABC-2 and the Bruininks-Oseretsky Test of Motor proficiency-second edition, (BOT-2) brief (although only standardised to 21 years) for adults (>17 years). Measures used to assess criterion A for adults over 21 years are also discussed later in this section; **Criterion (B)** was assessed using the M-ABC-2 Checklist (Henderson et al, 2007) completed by parents of children 8-15 years (standardised to 12 years), and the Adult Developmental Coordination Disorder/Dyspraxia Checklist (ADC) (Kirby, et al., 2010) completed by adults over 16 years; **Criterion (C)** was assessed using parental or individual report; **Criterion (D)** was assessed using the British Picture Vocabulary Scale (BPVS-III, Dunn & Dunn, 2009) for children aged under 16 years, and personal report by adults over 16 years.

Each assessment tool will now be discussed in detail;

3.2.1.1. Criterion A - The acquisition and execution of motor skills are below that expected given the individuals' chronological age and opportunity to practice.

3.2.1.1.1. Motor assessment for children (The Movement Assessment Battery for Children-2 test component, M-ABC-2, Henderson, et al, 2007)

The M-ABC-2 test component is an individually administered UK norm-referenced assessment tool for children aged 3-16 years. There are eight tasks designed to objectively assess 3 components of motor coordination; manual dexterity (three tasks), aiming and catching (two tasks) and static and dynamic balance (three tasks). The test is standardised on a sample of 1,172 children from the UK (representative of gender, ethnicity and socio-economic group according to population consensus data). The M-ABC-2 test is divided into three age-related bands; 3-6 years; 7-10 years; 11-16 years. Eight tasks vary for each age group to accommodate increased age and motor competence. Table 3.2. outlines the tasks for the two age groups used in this study.

Table 3.2. Tasks for two age groups in M-ABC-2 Test.

Component	Age band 2 (7-10yrs) tasks	Age band 3 (11-16yrs) tasks	Measure
Manual dexterity	1.Placing pegs	Turning pegs	Both hands separately; timed in seconds
	2.Threading lace	Make triangle using nuts and bolts	Both hands together; timed in seconds
	3.Drawing trial	Drawing trial	Drawing errors
Aiming and catching	4.Catching a ball with two hands	Catching a ball with 1 hand	Number of catches in 10 attempts
	5.Throwing bean bag to target	Throwing a ball to target on wall	Number of hits in 10 attempts
Balance	6.One-board balance	Two-board balance	Timed in seconds up to 30 seconds
	7.Walking heel-to-toe forwards	Walking heel-to-toe backwards	Number of correct steps up to 15
	8.Hopping on mats	Zig-zag hopping on mats	Number of correct hops up to 5

The M-ABC-2 takes approximately 30-40 minutes to administer. Individual raw scores for each component are transformed into standard scores (mean = 10, standard deviation = 3) and then into a percentile rank. Standard scores are related to age norms. The sum of the three component scores provides the Total Test Score (TTS) which is also standardised and converted to a percentile rank. The M-ABC-2 manual suggests that children with a composite score of 56 or less (<5th percentile) illustrate a “significant movement difficulty”. Children with scores 57-67 (6th-15th percentile) are identified as “at risk” of having movement difficulties, and those with a composite score >67 (15th percentile) illustrate “no movement difficulties”. Blank et al (2013) recommend a cut-off at the 15th percentile of a standardised test of motor performance.

The M-ABC-2 test is recommended by Blank et al. (2012) to assess movement difficulties in children and adolescents, as it is the most commonly used assessment tool for motor function and is also the best examined. The authors of the M-ABC (Henderson & Sugden, 1992) argue that the high levels of reliability and validity from the M-ABC generalise to the M-ABC-2 (Henderson et al, 2007), particularly as the item content is so similar. Therefore studies considering reliability/validity of the M-ABC can be generalised to the M-ABC-2.

Croce, Horvat and McCarthy (2001) investigated the concurrent validity between the M-ABC and Bruininks-Oseretsky Test of Motor proficiency (BOT). Both of these tests are designed to measure motor proficiency but there are subtle differences that make direct comparisons difficult. For example the M-ABC assesses motor difficulty using 3 components of motor coordination; manual dexterity, aiming and catching, and static and dynamic balance. The BOT assesses 4 elements of motor proficiency; fine motor control; manual coordination; body coordination; strength and agility. Notwithstanding these differences in design, correlations between the BOT and the M-ABC are acceptable at 0.76 ($p < 0.001$).

Additionally, Henderson et al., (2007) examined the test-retest reliability of the M-ABC-2 test using 60 children (20 from each age band). Results of Pearson product moment correlations illustrate Content validity was examined by an expert panel who agreed that the items in the M-ABC-2 test adequately represented the motor domain they are designed to assess. These assertions were substantiated by Brown and Lalor (2009). Wilson, Kaplan, Crawford, Campbell & Dewey (2000) assessed whether the M-ABC could differentiate between children with DCD and age matched controls. PE teachers were asked to identify two groups of children; those with motor ability 'below average for their age' and those with 'average motor ability'. 84% of the children from the below average group scored below the 15th percentile on the M-ABC and all the children from the average group scored above the 20th percentile on the M-ABC, indicating a good discriminate validity for the M-ABC.

Children aged 8-16 years were deemed to have met criterion (A) of DSM-5 if they had a composite score <15th percentile on the M-ABC-2. This criterion is recommended in the European guidelines (Blank, et al., 2012) for the use of motor tests during assessment of DCD.

3.2.1.1.2. Motor assessment for Adults (The Bruininks-Oseretsky Test of Motor proficiency-second edition, BOT-2, brief).

The BOT-2 brief is an individually administered U.S. norm-referenced assessment tool designed to characterise motor performance in individuals from 4-21 years. The brief form of the BOT-2 was chosen for this study, as it is a reliable and time effective motor screening tool. It contains at least one item from each BOT-2 subtest, and yields a single score of motor ability. This assessment was added to the adult's test battery because the M-ABC-2 is only standardised to age 16 years and the BOT-2 brief provides a standardised measure of motor proficiency to 21 years. The BOT-2 brief was therefore useful in addressing diagnostic criterion (A) of the DSM-5 for DCD for adults aged 17-32 years. Whilst the BOT-2 brief doesn't cover the entire

age range for the current study, in the absence of any other standardised motor test for adults, this was thought most appropriate. The BOT-2 brief has 12 items designed to assess 4 elements; fine motor control; manual coordination; body coordination; strength and agility. These elements are further divided into 8 sub-tests; Fine motor precision; fine motor integration; manual dexterity; bilateral coordination; balance; running speed and agility, upper-limb coordination and strength. Tasks designed to assess each subtest are described in Table 3.3.

The brief version of the BOT-2 takes approximately 20 minutes to administer. Raw scores for each item are converted into point scores, which are summed to give a total point score ($M=50$; $SD = 10$). These are converted into standard scores and percentile ranks. Standard scores of <30 (2nd percentile) are considered well below average; 31-40 (3-17th percentile) below average; 41-59 (18-83rd percentile) average; 60-69 (84-97th percentile) above average and >70 (98th percentile) well above average.

Standardisation of the BOT-2 involved a normative sample of 1,520 participants from the USA. Test-re-test reliability for the BOT-2 was examined for all age groups. For the age group relevant to this study (13-21 years) Pearson product moment correlation coefficient was 0.84 for the BOT-2 short form. Inter-rater reliability using two examiners and 47 participants (4-21 years) was investigated; Pearson product moment correlation coefficient was 0.98. Discriminant validity was investigated to assess whether the BOT-2 could differentiate between children with DCD and age matched controls. The DCD group had significantly lower scores than the typical group ($p < 0.001$) illustrating the ability of the BOT-2 to differentiate between children and adults with and without DCD, for both the complete and the short form.

Table 3.3. Tasks for each sub-test in the BOT-2 Brief Test

Elements	Sub-tests	Task	Measure
Fine Motor Control	Fine motor precision	Colouring in a star	Accuracy of colouring.
		Drawing a line through a path	Number of drawing errors.
	Fine motor integration	Copying overlapping circles	Accuracy of copying.
		Copying a diamond	Accuracy of copying.
Manual coordination	Manual dexterity	Stringing blocks	Number of blocks in 15 seconds.
	Bi-lateral coordination	Touch nose with index Finger; eyes closed	Number of nose touches up to 4
		Pivot thumbs and index fingers	Number of correct pivots up to 5
Body coordination	Balance	Walking forward heel-to-toe on a line	Number of steps up to 6
	Speed and agility	One legged side hop	Number of correct hops in 15 seconds
Strength and agility	Upper limb coordination	Catching a tossed ball – one hand	Number of correct catches up to 5
		Dribbling a ball – alternating hands	Number of correct dribbles up to 10
	Strength	Knee-ups or full Push-ups	Number of correct push-ups in 30 seconds

Although DSM-5 criteria now acknowledge the impact of DCD into adulthood (DSM-IV did not), there is a lack of information for adult assessment even though DCD is recognised as a lifelong condition (Losse, et al., 1991; Cousins & Smyth, 2003; Kirby, 2010). To date, there is no appropriate test to assess motor performance in adults older than 21 years or to make a diagnosis of DCD, as current motor assessment tools are tailored to assess motor competence below 21 years (M-ABC-2 up to 16 years and BOT-2 to 21 years). Additionally, adaptations of test batteries designed to assess children for use with adults need to be carefully considered to reflect appropriate daily activities. For example, the M-ABC-2 has a section on ball skills which are entirely fitting for school children but less so for the adult population. Current guidelines (Blank et al., 2012) for the assessment of adults suggest that a developmental and medical history is taken to ensure the difficulties were present early in development and not the result of

a neurological condition. The individual's educational, social and employment history are also necessary to assess how well they meet the requirements of daily living. The addition of the Adult Developmental Coordination Disorder Checklist (ADC, Kirby et al., 2010) is a valuable addition to the standardised assessment of DCD in adulthood. Further details of the ADC are discussed in section 3.2.1.2.2.

Therefore, the adults aged 17-32 years with DCD were deemed to have met criterion A) of the DSM-IV, and invited to take part in this study if they had a previous diagnosis of DCD from a recognised professional, and/or fell below the 15th centile on the M-ABC-2 (standardised to age 16), and below the 17th percentile on the BOT-2, indicating a movement performance well below average.

3.2.1.2 Criterion B - the motor skills deficit in Criterion (A) significantly and persistently interferes with activities of daily living and/or academic performance.

Blank et al. (2012) recommends that checklists and questionnaires are a useful addition to the battery of tests used to identify DCD; they can either be used to assess performance of daily living skills, or as an initial screening tool. The checklists used to assess criterion (B) for children and adults will be discussed below;

3.2.1.2.1. Children (M-ABC-2 Checklist, Henderson et al, 2007).

The M-ABC-2 checklist is a norm-referenced checklist designed to assess the impact on daily living of everyday tasks faced at home and school and is therefore used to address diagnostic criterion (B), activities of daily living, of the DSM-5 for DCD. It is designed to be completed by teachers of children aged 5-12 years old and takes approximately 10 minutes to complete. The checklist is divided into 2 parts – motor and non-motor. The motor section is further divided to assess (A) movement in a static/predictable environment and (B) movement in a dynamic/unpredictable environment.

Tasks are listed in increasingly challenging situations (child and environment stationary; child moving but environment predictable; child moving in an unpredictable environment) and include questions to assess ability with self-care (fastens buttons, washing hands), general skills for use in the classroom (using scissors to cut paper, carries a tray around a room avoiding moving persons), and recreational skills (hops on either foot, rides a bike without stabilisers). There are 15 items in each part. Teachers are asked to rate the motor skills of the child on a scale from 0-3 for the completion of the tasks. 0 indicates they complete the tasks very well, 1 =

just ok; 2 = almost there; 3= not close to mastering the task. The sum of scores from sections A and B are added together to give a Total Motor Score (TMS). These scores identify the motor performance of the child. The M-ABC-2 manual suggests that children with scores > 95th percentile are likely to have motor impairment affecting daily life. Children with scores between 85th and 94th percentile are “at risk” of motor impairment affecting daily life, and those with scores < 85th percentile do not have a motor impairment that affects daily life. The M-ABC-2 test identifies low scores as a poor performance; in the M-ABC -2 checklist high scores indicate a poor performance.

The validity and reliability of the M-ABC-2 checklist was investigated by Schoemaker, Niemeijer, Flapper and Smits-Engelsman (2012). They established a Cronbach’s alpha of 0.94 assessing the reliability of the scale, indicating all 30 items in the checklist are measuring DCD. Additionally, the total motor score from the Checklist was able to significantly discriminate between those with DCD and those without ($p < 0.001$).

As contact with teachers was not always possible, parents were asked to complete the checklist. Therefore as the checklist was not used in the standardised way it just provided an indication of the activities of daily living in relation to criterion (B). This is still relevant for the application of DSM-5 criterion (B) but addresses the impact of motor impairments within the home and school from a parental perspective. The information provided by the checklist was used to enhance knowledge of the impact of any motor impairment on daily living for children up to age 16 years (although only standardised to 12 years), it was not used as an independent assessment tool.

Children aged 8-16 years were deemed to have met criterion (B), if they had a composite score > 85th percentile or above, indicating that their motor difficulties are at least ‘at risk’ of affecting daily life. 3.2.1.2.2. Adults (The Adult Developmental Coordination Disorder/Dyspraxia Checklist, ADC, Kirby, Edwards, Sugden, Rosenblum, 2010)

The ADC has been designed to address criterion (B) of the DSM-5 and to help identify DCD in adulthood. Whilst the ADC is not a diagnostic tool, it is useful to indicate if there are areas of difficulty associated with DCD. It is important to note that the ADC does not only cover motor difficulties but encompasses areas such as organisational skills and social participation. The ADC takes approximately 15-20 minutes to administer, and can be completed by adults over 16 years. It is divided into three parts; part-one gathers information on the background of the individual particularly with reference to other diagnoses, and can be used to distinguish between

childhood motor problems and those acquired in adulthood such as multiple sclerosis. Part-two (section 1) has ten questions investigating any difficulties that might interfere with daily activities during childhood.

Part-three (section 2) has 30 questions designed to investigate any difficulties that might affect everyday life. Participants rate their difficulty under one of four headings; ‘never’; ‘sometimes’; ‘frequently’; ‘always’. Each heading is assigned a score (never = 0; sometimes = 1; frequently = 2; always = 3), with low scores indicating good performance. Section 1 and 2 are summed separately. If a participant has a score for section 1 greater than 17 they meet the criteria for having past difficulties with movement in childhood. This score is then added to that of section 2 to provide an overall total. If the score is from 56-65, the participant is regarded as ‘as risk’ of having DCD, if the total score is greater than 65 they are regarded as having ‘probable’ DCD.

The ADC has been trialled with 107 adults in the UK ($n=45$) and Israel ($n=62$) between 17-42 years (Kirby et al., 2010). 49 participants had previously been diagnosed or self-reported symptoms consistent with DCD and the remaining 58 participants provided the control group. Concurrent validity was investigated by comparing final scores on the ADC to the Handwriting Proficiency screening Questionnaire (HPSQ, Rosenblum, 2008). This particular assessment tool was chosen as difficulties with handwriting are specifically mentioned as part of the DSM-5 criteria (A) & (B) for DCD, discussed in Chapter 1. A significant moderate correlation was found for all three ADC subscales and the HPSQ mean final scores (ADC A: $r = 0.68$; ADC B: $r = 0.754$ ADC C: $r = 0.707$; $p < 0.001$). Construct validity was investigated and significant differences between groups for the mean final score of the three subscales were reported (DCD = 99.41, Control = 60.36; $p < 0.001$). Thus the questionnaire could distinguish between groups with and without DCD, those with DCD experienced significantly more difficulties with everyday life than their TD peers.

Participants aged 17-32 years with a score of >17 for section 1 and an overall score > 65 were deemed to have met criterion (B) of the DSM-5 and invited to take part in this study.

3.2.1.3. Criterion C – the onset of symptoms is in the early developmental period

As discussed in Chapter 1, Blank et al. (2012) does not recommend that DCD is diagnosed before 5 years of age, as young children may find the cooperation and motivation needed to complete the testing difficult. Additionally, young children with a delayed motor development

may catch up with their peers by 5 years old. Therefore Criterion (C) is assessed by personal report during a telephone interview. This was conducted, either directly with adults over 18 years or with the parents of children less than 18 years, to identify the pattern of difficulties the individual displays, including the onset of motor difficulties. The interview also consisted of questions focusing on the person's specific motor difficulties, their medical history and educational achievement.

Individuals aged 8-17 years met criterion (C) if either they or their parents reported the onset of motor difficulties early in development.

Individuals aged 18-32 years met criterion (C) if they (or where appropriate their parents) reported the onset of motor difficulties early in development.

3.2.1.4. Criterion D - the motor difficulties are no better explained by intellectual disability, visual impairment or neurological condition.

Assessments of visual impairment or neurological condition were considered during the telephone interview discussed above. Considerable discussion has been applied to the problem of defining intellectual disability and how that affects the diagnosis of DCD. Blank et al. (2012) argues that given the difficulties in deciding which specific IQ level can specify DCD and which level precludes it, the objective assessment of cognitive ability is not essential provided that there is a history of normal school academic achievement. Blank et al. (2012) recommend that provided the other criteria are met, and that the motor problems cannot be explained by the medical history and examination then the motor dysfunction can be classified as DCD. However, to remove any doubt (Blank et al., 2012) cognitive assessment was carried in the current study out to ensure the motor competencies were not impaired by intellectual disability. Cognitive assessment was carried out in line with recommendations from Henderson and Barnett (1998), who propose that for the assessment of IQ in children with motor difficulties the best strategy is to rely on verbal IQ thus removing any confounding impact that motor input may have on the result.

3.2.1.4.1. Children (The British Picture Vocabulary Scale, BPVS-III, Dunn & Dunn, 2009)

This is an individually administered standardized test instrument to assess the receptive vocabulary of 3-16 year old children. The participant hears a target word and is asked to choose a picture (from a selection of 4) that best describes the target word. There are 14 sets of 12 (x4) pictures, increasing in difficulty as the test progresses. The test is administered as described in the manual. The raw score is standardised and converted to a percentile rank. Standardised

scores that fall between 85 and 115 are considered to be within the average range for age. Scores of 69 and below indicate a significant difficulty. The BPVS is highly correlated with verbal intelligence (Wechsler 1992; Dunn & Dunn, 2009).

Children aged 8-16 years met criterion (D) if they had a standard score of 70 or above on the BPVS.

3.2.1.4.2. Adult: Cognitive ability inclusion criteria

In line with the recommendations by Blank et al. (2012) cognitive ability was investigated for adults 17 years and over by asking them to self-report their academic achievement. Participants who had attended normal state school and/or who had a minimum academic achievement of GCSE's (an indication of normal academic achievement) met criterion (D).

3.2.1.5 Assessment of attentional difficulties

Given the high rate of co-occurrences between DCD and ADHD (Kadesjö & Gillberg, 1999; Green et al., 2006; Blank et al., 2012) discussed in Chapter 1, additional assessments were performed to check for attentional difficulties. This was particularly important as the DSM-5 suggests that individuals with ADHD might have poor motor control because of increased levels of distractibility and impulsivity rather than motor impairment. There were no exclusion criteria applied for participation in this study, but difficulties in the area of hyperactivity or inattention were noted to ensure that any behaviours occurred because of motor difficulties rather than inattention.

3.2.1.5.1. Children (The Strengths and Difficulties Questionnaire, SDQ, Goodman, 1997)

The SDQ is a brief behavioural screening tool for children and adolescents aged 4-16 years. It is completed by parents or teachers to identify any behavioural problems. There are 25 questions covering 5 areas of behaviour; **conduct** (score >5 classified as abnormal) “often has temper tantrums”, “often lies or cheats” **emotional** (score >7 classified as abnormal) “often unhappy, down-hearted or tearful”, “many fears, easily scared”; **peer problems** (score >6 classified as abnormal) “rather solitary, tends to play alone”; “has at least one good friend”; **hyperactivity** (score >7 classified as abnormal) “constantly fidgeting or squirming”; “easily distracted, concentration wanders” and **prosocial behaviour** (score <4 classified as abnormal) “considerate of other people’s feelings” “kind to younger children”. Parents were asked to complete a 3-point Likert scale, to illustrate how each construct applies to the child. The scale ranges from 0-2 with 1 always meaning ‘somewhat true’ but the scoring of ‘not true’ and ‘certainly true’ is dependent

on the question. The scores of the first four items are summed to provide a Total Difficulties Score ranging from 0-40. These scores are divided into three bands; normal (total score of <13), borderline (scores of 14-16) and abnormal (scores >17), the higher the number the greater the behavioural difficulty. For the purposes of this study particular attention was paid to the scores for hyperactivity (discussed in section 3.2.1.5). Please see Table 3.5. for participant details. Concurrent validity of the SDQ was investigated by Goodman (1997) using the previously validated Rutter questionnaires (Elander & Rutter, 1996) as a comparison. Pearson product moment correlations for parent reports suggest good concurrent validity with correlations ranging from 0.88 for total deviance/difficulties score to 0.78 for emotional; 0.82 for hyperactivity and 0.88 for conduct problems. Goodman (2001) conducted a reliability and validity study using a sample of 10,438 British 5-15-year-olds, with parents of 96% of these children completed the SDQ. Participants were also given DSM-IV diagnoses after a comprehensive clinical review of interviews. Internal reliability from this investigation was satisfactory with Cronbach $\alpha = 0.73$). Test- retest reliability after 4 to 6 months provided a mean of 0.62.

3.2.1.5.2. Adults (The Conners Adult ADHD Rating Scales, CAARS, short version, Conners, Erhardt, Sparrow, 1999)

The CAARS is a norm-referenced self-reported questionnaire designed to assess inattention/impulsivity in adults. It takes approximately 15 minutes to administer and is suitable for adults over 18 years. There are 26 questions covering five behaviours; inattention; hyperactivity; impulsivity; self-concept problems and ADHD. Norms are divided by gender and age. Participants are asked to report the frequency of their behaviours on a 4-point Likert scale, where 0=not at all; 1=just a little, 2=often; 3=frequently. Raw scores for each behaviour are summed and converted into *T*-scores to provide a standard measure of comparison. Each scale has a mean of 50, and a *T*-score 45-55 will place the participant within the average band. For the purposes of the current study a *T*-score threshold of 65 (1.5 SD above the population mean) was considered abnormal. Particular attention was paid to the scores for inattention, impulsivity and the ADHD index as discussed in section 3.2.1.5. Please see Table 3.5. for participant details.

Concurrent validity between the CAARS and the previously verified Wender Utah Rating Scale (WURS, Ward, Wender & Reimherr, 1993) was investigated by Erhardt, Epstein, Conners, Parker and Sitarenios (1999). Pearson product moment correlations were moderately significantly correlated for all measures and ranged from $r = 0.37$ for inattention problems to $r = 0.67$ for impulsivity. This moderate correlation was expected as the CAARS and WURS assess

inattention/impulsivity at different time points; the CAARS during adulthood and WURS during childhood. Additionally, Pearson product moment correlations for test-retest reliability were strong over a period of 1 month, with alpha coefficients ranging from 0.80 for impulsivity to 0.91 for problems with self-concept.

Table 3.4. Summary of assessments used to apply DSM-5 (APA, 2013) criteria for participants with DCD in this study ².

DSM-5 Criteria	Children 8-16 years		Adults 17-32 years	
	Assessment tool	Inclusion criteria DCD	Assessment tool	Inclusion criteria DCD
A) Motor coordination below that expected. . .	M-ABC-2 test component	Total score <15 th percentile	M-ABC-2 test Component and BOT-2	Total score <15 th percentile. Total score <17 th percentile
B) Interference with academic/ daily living	M-ABC-2 checklist.	Total score >85 th percentile.	ADC	Total score >65
C) Onset early in development	Parental report	Onset was early in development	Personal report	. Onset was early in development
D) Not attributable to neurological impairment or intellectual disability.	BPVS & Parental report	Receptive vocabulary above 70 No severe neurological, disorder or visual impairment	Personal report.	A minimum of GCSE qualifications No severe neurological, disorder or visual impairment
In addition: record of behaviour problems	SDQ	Difficulties with hyperactivity/ inattention noted (score >7).	CAARS	Difficulties with hyperactivity/ inattention noted (score >65).

3.2.2. Cohort of participants for this thesis

Thirty five individuals with Developmental Coordination Disorder (DCD) met the inclusion criteria (summarised in Table 3.4.) to take part in this study. Given that all participants for this

² Definitions for the adult age range are different for assessments (16 years) compared to the study cohort (18 years) because assessment tools only go to age 16.

group came from an already established database and were pre-screened to meet the diagnostic criteria for DCD, there were no exclusions for participants with DCD. Participants were divided into 3 age groups; 8-12years ($n = 12$), 13-17years ($n = 12$) and 18-32years ($n = 11$). Participants with DCD were age- (to within 6 months for children <18 years and 1 year for adults), and gender-matched to 35 TD controls, thus accounting for any developmental constraints which might affect the gait variables being measured.

3.2.2.1. Typically Developing Individuals

All TD participants were age- (to within 6 months for children <18 years and 1 year for adults) and gender-matched to the DCD participants. More males than females took part in this study to reflect the greater prevalence of DCD in the male population. Inclusion criteria for TD participants stipulated a personal report (or parental report where appropriate) of no motor difficulties, together with a score >16th percentile on the M-ABC-2 balance sub-section (this measure was most relevant to walking) as this indicated a balance performance within the typical range, together with no previous movement difficulties (self-reported). Individuals over 16 years (and parents for children under 16 years) were asked to report if they/their children had any previously diagnosed medical conditions and completed the CAARS/SDQ (depending upon age) to detect any attentional difficulties. There were no reports of medical difficulties and all TD participants fell within the average range for attention, therefore there were no exclusions. In line with Geuze et al. (2001) IQ was assumed to be within the normal range as all control children attended main stream school, parental report confirmed that there were no intellectual difficulties. All adults who participated in this study had also attended main stream schools, and self-reported no intellectual difficulties, achieving minimum academic qualifications of GCSE qualifications.

Please see Table 3.5. for demographic information for all participants; the significance levels illustrate that there were no differences in the mean age, height or leg length of each DCD-TD group, but significant group differences in the M-ABC-2 score for balance. There were also group differences in the hyperactivity scores for both the children and teenagers. However, careful monitoring of participants as they participated in the study can confirm that a higher hyperactivity score did not affect the ability to complete the walking tasks.

Table 3.5. Means, (standard deviations) of demographic data for participants in this study. Significant group differences (TD, DCD) for each measure are also reported.

Measure	Age group	DCD group Mean (SD)	TD group Mean (SD)	Significance
Gender ratio M:F	Child (8-12 yr.)	10:2 (n=12)	10:2 (n=12)	
	Teenage (13-17yr.)	9:3 (n=12)	9:3 (n=12)	
	Adult (18-32 yr.)	7:4 (n=11)	7:4 (n=11)	
Age	Child (8-12 yr.)	10y 4m (1.25)	10y 3m (1.31)	$p > 0.05$
	Teenage (13-17yr.)	16y 2m (1.27)	16y 0m (1.65)	$p > 0.05$
	Adult (18-32 yr.)	24y 2m (5.08)	27y 7m (4.97)	$p > 0.05$
Height (cm)	Child (8-12 yr.)	141.67 (14.01)	143.08 (7.75)	$p > 0.05$
	Teenage (13-17yr.)	172.53 (9.73)	172.92 (9.48)	$p > 0.05$
	Adult (18-32 yr.)	167.01 (9.30)	174.18 (10.59)	$p > 0.05$
Leg length (cm)	Child (8-12 yr.)	74.60 (107.81)	75.17 (34.86)	$p > 0.05$
	Teenage (13-17yr.)	90.83 (67.13)	92.50 (41.23)	$p > 0.05$
	Adult (18-32 yr.)	88.45 (39.59)	91.72 (75.77)	$p > 0.05$
M-ABC balance (%)	Child (8-12 yr.)	2.59 (1.90)	69.75 (25.50)	$p < 0.001$
	Teenage (13-17yr.)	2.99 (3.01)	61.58 (25.21)	$p < 0.001$
	Adult (18-32 yr.)	2.78 (2.84)	54.27(25.36)	$p < 0.001$
SDQ Hyperactivity	Child (8-12 yr.)	Abnormal N = 6	Abnormal N = 0	
	Teenage (13-17yr.)	Abnormal N = 3	Abnormal N = 0	
CAARS Hyperactivity	Adult (18-32 yr.)	Abnormal N = 1	Abnormal N = 0	

3.3. Experimental set-up for walking paradigms

This section describes the walking protocol relating to chapters 4-7. Gait was measured under four different conditions, level walking; walking on an irregular terrain; visually occluded level walking and visually occluded walking on an irregular terrain. The basic experimental set-up was the same for all conditions and is described below. Any deviation from this set up is described under the appropriate section. Additionally, the motion capture system, method of data extraction and statistical analysis for all conditions are described later in this chapter.

3.3.1. Materials and procedures

A 6m x 1m flat walkway was laid out comprising six 1m² interlocking high density, non-slip sports mats. The walkway was edged in a contrasting colour (red) to clearly delineate the path (blue) for participants to walk along. Two cones were situated directly opposite each other, at either end of the walkway, illustrated in Figure 3.1. For all conditions participants walked steadily at a self-selected pace, for two minutes around the cones placed at either end of the walkway. They walked in a clockwise direction and in as straight a line as possible. All participants were given a demonstration and one practice trial (one walk from start to end cone) to familiarise themselves with each experimental condition.

Participants attended the sessions barefoot whilst wearing a t-shirt and shorts. Measurements of height and leg length (greater trochanter to floor) were taken, as these dimensions are known to affect some gait variables such as stride length (Rodgers, 1988).

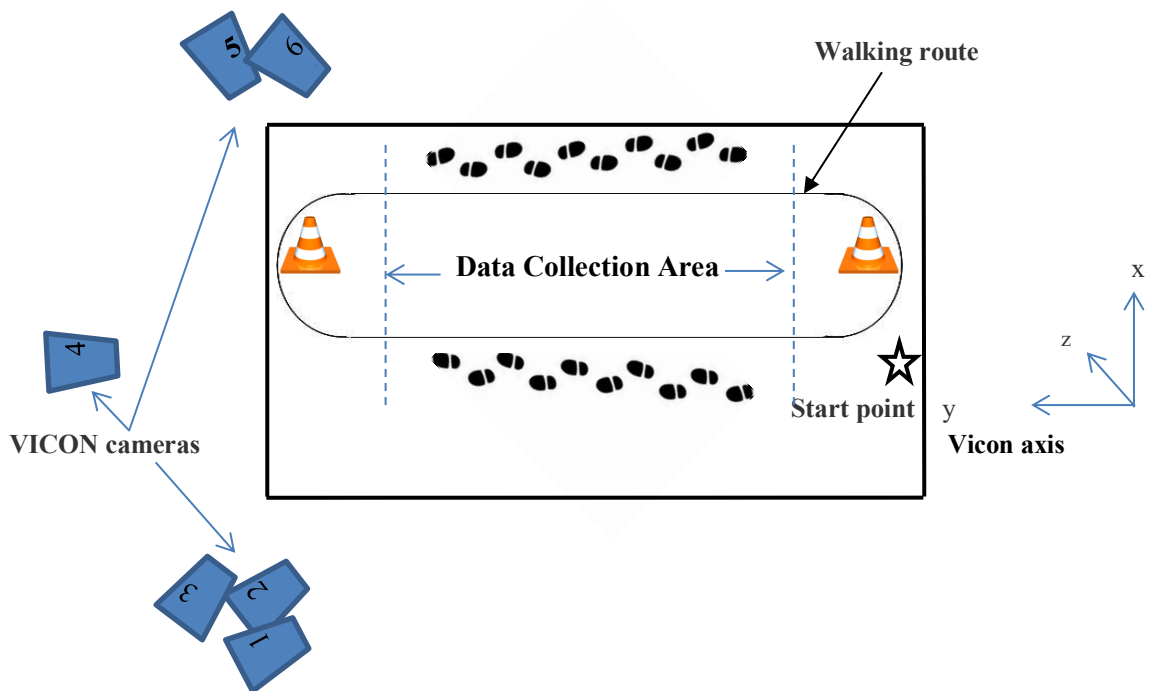


Figure 3.1. Birds-eye view of experimental set-up for all conditions, showing positions of the 6 cameras and VICON axis; indicating which direction each axis monitored; x= medio-lateral movement; y = anterior-posterior movement; z = vertical movement, discussed in section 3.3.2. Footsteps illustrate the direction of walk around the cones.

3.3.1.1. Level walking

Condition 1 was level walking; participants walked around the *level* and uncluttered walkway as described in section 3.3.1. for 2 minutes.

3.3.1.2. Walking on an irregular terrain.

The walkway was as described in 3.3.1. To make the irregular terrain ‘cobbles’ (9cm wide x 10cm long x 2cm high) were stuck at irregular intervals on to the centre 4 sports mats (see Figure 3.2. for photo), 45-50 ‘cobbles’ per mat. The ‘cobbles’ were made of the same non-slip material as the sports mats and were spaced at a minimum distance of 4cm and maximum distance of 10cm apart, to ensure participants had to walk on the ‘cobbles’ rather than the flat spaces between (illustrated in Figure 3.2.). All other materials remained the same as for level walking. Participants walked around the irregular walkway for 2 minutes.



Figure 3.2. Experimental set-up for irregular terrain condition showing position of the 6 cameras (walkway for level condition is on the left), together with detail of ‘cobbles’ used in irregular terrain condition. (*Comment*, although the cone is to one side in this photo, it was placed centrally for data collection).

3.3.1.3. Visual occluded walking

Vision of the feet was occluded with a small (20x15cm) light ‘tray’ which participants wore on their upper chest. It was supported by strong ribbon around the neck, and was based on waterproof map carriers (illustrated in Figure 3.3.). Two trays were provided; one was clear (weight 100g), and one was opaque with a cardboard insert to block vision of the feet (weight 125g). The clear manipulation was introduced to indicate whether the presence of the tray has any negative effect on gait control.

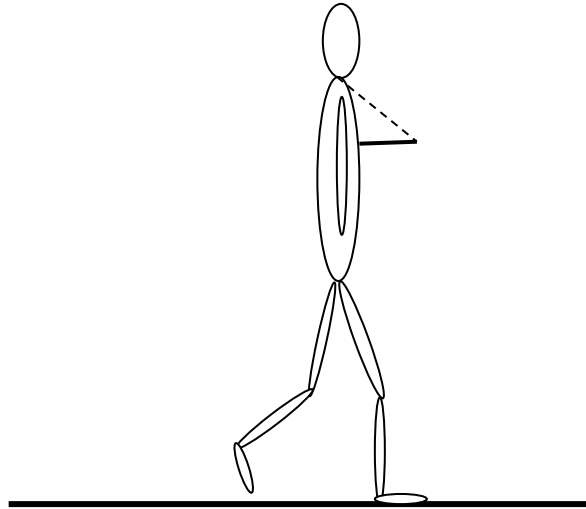


Figure 3.3. Schematic representation of tray used to occlude vision of the feet.

3.3.1.4. Order of trial presentation

Participants walked along two different randomly assigned terrains; a *level* and an *irregular* walkway for 2 minutes, under two randomly assigned visual conditions; wearing either the *clear* or the *opaque tray*. This resulted in 6 conditions, (level walk, level walk with opaque tray, level walk with clear tray, irregular walk, irregular walk with opaque tray, and irregular walk with clear tray). The three level walking conditions were always completed in one block (level walk, level walk with opaque tray, level walk with clear tray in random order) and were either followed or preceded by a block of all three irregular walking conditions (irregular walk, irregular walk with opaque tray, irregular walk with clear tray, in random order) this resulted in a quasi-random assignment of walking trial.

The perturbations (irregular terrain, visual occlusion) were designed to examine participants planning skills required to traverse the pathway with different sensory constraints. For example, the irregular terrain examined walking patterns whilst negotiating altered proprioceptive feedback from the ground terrain, whilst wearing the opaque tray examined the planning skills needed to negotiate the terrain with reduced visual feedback from the feet. The level of sensory processing required whilst traversing the terrains was designed to increase with each perturbation. Starting with *level walking* as the easiest condition (with visual information fully available and proprioceptive feedback from the ground constant and predictable), progressing through the other conditions *level walk with opaque tray* (visual information reduced, proprioceptive feedback constant and predictable), *irregular walk* (visual information fully available, proprioceptive feedback unpredictable) through to the most challenging condition

irregular walk with opaque tray which examined both the visually demanding planning required due to occlusion of the feet and the altered proprioceptive feedback from the ground.

It could be argued that a random presentation of walking trial would alter the amount of experience a participant has which could affect the findings. For example, if a participant begins their trial with irregular walk with an opaque tray (i.e. most challenging condition) this could provide a practice effect for all subsequent conditions, as the participant would have experience of both sensory conditions. However, if a participant starts with the easiest condition (level walking) the participant would not have experienced either sensory perturbation and cannot provide any practice effect for subsequent trials. In contrast, if the walking trials were presented in an organised way (i.e. from easiest to most difficult) a lack of any statistical differences in the most difficult condition would be difficult to explain, as it could either be due to practice effects of this trial being presented last rather than the effects of the condition manipulation. Therefore for this experiment the presentation of walking trials was quasi randomly assigned, as described above. Table 3.6. shows how many participants in each group and age band had level walking condition first (The order of trial presentation for all walking conditions is listed in appendix II).

Table 3.6. Number of participants with level and irregular conditions first

Group	Child N = 12	Teenage N = 12	Adult N = 11
	Level walk first	Level walk first	Level walk first
TD	5	4	4
DCD	6	3	2

3.3.2. Motion Capture system

A VICON 3D motion analysis system (Oxford Metrics Ltd, Oxford UK) was chosen for data collection as its accuracy and reliability identify it as the ‘gold standard’ for motion analysis (Barker, Craik, Freedman, Herrmann & Hillstroom, 2006). The VICON cameras have a sampling frequency of 120Hz; one frame every 8.33ms which compares favourably with most walking studies, some of whom collect data at a rate of only 60Hz (e.g. Sutherland et al 1998; Woodruff, et al., 2002; Mickleborough et al., 2000; Winter, Patla, Frank & Walt, 1990).

The system, comprising a data station and 6 infrared cameras (), was used to track the motion of small reflective markers (14mm diameter) attached to 11 bony landmarks: centre forehead, chin, chest (manubrium of the sternum), hips (trochanter major), knees (lateral epicondyle), ankles (lateral malleolus) and feet (caput for the 5th metatarsal), in line with established protocols designed to assess human gait (Whittle, 2012). Please see Figure 3.4. for illustration.

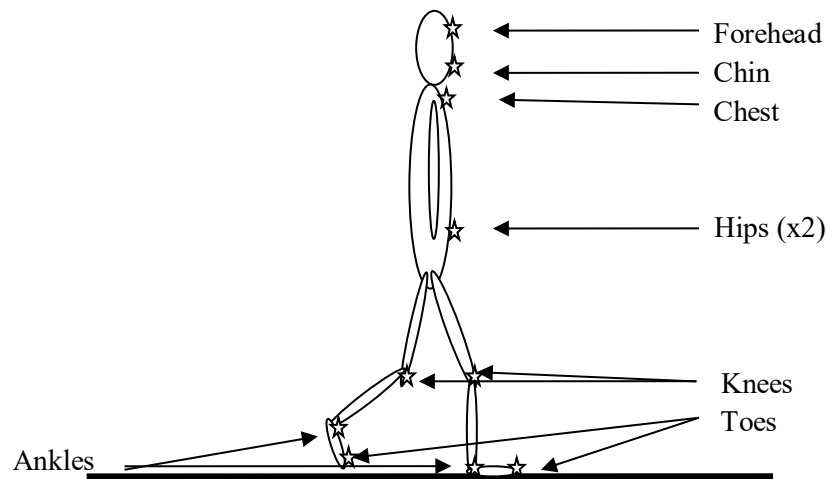


Figure 3.4. Schematic representation of position of reflective markers.

All cameras were positioned towards the end of the walkway to ensure maximum coverage of the markers (See Figure 3.1.). Video footage of each walk (torso to feet only, for anonymity) was recorded, at a sampling frequency 30 Frames per Second, to provide back-up to address queries in the VICON data. This enabled the investigation of any gaps in the data by viewing exactly how the participant was walking and where any obstructions to data collection came from. The VICON system was set up to capture a 4m x 1m area whilst participants walked straight ahead along the walkway. Data were collected in one direction only, as the participant walked towards the VICON cameras. Data collection started when heel strike of the lead foot entered the capture area and finished as toe-off of the lag foot left the capture area. Data collected along the x-axis tracked medio-lateral movement, along the y-axis anterior-posterior movement, and along the z-axis vertical movement.

2-D kinematic data collected from the Vicon cameras was reconstructed into 3-D trajectories and labelled using VICON workstation. If there were any gaps in the data (<50 frames) they were filled using VICON software. Data with long gaps were excluded from further analysis

(this led to approx. 2% data loss). This 3-D data were smoothed using a Butterworth low-pass filter (cut-off 10 Hz). The Butterworth low-pass filter is a widely used low pass filter in motion capture data analysis used to screen the noise and make the data smoother. 10Hz was chosen as a commonly used frequency in gait analysis which can suppress the noise whilst leaving the variability we are still interested in for motion capture analysis. After the data were smoothed it was then exported into MATLABTM (The Mathworks Inc.) to extract the gait variables of interest using tailored MATLABTM routines (see section 3.3.3. for details on gait analysis). Twelve measures were extracted, including; Step length; Proportional Step length; Step Width Ratio; Percentage time spent in Double Support; Vertical and Lateral movement of the trunk and Speed. Angles of head, trunk, thigh, shank, and foot were also extracted.

3.3.3. Data extraction

3.3.3.1. The Foot Velocity Algorithm (FVA, O'Connor, Thorpe, O'Malley, Vaughan, 2007)

The identification of certain points in the gait cycle is essential for detailed analysis. Particularly important are the measurement of heel strike (HS), marking a period of double stance (both feet on the ground) and toe-off (TO), marking a time of single stance (one foot on the ground). Analysis of these events can be used to establish many of the key measurements for objective gait analysis (Robinson & Smidt, 1981) such as stride length, step width and time spent in single or double support. The gold standard for measurement of HS and TO is the force plate (O'Connor, Thorpe, O'Malley & Vaughan, 2007). This can accurately time HS and TO - provided that the foot lands 'cleanly' on to the force plate. However, this method is not always suitable for atypical populations, such as those with balance problems, as it may inhibit the ability to step 'cleanly' on to the force plate (Mickleborough, van der Linden, Richards & Ennos, 2001). Furthermore, only one or two force plates are used, which limits the number of steps available to analyse.

Numerous options have been investigated within the gait research community to overcome these problems, one of which includes the use of kinematic data as produced by systems such as the VICON 3D motion analysis system. Manual identification of HS and TO is possible to within acceptable tolerances, using the speed curves and marker trajectories from kinematic data for normal gait (Mickleborough, et al., 2001). However, whilst this method has been used before for the analysis of gait in children with DCD (Deconinck et al., 2006^b), the time-consuming and subjective nature of visual analysis is not ideal.

Several researchers have proposed the use of algorithms, used in conjunction with kinematic data collection systems, to provide a more objective gait event detection measure. Several algorithms were considered for use in this thesis including the Hreljac-Marshall Algorithm (HMA, Hreljac & Marshall, 2000), the High Pass Algorithm (HPA, Desailly, Daniel, Sardain & Lacouture, 2009) and the Foot Velocity Algorithm (FVA, O'Connor, et al., 2007). All of these algorithms used kinematic data which were not reliant on other devices such as force plates or foot switches. This was an important consideration to ensure methods were suitable for this study where only kinematic data were available.

The HMA works on the premise that the heel marker's maximum acceleration peak (vertical) occurs at HS, and the toe marker's maximum acceleration peak (forward) occurs at TO. The HPA uses high pass filtering (to eliminate static offset) of forward motion of the heel and toe markers. The FVA is based on a simple speed curve collected from the vertical displacement of the heel and toe trajectories recorded by VICON. The vertical speed of the foot centre (extrapolated from the toe and ankle coordinates) is plotted and automatically determines the times of HS and TO. The advantage of using this measure is that the vertical speed curve of the foot centre has a representative shape throughout the gait cycle which enables Heel-strike and Toe-off to be easily identified.

A review of all three methods was carried out by Desailly, et al. (2009) who investigated the accuracy of these algorithms to detect gait events at two time points; Heel-Strike and Toe-Off. Accuracy was defined as the net difference between event times identified by the force plate compared to estimated event times identified by the algorithms; the larger the mean difference the lower the accuracy. Desailly, et al. (2009) found that the HMA lacked accuracy particularly in the detection of Heel-Strike (confirmed by O'Connor, et al., 2007). The HPA and FVA performed equally well on the 8 typical adults tested, although the HPA was more accurate and precise for the detection of gait events for individuals with Cerebral Palsy. Leitch, Stebbins, Paolini and Zavatsky (2011) compared these two methods (along with two others) to the timings on a force plate for a running study; they found that the most consistent method of Heel-Strike detection was the FVA. Given the lack of accuracy of Heel-Strike detection of the HMA this method was disregarded. The FVA was chosen to determine the timing of Heel-Strike (HS) and Toe-Off (TO) in this thesis, as it not only provides a fast and accurate method to identify HS and TO in the gait cycle (O'Connor, et al., 2007), but it also provides the most consistent method of HS detection from the algorithms assessed. It has also received positive validation of

HS and TO data collected from a force plate, for 54 participants with a typical gait and 3 with spastic diplegia (O'Connor, et al., 2007).

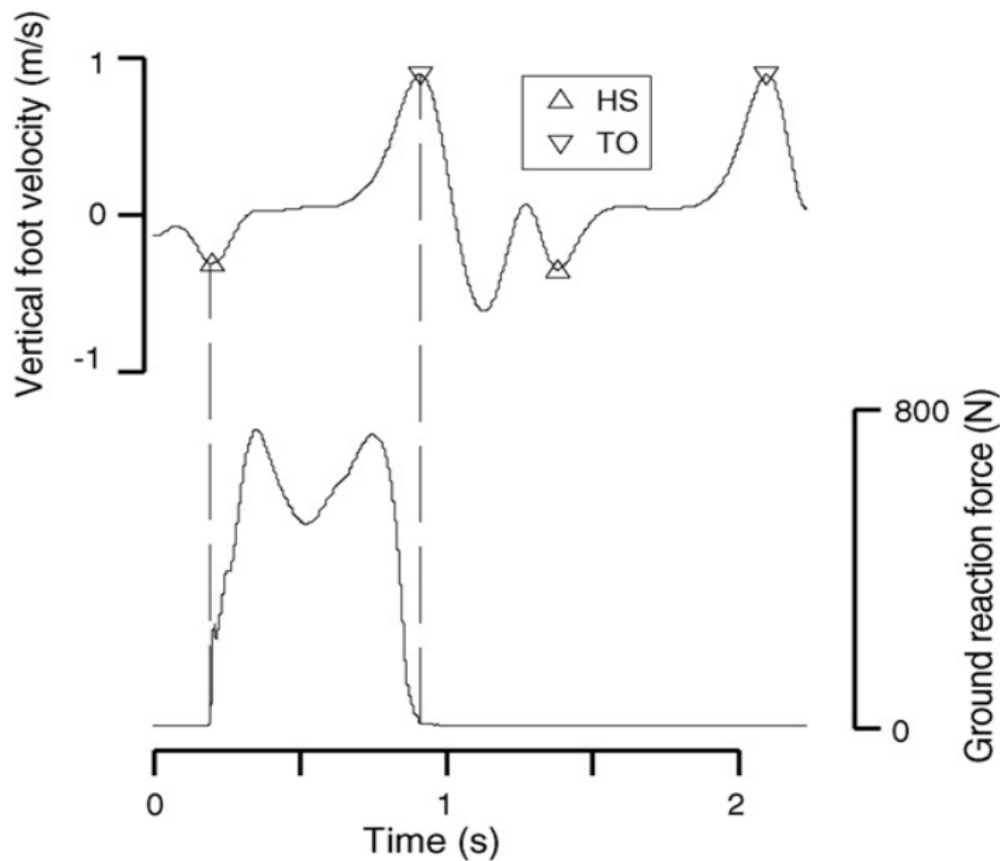


Figure. 3.5. The vertical speed of the foot centre of a man walking, with triangular markers indicating the timing of Heel-strike (HS) and Toe-off (TO) as determined by the foot speed algorithm, and a simultaneous recording from a force plate which provides the “true” times for HS and TO for one step. *From O'Connor, et al 2007. p471.*

The FVA, (O'Connor, et al, 2007) was implemented in MATLABTM and applied to the walk data. The major peaks in the vertical speed curve can be identified as the time of Toe-Off (downward triangles in Figure 3.5). Heel-Strike is slightly more complex to identify as it has an additional constraint, the heel marker must be near the ground. A threshold is imposed to exclude heel heights below 35%. Therefore, the first deeper trough is excluded from analysis, as this point occurs when the foot is in ‘swing’, and the second trough, identified by the upward triangle in Figure 3.5., is used for analysis. All time points for Toe-Off and Heel-Strike were

then identified by eye, using the vertical speed curves, and manually inserted into the programme. Results from the MATLAB processing were exported to a Microsoft excel folder and entered into SPSS for statistical analysis.

3.3.3.1. Analysis of movement data

Data were collected from between 3-12 walks (a walk is defined as one walk from the start cone to the end cone) for each condition, each consisting of 1-3 complete strides per walk. This provided a mean of 8 walks for analysis across all four conditions (DCD = 7.22; TD = 8.70, see Table 3.6. for details) and therefore a mean of between 8-24 strides for analysis.

Unfortunately, two participants (each in one condition only) only produced 2 full strides during their walks for analysis. To ensure that valid data were produced two analyses were conducted; firstly the analysis was run including these participants, then it was re-run without them. The statistical relationships remained unchanged with or without this data, so these participants have remained in the analysis.

Table 3.6. Mean number of strides analysed per condition/group

	Level walking (Chapter 4 &5)		Irregular terrain (Chapter 6)		Visually occluded (Chapter 7)			
	DCD	TD	DCD	TD	Level		Uneven	
	DCD	TD	DCD	TD	DCD	TD	DCD	TD
Child	8.25	8.83	7.17	7.92	8.37	9.17	6.84	8.50
Teenager	7.50	9.58	6.17	8.83	6.92	9.13	6.75	8.96
Adult	7.73	8.18	6.64	8.45	7.46	9.32	6.96	8.64

3.4. Statistical analysis

SPSS 19 was used for all statistical analysis. The data were initially investigated to ensure they were suitable for parametric testing. Therefore the data were tested for normal distribution and homogeneity of variance. To statistically test for normal distribution the Kolmogorov-Smirnov (K-S) test was used which provides a level of significance, indicating how far distribution deviates from normal. If distribution is found to be deviant the K-S test was significant ($p < 0.05$). Levene's test for equality of variance was used to test for homogeneity of variance.

When Levene's test was not significant ($p > 0.05$), the variances between the two groups are approximately equal, so the data meet the assumptions for parametric testing.

Where data failed to meet the assumptions for parametric testing further analysis was needed to evaluate the correct statistical procedure. Descriptive statistics were used to identify skewness in the data. If a positive skew was observed (scores near low end of the scale), together with unequal variance, Log transformation was applied to the data before statistical analysis. However, some transformations were not successful in preparing the data for parametric testing as the data had a positive skew for one population and a negative skew for the other. These data were therefore statistically analysed in their original, pre-transformed state.

Descriptive statistics are reported for all statistical explorations in this thesis, providing the means and standard deviation (SD) as a measure of variability. SD's inform us about the distribution around the mean, and consequently, how well the mean represents the data. Inferential statistics are reported to compare mean scores for the independent variables of 'group' (DCD, TD) and 'age' (child, teenage, adult) on the 12 dependent variables listed in section 3.3.2.

Analysis of variance, (ANOVA) was used for most of the statistical analyses as it allows investigation between more than two groups, a vital consideration for this thesis. Significant interactions found from the analysis were explored using simple main effects and significant main effects were explored using post-hoc tests. The Bonferroni correction was used for all post-hoc tests to control for Type 1 error whilst conducting pairwise comparisons. Statistical significance was set at the 5% level.

Effect sizes, which provide an objective measure of the extent of the effect (Field, 2009) are reported for all significant results. Partial eta squared (η^2) describes the proportion of the variance a variable explains that is not explained by other variables (Field, 2009). A test with power of $\eta^2 = 0.25$ suggests a large effect size, $\eta^2 = 0.09$ medium and $\eta^2 = 0.01$ small (Cohen, 1992). Details of specific statistical procedures and transformations are recorded in the results sections in Chapters 4-7. Given that the 6 conditions were quasi randomly assigned to each participant, it was important to investigate if differing sensory experiences (discussed in section 3.3.1.4) had a disproportionate impact on some groups and/or ages whilst traversing the pathway. To address this issue and to ensure findings were interpreted correctly an ANCOVA was run with "order" as the covariate to partial out the effects of the random presentation of

order of walking trial. ANVOCA's are used to measure variables that may have an influence on the results of an investigation but are not one of the main dependent variables (Covariate) being measured. ANCOVA was used for all experimental investigations in Chapters 4-7 to analyse the effects of the level walk condition first (1) or not (2). Results to these investigations are discussed within each chapter.

Chapter 4: Walking patterns in DCD

4.1. Introduction

Whilst there has been much work characterising typical walking, there has been rather less in other populations. Some researchers have investigated the increased incidence of falling in older adults (Lord, Lloyd & Li, 1996; Maki, 1997; Winter, 1995), and others have concentrated on populations with severe neurological conditions such as Cerebral Palsy (Damiano & Abel, 1996; Massaad, Dierick, van den Hecke & Detrembleur, 2004; Sutherland, 1978). However, one group that has received little attention, and yet has everyday movement difficulties are those with DCD. As discussed in Chapter 2, only a small number of studies have investigated the walking patterns of individuals with DCD, and these have been inconsistent in their findings. Deconinck, et al., (2006) found that children with DCD show altered patterns of gait while walking on a treadmill, but other research has been unable to substantiate this (Cherng et al., 2009; Deconinck et al., 2010). In addition, the mechanisms behind these differences are poorly understood and have been difficult to quantify.

Themes emerging from the literature, discussed in Chapter 2, suggest that when walking in a relatively stable environment (along a level and uncluttered pathway), the mean spatio-temporal gait variables (e.g. step length, speed etc.) for children with DCD show only subtle differences to those of typical gait (Woodruff et al., 2002; Cherng, et al., 2009; Deconinck, et al., 2010). Group differences seem to arise in more challenging situations, such as when walking on a treadmill (Deconinck, et al., 2006^a), when visual information is removed (Deconinck, et al., 2006^b) or when variability is measured. For example studies by Woodruff et al. (2002), Deconinck et al. (2006^a) and Rosengren, et al. (2009) have found greater variability in movement performance for individuals with DCD compared to their TD peers even within a stable environment. This increased variability might highlight underlying mechanistic issues in movement control for individuals with DCD which negatively affects their ability to negotiate their environment. For example, Rosengren et al. (2009) argue that increased variability for individuals with DCD could be an adaptive response to compensate for balance difficulties. Research investigating increased variability in walking patterns in typical adults support this hypothesis and indicates that variability in step length may be causally linked to greater risk of falling (Maki, 1997;) and reduced automaticity (Shumway-Cook & Woollacott, 2002). This is an area of particular interest to this study as individuals with DCD have been shown to be more affected by concurrent secondary tasks whilst performing movement activities (Laufer, Ashkenazi & Josman, 2008), which may affect their ability to adaptively negotiate their

environment whilst simultaneously attending to balance constraints (Geuze, 2003; Rosengren et al., 2009).

One line of enquiry that might highlight underlying mechanisms used whilst walking is to analyse the organisation of the multiple joints (hip, knee, ankle, toes) and segments (trunk, thigh, shin & foot) in the leg. To walk efficiently it is important that the joints and segments are systematically organised to control the foot trajectory as we proceed through the environment (Winter, 1992). Efficient coordination of the joints and segments ensures a smooth progression for the Centre of Mass; one of the most important requirements for gait (Shumway-Cook & Woollacott, 2012). Therefore, in order walk efficiently the individual needs to be able to control the varying ranges of angular motion at each joint (and segment) which can independently rotate, and move to flex and extend the body parts. This control ensures that all the different sub-systems (joints and segments) work together to keep the body upright and stay balanced whilst simultaneously propelling it forwards (discussed in Chapter 1).

Deconinck, et al., (2006^a) and Rosengren, et al. (2009) found differences in the angular measurement of the lower limbs of children with DCD whilst walking on a treadmill. However, there is very little research to predict whether group differences in walking parameters are still apparent beyond childhood. Research by Visser, Geuze and Kalverboer (1998) suggests that movement competence for teenagers with DCD improves with age. Visser, et al., (1998) used a longitudinal study to investigate the relationship between the adolescent growth spurt and motor competence, assessed using the Movement Assessment Battery for Children (Henderson & Sugden, 1992), for individuals with and without DCD. Results suggested that rapid growth during the teenage years has a negative effect on motor skills, supporting previous research by Tanner (1978) and Shepard (1981). Explanations are proposed by Kanehisa, Ikegawa, Tsunoda and Fukugana (1995) who argue that during adolescence (particularly for boys) muscle mass (body weight) increases rapidly, but strength does not increase at the same rate. Tanner (1978) argues that the adolescent may not have sufficient muscle strength to control movement which is hypothesised to affect balance (Tanner, 1978; Shepard, 1981). Therefore, for a temporary period of development an adolescent boy can ‘outgrow’ his strength.

Interestingly, this affect was more apparent in the typically developing teenagers than the DCD group, who actually improved their motor competence during this time. Explanations for this effect are argued by Beunen and Malina (1988) who suggest that the rate of development during the growth spurt is inversely proportional to the level of motor performance before the spurt. Thus children who are well coordinated at the start of the growth spurt, (such as the typically

developing teenagers in the current study) are more at risk of the negative effect on motor skills than poorly coordinated children (such as the teenagers with DCD).

In contrast to the findings from Visser et al.'s (1998) study Losse et al. (1991), Cousins and Smyth (2003) and Kirby et al. (2010) argue that movement difficulties continue to adulthood for individuals with DCD. However, it could be argued that the tests used to investigate movement competence for the adults with DCD were more complex (e.g. obstacle avoidance, handwriting, block construction, dual task performance) than the Movement Assessment Battery for Children, age band 11-12 years, (Henderson & Sugden, 1992) used by Visser et al. (1998). Furthermore, Cousins and Smyth (2003) identified that the best discriminating factor for individuals with and without DCD was whether or not they were drivers. Therefore the restricted information available suggests that for complex tasks such as driving, difficulties persist to adulthood for individuals with DCD (Cousins and Smyth, 2003), but for less complex tasks (such as walking) a positive correlation between age and motor proficiency might be expected (Visser et al., 1998).

This chapter will describe the walking patterns of individuals with and without DCD by investigating spatio-temporal measures and variability. These investigations will be enhanced with data collected from the angular displacement of the joints and segments. Evidence will be presented from research exploring walking patterns of individuals with DCD to highlight constraints to efficient, coordinated movement of the lower limbs. This evidence will be compared to findings from research in both typical and atypical populations to identify possible mechanisms contributing to these constraints. Finally, developmental issues pertinent to this study will be discussed.

It is clear from the descriptions of leg movements discussed in Chapter 2, that each gait event has a functional objective and a precise pattern of motion for the joints and segments to efficiently achieve those objectives. Breaking down the gait cycle into specific events allows the contribution of each joint and segment to be assessed. Perry and Burnfield (2010) suggest that this approach is particularly useful for exploring the functional effects of atypical walking as joint angles and postural responses at one gait event might be inappropriate at other gait events and could indicate a dysfunction. The aims of this study were to build upon the small number of previous studies that have investigated the walking patterns of children with DCD (under 12 years of age) by considering gait patterns across a broader age range of individuals (aged 8-32 years), to explore both group differences and developmental trends. Additionally, the inclusion of kinematic and spatio-temporal measures together with variability in one study offer a novel and more integrated description of the atypical gait patterns for individuals with DCD than has

previously been reported. An important element of this study was to address some of the methodological limitations of previous work in this area. These issues were addressed by using stringent inclusion criteria for the participants with DCD, and collecting data within a realistic, but controlled laboratory environment.

4.2. Hypotheses

Given the conflicting findings from previous research investigating the walking patterns of children with DCD and the lack of research with teenagers and adults, it is difficult to present a specific hypothesis.

However, if differences in walking patterns observed on a treadmill carry over to walking on level ground (Deconinck et al, 2006^a), it could be hypothesised that children with DCD will adopt a ‘safer’ walking style (slower, shorter and wider steps; greater forward incline of the trunk), together with differences in the angular measures of lower limbs compared to their typically developing peers.

Additionally, given that the development of gait is mature by 7 years (Sutherland et al., 1980) it is hypothesised that there will be a minimal effect of age on gait pattern for the control group. Conversely, children with DCD have shown significant differences in walking patterns compared to their TD peers (Deconinck et al. 2006^a; Rosengren, et al., 2009). Furthermore, even though movement difficulties are known to continue to adulthood for individuals with DCD (Losse et al., 1991; Cousins & Smyth, 2003), the restricted evidence available suggests that for a basic task like walking, there would be no group differences between teenagers (Visser et al., 1998) or adults (Cousins and Smyth, 2003) with and without DCD. Therefore an age-by-group interaction is hypothesised (significant group differences for children, but not for teenagers and adults).

In line with Woodruff et al. (2002) and Rosengren et al. (2009) the participants with DCD are expected to have significantly more variability in their control of walking compared to their TD peers.

4.3. Methods

Full details of methods, recruitment and materials employed that are consistent across all studies can be found in chapter 3. Where necessary, a brief resume is given.

4.3.1. Participants

Thirty five individuals with Developmental Coordination Disorder (DCD) aged 8-32 years and 35 typically developing (TD) individuals participated in this study. Participants were divided into 3 age groups; 8-12years ($n=24$), 13-17years ($n=24$) and 18-32years ($n=22$). Details of selection and demographic information for all participants can be found in chapter 3.

4.3.2. Materials and procedures

Details of the materials used and procedures can be found in chapter 3.

4.3.3. Data collection

Details of data collection methods can be found in chapter 3.

The gait parameters measured in this study were divided into three categories; 1) spatiotemporal; 2) variability and 3) angular rotations about the head, torso and legs.

4.3.3.1. Spatio-temporal measures

Speed:

Measured in meters /second taken from chest marker.

Foot measures:

Foot placement measures were taken from the ankle and toe markers from each foot. The Foot Speed Algorithm (FVA, O'Connor, Thorpe, O'Malley & Vaughan, 2007) was chosen to determine the timing of Heel-strike (HS) and Toe-off (TO) as it provides a fast and accurate method to identify key points in the gait cycle). *Proportional step length* - anterior-posterior distance from lag ankle to lead ankle at their respective Heel-strike, then divided by leg length; *Step width ratio (SWR)* - medio-lateral distance from lag-ankle to lead-ankle at their respective Heel-strike as a ratio with hip width; *Percentage gait cycle in double support (%DS)* – amount of time during one gait cycle spent with both feet on the ground, expressed as a percentage of the whole stride, measured from ankle markers.

Trunk measures;

Trunk measurements were taken from an estimated Centre of Mass (CoM) (centre of the two hip markers). *Vertical movement of the trunk* - mean maximum vertical amplitude of the

estimated CoM.; *Lateral movement of the trunk* – mean maximum medio-lateral amplitude of the estimated CoM.

4.3.3.2. *Variability*

Step-to-step variability was analysed for all of the above spatio-temporal measures using standard deviations (SD) of each individual's data. This measure was introduced to try and tease apart some of the underlying processes used whilst walking.

4.3.3.3. *Angles of the Head, Trunk and Legs*

Head and trunk angles

The angle of the head and trunk were calculated at two key points in the gait cycle; Heel-Strike and Toe-Off, which mark the transition between stance (Heel-strike) and swing (Toe-Off; Winter, 2012; Perry & Burnfield, 2010), discussed in Chapter 2. The angle between the front segment (measured from markers on the forehead and chin = Head; and chest and midpoint between the hips = Trunk) and the horizontal plane is presented, see Figure 4.1. for illustration.

Leg angles

Following Perry and Burnfield's (2010) recommendation, the angular displacement of the joints and segments will be analysed at the four main gait events of ***Heel-Strike, Opposite Heel-Strike, Toe-off and Opposite Toe-Off***, which mark the transition between the two main periods of the gait cycle; stance (Heel-Strike) and swing (Toe-Off; Winter, 2012; Perry & Burnfield, 2010). These gait events have been previously used to investigate joint and segment angles whilst walking for the elderly (Tang, Woollacott, Chong, 1998; Kang & Dingwell, 2008; Ihlen, Sletvold, Goihl, Wik, Vereijken, Helbostad, 2012), and populations with DCD (Deconinck, et al, 2006a; Rosengren, et al, 2009). Segment angles were calculated from the horizontal plane, from these the absolute joint angles were calculated, as illustrated in Figure 4.1.

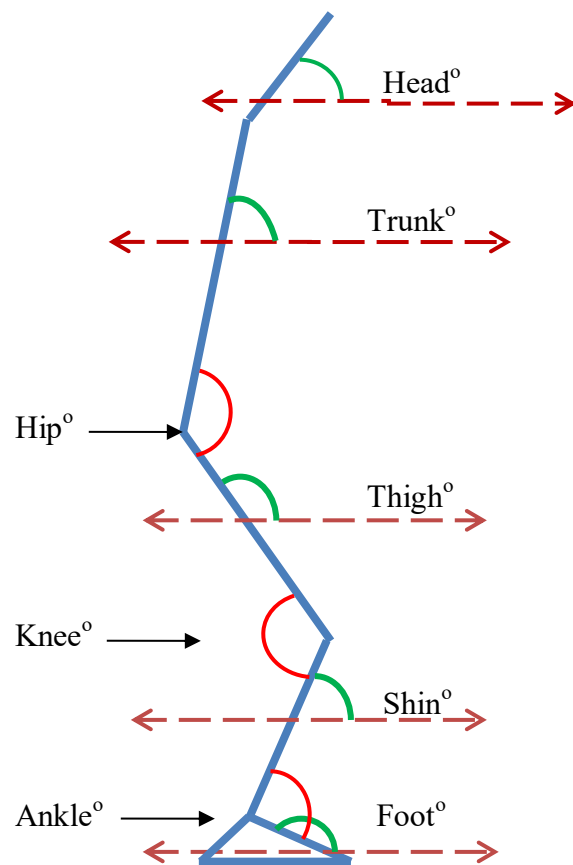


Figure 4.1. Illustration of angle calculations for head, trunk and legs.

4.3.4. Statistical analysis

Two-way independent ANCOVA's were used to partial out the effect of order of trial presentation (discussed in Chapter 3) whilst investigating the effects of group (DCD, TD) and age (child, teenage, adult) on the spatio-temporal measures, discussed above, together with variability of all spatio-temporal measures. Step-to-step variability was analysed using standard deviations (SD) of each individual's data.

A three-way mixed group ANCOVA was used to partial out the effect of order of trial presentation whilst investigating the effects of group (DCD, TD), age (Child, Teenage, Adult) and gait event (Toe-off; Heel-strike) on the angles of the head and trunk.

Multivariate Analysis of Variance (MANCOVA) was used to partial out the effect of order of trial presentation whilst investigating the effects of group (DCD, TD) and age (Child, Teenage, Adult) on 6 Dependent Variables (hip, knee, ankle; thigh, shin, foot) whilst walking on level ground. The advantages of running one MANCOVA rather than 6 separate ANCOVAs reduces the probability of a Type I error. Furthermore, MANCOVA analyses all the dependent variables simultaneously and examines the relationship between the dependent variables (Field, 2009). Given the inter-related properties of the angles of joints and segments in the legs this was an important consideration for statistical analysis. Four separate MANCOVA's were conducted to investigate effects at the four gait events of Heel-Strike (HS), Opposite Toe-Off (OTO), Opposite Heel-Strike (OHS) and Toe-Off (TO).

The test statistic chosen to represent the statistical findings was Pillai's Trace; this was based on evidence from Bray and Maxwell (1985) who suggest that when sample sizes are even this is the most robust test to perform to accommodate violations of assumptions. Box's test was significant (i.e. violated assumption of variance-covariance matrices) for HS, OHS, and OTO. However Levene's test of equality of variance was not significant for any gait event indicating no further violations. Field (2009) argues that if sample sizes are equal, Box's test can be ignored as it is "unstable" (p604) and Pillai's statistics are robust.

Significant results from the MANCOVAs were followed up with separate ANCOVAs (group-by-age) for each segment (thigh, shin, foot) and/or joint (hip, knee, ankle) angle. Significant interactions found from the ANCOVAs were explored using simple main effects and significant main effects were explored using post-hoc tests.

Finally, where effects of order of trial presentation significantly affect the results both the (M)ANOVA and (M)AVCOVA are reported, however, when there is no effect of order of trial presentation on the significance of results then only (M)ANCOVA is reported.

4.4. Results

4.4.1. Spatio-temporal measures

Means, SD's and significance for spatio-temporal measures can be seen in Table 4.1.

As speed has a direct positive relationship to leg length it was decided to partial out leg length with ANCOVA (in addition to order as a covariate) to investigate this issue further. Neither order of walking trial ($F(1,62) = 0.181, p = 0.672, \eta^2 = 0.003$) nor leg length ($F(1,62) = 0.002, p = 0.962, \eta^2 < 0.001$) made a difference to the significance of walking speed. Additionally, there was no significant age ($F(2,62) = 0.267, p = 0.767, \eta^2 = 0.009$), group ($F(1,62) = 0.1984, p = 0.164, \eta^2 = 0.031$) or age-by-group interactions ($F(2,62) = 0.169, p = 0.845, \eta^2 = 0.005$) for speed.

For proportional step length results from the ANCOVA revealed that order of walking trial did make a difference to the significance of proportional step length ($F(1,63) = 12.333, p = 0.001, \eta^2 = 0.164$). Once order had been taken into account the significance of group effects changed from non-significant (ANOVA; $F(1,64) = 3.781, p = 0.056, \eta^2 = 0.056$), to significant (ANCOVA; $F(1,63) = 5.448, p = 0.023, \eta^2 = 0.080$). The DCD group showed a significantly shorter proportional step length (0.61) than their typically developing peers (0.64). The significance of age effects also changed from non-significant (ANOVA; $F(2,64) = 2.546, p = 0.086, \eta^2 = 0.074$) to significant (ANCOVA = $F(2,63) = 3.927, p = 0.025, \eta^2 = 0.111$) after controlling for order. Teenagers showed a significantly shorter proportional step length (0.60) than the children (0.64) and adults (0.64). The age-by-group interaction remained non-significant after controlling for age (ANOVA; $F(2,64) = 0.408, p = 0.666, \eta^2 = 0.013$; ANCOVA; $F(2,63) = 0.189, p = 0.828, \eta^2 = 0.006$). For step width ratio (SWR) there was no significant effect of order ($F(1,63) = 1.271, p = 0.264, \eta^2 = 0.020$). There was a significant main effect of age ($F(2,63) = 10.454, p < 0.001, \eta^2 = 0.249$). Post-hoc tests (using the Bonferroni adjustment) show that this is due to a wider relative step width ratio in the children compared to the teenager group ($p < 0.001$) and the child compared to the adult group ($p < 0.05$). In addition, neither the main effect of group ($F(1,63) = 3.482, p = 0.067, \eta^2 = 0.052$) nor the age-by-group interaction ($F(2,63) = 0.174, p = 0.840, \eta^2 = 0.006$) were significant.

There were no significant effects of order for percentage double support ($F(1,63) = 0.169, p = 0.682, \eta^2 = 0.003$); Vertical ($F(1,63) = 2.073, p = 0.155, \eta^2 = 0.032$) or Lateral trunk movements ($F(1,63) = 0.299, p = 0.586, \eta^2 = 0.005$). There were also no main effects of group, age or age by group interactions for percentage double support, or vertical and lateral trunk movement F -values and significance for all results are listed in Table 4.1.

Table 4.1. Means, standard deviations (SD's) and significance values for spatio-temporal measures.

Measure	Age Group (Years)	DCD group Mean (SD)	TD group Mean (SD)	Significance <i>P</i> values
Speed (m/s)	Child (8-12)	0.99 (0.20)	1.05 (0.17)	Age; $F = 0.267, p = 0.767$. Group; $F = 1.984, p = 0.164$. Interaction; $F = 0.169, p = 0.845$.
	Teenager (13-17)	1.06 (0.22)	1.12 (0.12)	
	Adult (18-32)	1.06 (0.17)	1.10 (0.18)	
Proportional step length (SL/leg length)	Child (8-12)	0.61 (0.08)	0.66 (0.05)	Age; $F = 3.927, p = 0.025$. Group; $F = 5.448, p = 0.023$. Interaction; $F = 0.189, p = 0.828$.
	Teenager (13-17)	0.58 (0.09)	0.62 (0.05)	
	Adult (18-32)	0.63 (0.05)	0.64 (0.07)	
Step width ratio (SWR=SW/hip width)	Child (8-12)	0.82 (0.2)	0.90 (0.12)	Age; $F = 10.454, p < 0.001$ Group; $F = 3.482, p = 0.067$ Interaction; $F = 0.174, p = 0.840$
	Teenager (13-17)	0.63 (0.2)	0.67 (0.13)	
	Adult (18-32)	0.65 (0.21)	0.74 (0.13)	
% Double Support (% gait cycle spent in DS)	Child (8-12)	15.65 (3.05)	15.05 (1.39)	Age; $F = 0.985, p = 0.379$ Group; $F = 1.568, p = 0.215$ Interaction; $F = 2.624, p = 0.798$
	Teenager (13-17)	17.67 (4.46)	15.80 (2.19)	
	Adult (18-32)	16.74 (5.66)	16.04 (1.13)	
Vertical trunk Movement (mm)	Child (8-12)	33.43 (7.75)	38.84 (5.21)	Age; $F = 2.379, p = 0.101$ Group; $F = 0.354, p = 0.554$ Interaction; $F = 0.890, p = 0.416$
	Teenager (13-17)	41.94 (10.16)	42.11 (7.88)	
	Adult (18-32)	42.38 (12.86)	40.03 (8.61)	
Lateral trunk Movement (mm)	Child (8-12)	73.69 (22.77)	60.22 (21.95)	Age; $F = 1.148, p = 0.324$ Group; $F = 0.121, p = 0.729$ Interaction; $F = 1.385, p = 0.248$
	Teenager (13-17)	57.33 (27.26)	53.82 (20.08)	
	Adult (18-32)	54.73 (20.08)	66.21 (31.90)	

Key: significant results are underlined.

4.2. Variability

Means, SD's and significance for variability of step width ratio, percentage of time spent in double support, and vertical and lateral movement of the trunk can be seen in Table 4.2. Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of proportional step length variability ($F(1,63) = 1.959, p = 0.166, \eta^2 = 0.030$). A significant main effect of age was found ($F(2,63) = 5.397, p = 0.007, \eta^2 = 0.146$), with the teenage age group having a greater variability than both children ($p = 0.028$) and adults ($p = 0.021$), illustrated in Figure 4.2. Additionally, a significant main effect of group was found for proportional step length variability ($F(1,63) = 8.550, p = 0.005, \eta^2 = 0.119$) with the DCD group significantly more variable (0.82) than their TD peers (0.58). The interaction between age and group was not significant ($F(2,63) = 1.137, p = 0.327, \eta^2 = 0.035$).

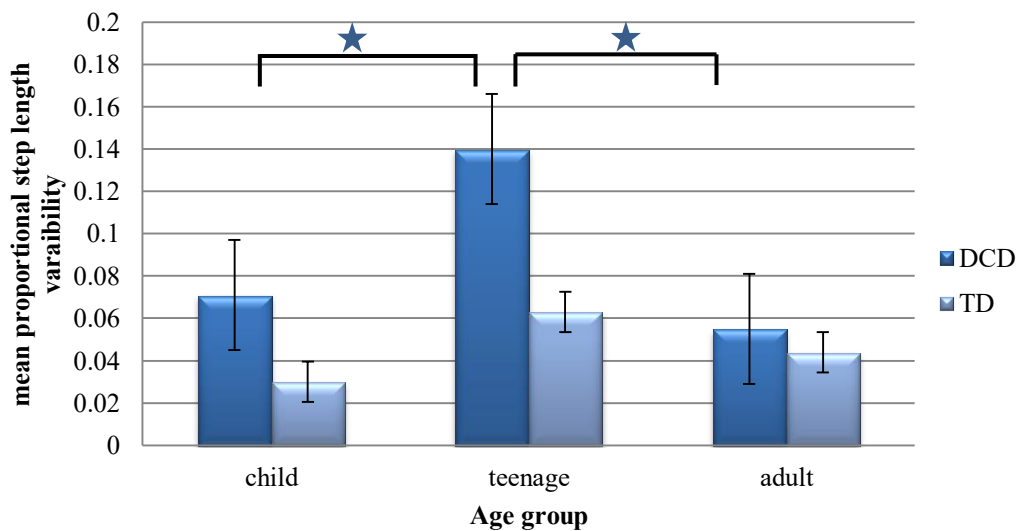


Figure 4.2. Mean of proportional step length variability over three age ranges for DCD and TD groups. Error bars represent standard error, ★ = $p < 0.05$

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of step width ratio variability ($F(1,63) = 0.009, p = 0.923, \eta^2 < 0.001$). A significant main effect of age was found ($F(2, 63) = 5.004, p = 0.010, \eta^2 = 0.137$). Post-hoc tests (using the Bonferroni adjustment) show that this is due to greater variability in relative step width ratio in the teenager group compared to both the children ($p=0.045$) and the adult group ($p=0.011$). In addition, there was a main effect of group ($F(1, 63) = 7.192, p = 0.009, \eta^2 = 0.102$), with the

DCD group more variable than the TD group. The interaction between age and group was not significant.

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of percentage time spent in double support variability ($F(1,63) = 0.032, p = 0.859, \eta^2 = 0.001$). For the variability of percentage gait cycle spent in double support, there was a significant group effect ($F(1,63) = 10.099, p = 0.002, \eta^2 = 0.138$) with the DCD group more variable (3.97) compared to the TD group (1.46). There was no age effect or interaction between age and group ($F(2,63) = 0.365, p = 0.696, \eta^2 = 0.011$).

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of the variability of vertical trunk movement ($F(1,63) = 0.159, p = 0.692, \eta^2 = 0.003$). There were no age or group effects, suggesting that both groups and all age groups as a whole do not differ in the variability of vertical trunk movement. However, there is a significant interaction between age and group ($F(2,63) = 3.1064, p = 0.050, \eta^2 = 0.089$). Simple main effects show this is due to a significant difference between the TD and the DCD groups in the teenage range ($p = 0.004$), as the teenagers with DCD are significantly more variable (6.04) than their TD peers (3.86).

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of lateral trunk movement variability ($F(1,63) = 0.058, p = 0.811, \eta^2 = 0.001$). A significant main effect of group was found ($F(1,63) = 9.252, p = 0.003, \eta^2 = 0.128$), with the DCD group showing a greater variability (11.73) than the TD group (7.86). No effect of age or group x age interaction was found. A summary of F -values and significance for all process results are listed in Table 4.2.

Table 4.2. Means, Standard Deviations (SD) and significance for Variability.

Measure	Age group	DCD group Mean (SD)	TD group Mean (SD)	Significance <i>P</i> values
Step width ratio (SWR) variability	Child (8-12)	0.23 (0.08)	0.15 (0.05)	<u>Age; $F = 5.004, p = 0.010$</u> <u>Group; $F = 7.192, p = 0.009$</u> Interaction; $F = 2.701, p = 0.075$.
	Teenager (13-17)	0.24 (0.09)	0.16 (0.05)	
	Adult (18-32)	0.13 (0.05)	0.14 (0.09)	
% Double Support variability	Child (8-12)	3.60 (4.52)	1.38 (0.47)	Age; $F = 0.926, p = 0.401$ <u>Group; $F = 10.099, p = 0.002$</u> Interaction; $F = 0.365, p = 0.696$.
	Teenager (13-17)	5.17 (5.20)	1.73 (0.77)	
	Adult (18-32)	3.14 (3.80)	1.26 (0.56)	
Vertical trunk variability	Child (8-12)	4.04 (2.30)	5.04 (4.22)	Age; $F = 0.715, p = 0.473$. Group; $F = 3.488, p = 0.066$ <u>Interaction; $F = 3.106, p = 0.050$</u>
	Teenager (13-17)	8.87 (9.95)	2.99 (1.11)	
	Adult (18-32)	5.21 (2.61)	3.55 (1.67)	
Lateral trunk variability	Child (8-12)	28.67 (15.61)	16.77 (9.17)	Age; $F = 1.634, p = 0.203$ <u>Group; $F = 9.252, p = 0.003$</u> Interaction; $F = 1.552, p = 0.220$
	Teenager (13-17)	22.68 (10.11)	13.43 (6.31)	
	Adult (18-32)	18.27 (9.48)	16.95 (8.11)	

Key; significant results are underlined

4.4.3. Angles of the head and trunk

Means, SD's and significance for angles of the head and trunk can be seen in Table 4.3 and 4.4 . Two participants from the teenage age group (1x DCD and their matched TD control) had to be removed from this analysis as the chin and chest markers were obscured. This left 68 participants (34 DCD, 34 TD group), divided by age into; child $n = 24$, teenager, $n = 22$, adult $n = 22$.

4.4.3.1. Head angles

Order of walking trial did make a difference to the significance of head angle ($F(1,61) = 6.978$, $p = 0.010$, $\eta^2 = 0.103$). Therefore once order had been taken into account the significant main effect of event for the angle of the head at TO and HS (ANOVA result = $F(1,62) = 4.865$, $p = 0.031$, $\eta^2 = 0.073$) was no longer significant (ANCOVA result = $F(1,61) = 3.260$, $p = 0.076$, $\eta^2 = 0.051$). However, all other event-by-age or event-by-group interactions remained non-significant after partialling out order as a covariate. (ANCOVA F values ranged from 0.150 for event-by-age to 1.560 for event-by-order).

However, the significant effect of group (ANOVA result = $F(1,62) = 5.360$, $p = 0.024$, $\eta^2 = 0.080$) remained significant after controlling for the effects of order (ANCOVA result = $F(1,61) = 5.020$, $p = 0.029$, $\eta^2 = 0.076$) indicating that the head angle overall was different for the two groups. Mean values show that that the DCD group had smaller head angles (head tipped more towards the ground) at both gait events (HS = 71.09° ; TO = 71.79°) compared to the TD group (HS = 75.40° , TO = 76.83°), illustrated in Figure 4.3. There was no age effect, or interaction between age and group.

Finally, age (ANOVA result = $F(2,62) = 0.919$, $p = 0.404$, $\eta^2 = 0.029$) and age-by-group (ANOVA result = $F(2,62) = 0.232$, $p = 0.794$, $\eta^2 = 0.007$) effects remained non-significant after controlling for the effects of order (age ANCOVA result = $F(1,61) = 1.043$, $p = 0.359$, $\eta^2 = 0.033$; age-by-group ANCOVA result = $F(2,61) = 14.243$, $p = 0.893$, $\eta^2 = 0.004$).

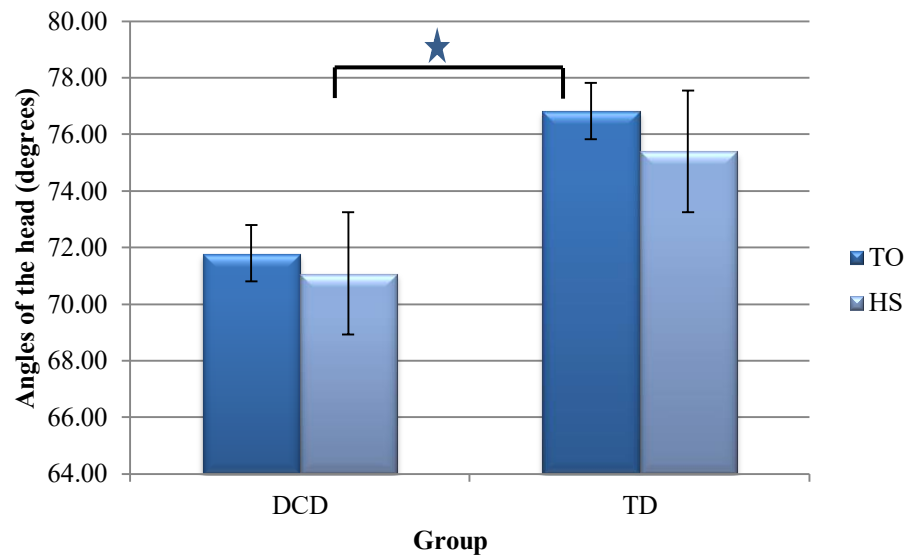


Figure 4.3 Mean of angles of the head at Heel-Strike and Toe-off for DCD and TD groups whilst walking on level ground. Error bars represent standard error, ★ = $p < 0.05$

Table 4.3. Means and Standard Deviations (SD), for angle of the head whilst walking on level ground.

Measure	Age	DCD group	TD group	Significance
Head angle	group	Mean	Mean	<i>P</i> values
(degree)		(SD)	(SD)	
Toe Off	Child	73.09	77.18	Age = n/s Group; $p = 0.029$ DCD < TD
	(8-12)	(5.08)	(5.87)	
	Teenager	70.15	74.69	
	(13-17)	(8.94)	(12.45)	
	Adult	72.14	78.61	
Heel Strike	(18-32)	(8.83)	(10.25)	
	Child	72.23	75.09	
	(8-12)	(4.61)	(5.44)	
	Teenager	69.63	72.96	
	(13-17)	(10.90)	(9.26)	
	Adult	71.40	78.14	
	(18-32)	(9.44)	(8.50)	

Key; n/s = not significant; TO = Toe-off; HS = Heel-strike

4.4.3.2. Trunk angles

Order of walking trial made no difference to the significance of trunk angle ($F(1,61) = 0.059$, $p = 0.808$, $\eta^2 = 0.001$). There was a significant effect of age ($F(2,61) = 5.305$, $p = 0.008$, $\eta^2 = 0.148$), suggesting that overall trunk angles are differentially affected by age, pairwise

comparisons show that teenagers having a significantly ($p = 0.005$) smaller trunk angle (87.68°), leaning more towards the ground) than adults (91.71°). Illustration of this effect can be seen in Figure 4.4.

Additionally, there was a significant age-by-event interaction for the angle of the trunk at TO and HS whilst walking on level ground ($F(2,61) = 3.253$, $p = 0.045$, $\eta^2 = 0.096$). Simple main effects show that this is due to a significantly larger incline (more upright) for trunk angle for adults at TO (92.17°) compared to HS (91.27° , $p = 0.016$), however for the teenagers and children there were no differences between event. There were no other significant group or event-by-group interactions (F values ranged from 0.336 for event-by-group-by-age to 3.720 for event-by-group).

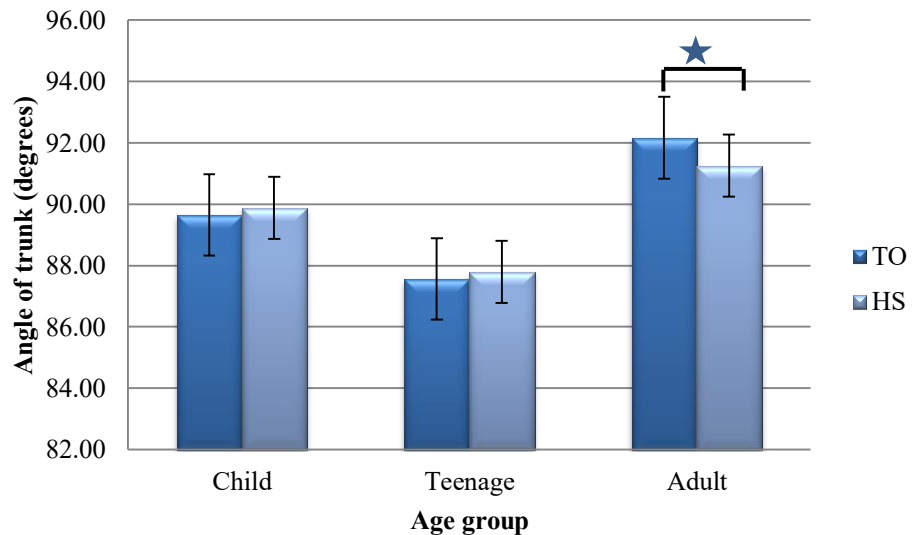


Figure 4.4. Means of angles of the trunk over three age ranges for TO and HS.

Error bars = standard error; ★ = $p < 0.05$

Table 4.4. Means and Standard Deviations (SD), for angle of the trunk whilst walking on level ground.

Measure	Age	DCD group	TD group	Significance
Trunk angle (degree)	group	Mean (SD)	Mean (SD)	<i>P</i> values
Toe Off	Child	90.84	88.46	Group = n/s Age; $p = 0.008$ T < A Event-by-age Interaction; $p = 0.045$
	(8-12)	(4.28)	(4.85)	
	Teenager	86.06	89.07	
	(13-17)	(4.29)	(4.46)	
	Adult	92.13	92.20	
	(18-32)	(3.99)	(4.93)	
Heel Strike	Child	90.61	89.16	Event-by-age Interaction; $p = 0.045$
	(8-12)	(3.57)	(4.03)	
	Teenager	86.13	89.47	
	(13-17)	(3.64)	(3.67)	
	Adult	90.65	91.88	
	(18-32)	(4.31)	(4.03)	

Key; n/s = not significant.

4.4.3.3. Leg angles

Means and standard deviations for segment (thigh, shin, foot) and joint (hip, knee, ankle) angles at all four gait events can be found in the appendices (number II) Tables A5.1 (segment angles) and A5.2 (joint angles). A summary of significant results can be found in Table 4.7.

Illustrations of group and age effects can be found in Figures 4.10 and 4.11

For all analyses of joint and segment angles 1 adult with DCD and 1 teenager with DCD and their matched pairs had to be removed as there were not enough complete strides to analyse. This left 66 participants (33 DCD, 33 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 20$.

Angles at Heel-strike

At Heel-strike results from the MANCOVA showed that order of walking trial did not make a difference to the significance of leg (segment and joint) angles ($F(6,54) = 0.814$, $p = 0.564$, $\eta^2 = 0.083$, Pillai's Trace = 0.083). There were significant age effects ($F(12,110) = 2.319$; $p = 0.011$, $\eta^2 = 0.202$, Pillai's Trace = 0.404), indicating that overall leg angles are differentially affected

by age. There were no group effects ($F(6, 54) = 1.200$; $p = 0.321$, $\eta^2 = 0.118$, Pillai's Trace = 0.118), or group-by-age interactions ($F(12,110) = 1.734$; $p = 0.069$, $\eta^2 = 0.159$, Pillai's Trace = 0.318) for leg angles at Heel-strike.

Follow-up ANCOVAs show a significant age effects for the *Hip* ($F(2, 59) = 3.710$, $p = 0.03$, $\eta^2 = 0.112$); Pairwise comparisons (using the Bonferroni correction) and mean values show this is due to a significantly ($p = 0.03$) smaller hip angle (160°) i.e. more flexed for the teenagers compared to the adults (164°). At the *Thigh* there were significant age effects ($F(2, 59) = 3.766$, $p = 0.03$, $\eta^2 = 0.109$). Pairwise comparisons and mean values show this is due to the teenagers having a significantly ($p = 0.04$) larger angle (108°), i.e. more flexed, than children (106°). Finally, at the *Knee* there were significant age effects ($F(2, 59) = 4.311$, $p = 0.02$, $\eta^2 = 0.128$). Pairwise comparisons and mean values show that teenagers have a significantly ($p = 0.04$), smaller angle (164°), i.e. more flexed, than adults (168°). See Figure 4.5. for illustration of these effects.

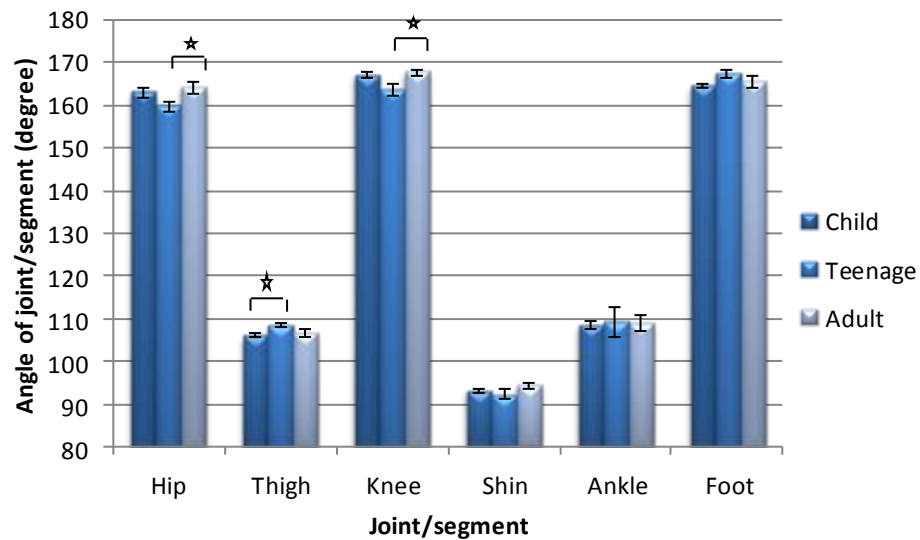


Figure 4.5. Age effects for joint and segment angles at Heel-strike (★ $p < 0.05$)

Angles at Opposite Toe-Off

At Opposite Toe-Off results from the MANCOVA showed that order of walking trial did not make a difference to the significance of leg (segment and joint) angles ($F(6,54) = 0.814$, $p = 0.286$, $\eta^2 = 0.124$, Pillai's Trace = 0.124). There were no significant group ($F(6, 54) = 1.042$; $p = 0.409$, $\eta^2 = 0.104$, Pillai's Trace = 0.104) or age effects ($F(12,110) = 1.145$; $p = 0.332$, $\eta^2 = 0.111$, Pillai's Trace = 0.222) or any group-by-age interactions ($F(12,110) = 1.137$; $p = 0.338$, $\eta^2 = 0.110$, Pillai's Trace = 0.221) for leg angles at Opposite Toe-Off.

Angles at Opposite Heel-Strike

At Opposite Heel-strike results from the MANCOVA showed that order of walking trial did not make a difference to the significance of leg (segment and joint) angles ($F(6,54) = 0.481$, $p = 0.819$, $\eta^2 = 0.051$, Pillai's Trace = 0.051). There were however, significant group effects for leg angles ($F(6, 54) = 3.508$; $p = 0.005$, $\eta^2 = 0.280$, Pillai's Trace = 0.280), indicating that overall there is an effect of group on leg angles at Opposite Heel-Strike (see Figure 5.9 for illustration). Additionally there were significant age effects for the leg angle ($F(12,110) = 2.340$; $p = 0.010$, $\eta^2 = 0.203$, Pillai's Trace = 0.407), indicating that overall there is an effect of age on leg angles at Opposite Heel-Strike (see Figure 4.6 for illustration). There were no group-by-age interactions for leg angles at Opposite Heel-Strike ($F(12,110) = 1.005$; $p = 0.449$, $\eta^2 = 0.100$ Pillai's Trace = 0.198).

Group effects at Opposite Heel-Strike

Follow-up ANCOVAs show significant group effects for the *Hip* ($F(1, 59) = 8.246$, $p = 0.006$, $\eta^2 = 0.123$). Mean values reveal that the DCD group have a smaller hip angle (193°), i.e. more flexed than the TD group (197°). At the *Thigh* significant group effects were found ($F(1, 59) = 8.424$, $p = 0.005$, $\eta^2 = 0.125$), with the DCD group have a larger Thigh angle (76°), i.e. more flexed than the TD group (74°). At the *Shin* significant effects were found ($F(1, 59) = 5.903$, $p = 0.02$, $\eta^2 = 0.091$), with the DCD group have a larger angle (52°), i.e. more extended than the TD group (50°). Finally, at the *Foot* significant effects were also found ($F(1, 59) = 7.490$ $p = 0.008$, $\eta^2 = 0.113$), with mean values revealing that the DCD group have a larger Foot angle (165°), i.e. more flexed than the TD group (162°). See Figure 4.6. for illustration of these effects.

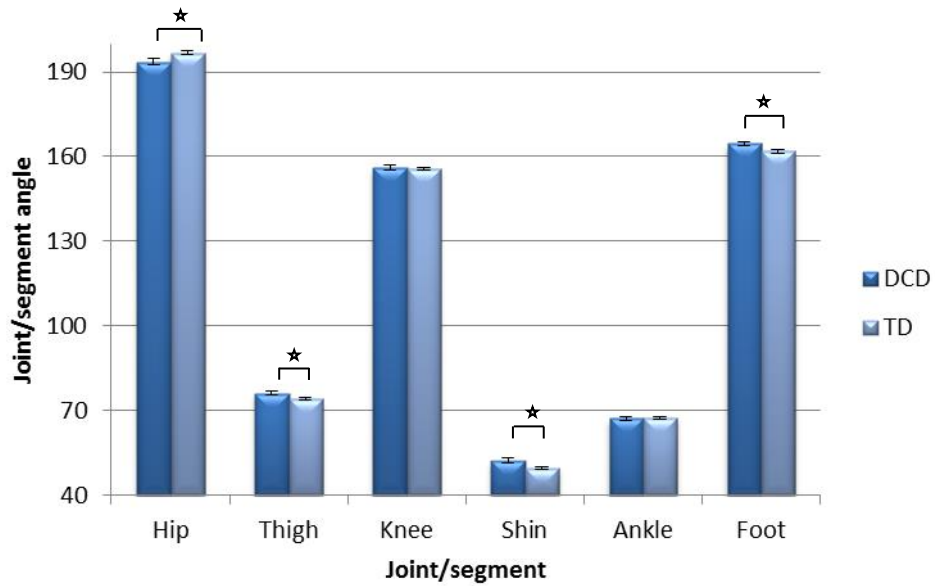


Figure 4.6. Group effects for joint and segment angles at Opposite Heel-strike (★ = $p < 0.05$)

Age effects at Opposite Heel-Strike.

A follow-up ANCOVA revealed significant age effects for all variables except the Knee and Ankle. At the *Hip* a significant main effect of age was found ($F(2, 59) = 8.350, p = 0.001, \eta^2 = 0.221$). Pairwise comparisons and mean values show that this is due to the teenagers having a significantly smaller hip angle (192°), i.e. more flexed, than both children ($p = 0.02, 197^\circ$) and adults ($p = 0.03, 197^\circ$). At the *Thigh* a significant age effects were found ($F(2, 59) = 3.696, p = 0.031, \eta^2 = 0.111$). Pairwise comparisons and mean values show that the teenagers having a significantly ($p = 0.027$) larger angle (76°), i.e. more flexed, than children (74°). At the *Shin* significant age effects were found ($F(2, 59) = 3.814, p = 0.03, \eta^2 = 0.114$). Pairwise comparisons and mean values show this is due to the teenagers having a significantly ($p = 0.042$), larger angle (52°), i.e. more extended, than children (49°). Finally, at the *Foot* significant age effects were found ($F(2, 59) = 5.855, p = 0.005, \eta^2 = 0.166$). Pairwise comparisons and mean values show this is due to a smaller foot angle, i.e. more extended, for children (161°) compared to the teenagers ($p = 0.010, 165^\circ$) and the children compared to the adult group ($p = 0.021, 164^\circ$). See Figure 4.7 for illustration of these effects.

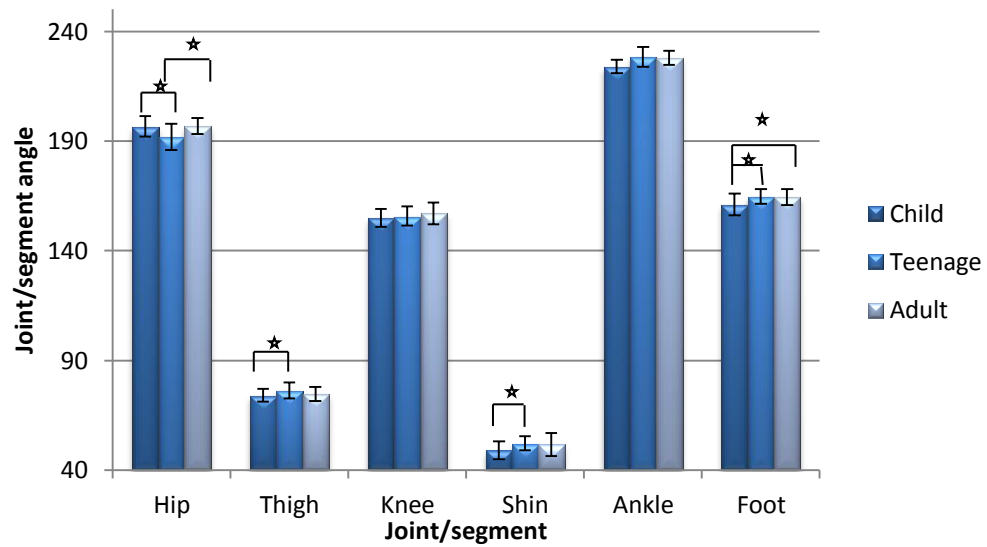


Figure 4.7 Age effects for joint and segment angles at opposite Heel-strike (* $p < 0.05$)

Angles at Toe-off

At Toe-off results from the MANCOVA showed that order of walking trial did not make a difference to the significance of leg (segment and joint) angles ($F(6,54) = 1.222$, $p = 0.309$, $\eta^2 = 0.120$, Pillai's Trace = 0.120). There were significant group effects for leg angle ($F(6, 54) = 3.599$; $p = 0.004$, $\eta^2 = 0.286$, Pillai's Trace = 0.286), indicating that overall there is an effect of group on leg angles at Toe-off. See Figure 5.11 for illustration. There were also significant age effects for leg angle ($F(12,110) = 2.309$; $p = 0.011$, $\eta^2 = 0.201$, Pillai's Trace = 0.402), indicating that overall there is an effect of age on leg angles at Toe-off. See Figure 5.12 for illustration. There were no group-by-age interactions at Toe-off ($F(12,110) = 1.221$; $p = 0.278$, $\eta^2 = 0.118$, Pillai's Trace = 0.235).

Group effects at Toe-off

A follow-up ANCOVA revealed significant group effects for the *Knee* ($F(1, 59) = 6.186$, $p = 0.016$, $\eta^2 = 0.09$), *Shin* ($F(1, 59) = 9.635$, $p = 0.003$, $\eta^2 = 0.140$), *Ankle* ($F(1, 59) = 12.774$, $p = 0.001$, $\eta^2 = 0.178$) and *Foot* ($F(1, 59) = 13.835$, $p < 0.001$, $\eta^2 = 0.190$). This was due to a larger angle (i.e. more extended) in the DCD group compared to the TD group for knee angle (DCD = 124°; TD = 121°) and shin angle (DCD = 31°; TD = 28°). At the ankle group differences were due to a smaller angle (i.e. more flexed) in the DCD group compared to the TD group (DCD = 83°; TD = 93°). Finally, at the Foot significant group effects were due to larger angle i.e. more flexed for the DCD compared to the TD group (DCD = 127°; TD = 115°). See Figure 4.8. for illustration of these effects.

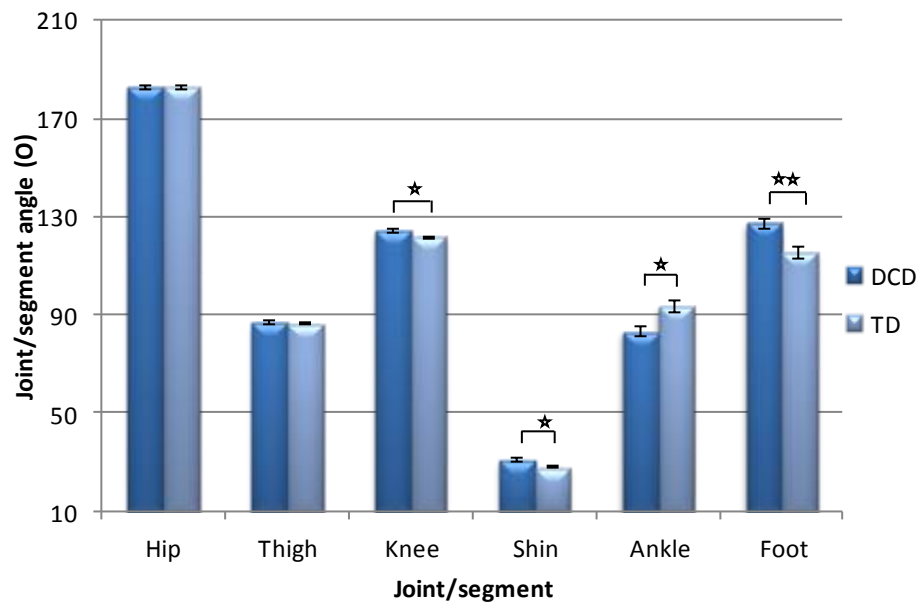


Figure 4.8. Group means for joint and segment angles at Toe-off (* = $p < 0.05$; ** = $p < 0.001$)

Age effects at Toe-off

A follow-up ANCOVA revealed significant age effects at the *Hip* ($F(2, 59) = 6.923$, $p = 0.002$, $\eta^2 = 0.190$). Pairwise comparisons and mean values show that the adults having a significantly, larger hip angle (187°), i.e. more extended, than both children ($p = 0.025$, 182°) and teenagers ($p = 0.003$, 180°). See Figure 4.9. for illustration of these effects.

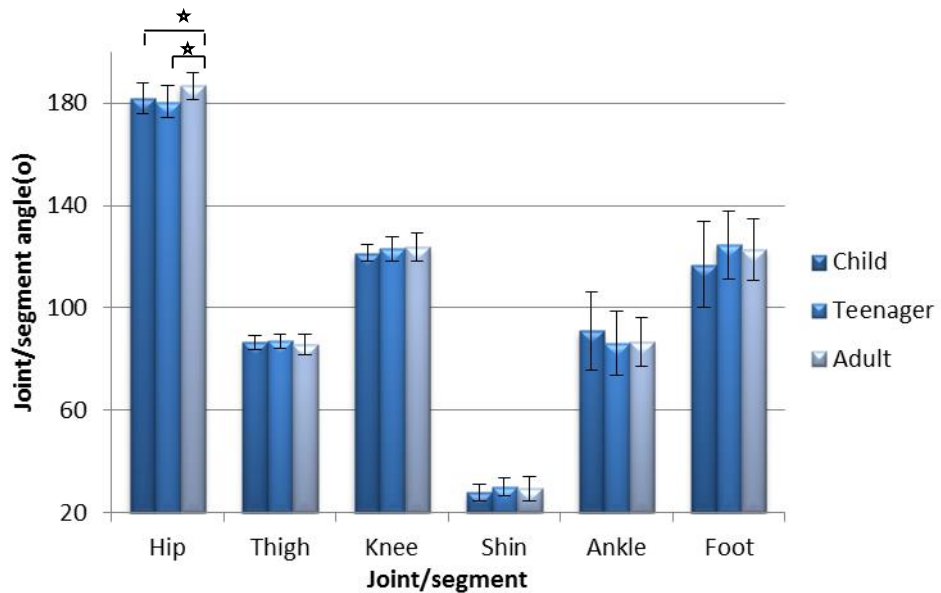


Figure 4.9 Age means for joint and segment angles at Toe-off (* = $p < 0.05$). Error bars = standard error

Table 4.7 Summary of significant effects for leg angles (segment and joint) at four gait events
(> = more flexed; < = less flexed).

Summary of significant effects				
Statistical test	Heel-strike	Opposite Toe-off	Opposite Heel-strike	Toe-off
MANCOVA	Age	No effects	Age & Group	Age & Group
ANCOVA	Hip; T > A		Hip; T > C&A DCD>TD	Hip; A< C & T
	Thigh; T > C		Thigh; T > C DCD>TD	
			Shin; T < C DCD<TD	Shin; DCD < TD
	Knee; T > A			Knee; DCD < TD
				Ankle; DCD > TD
			Foot; C < T&A DCD > TD	Foot; DCD > TD
<i>key</i> , C = Child; T = Teenage; A = Adult				

Group effects

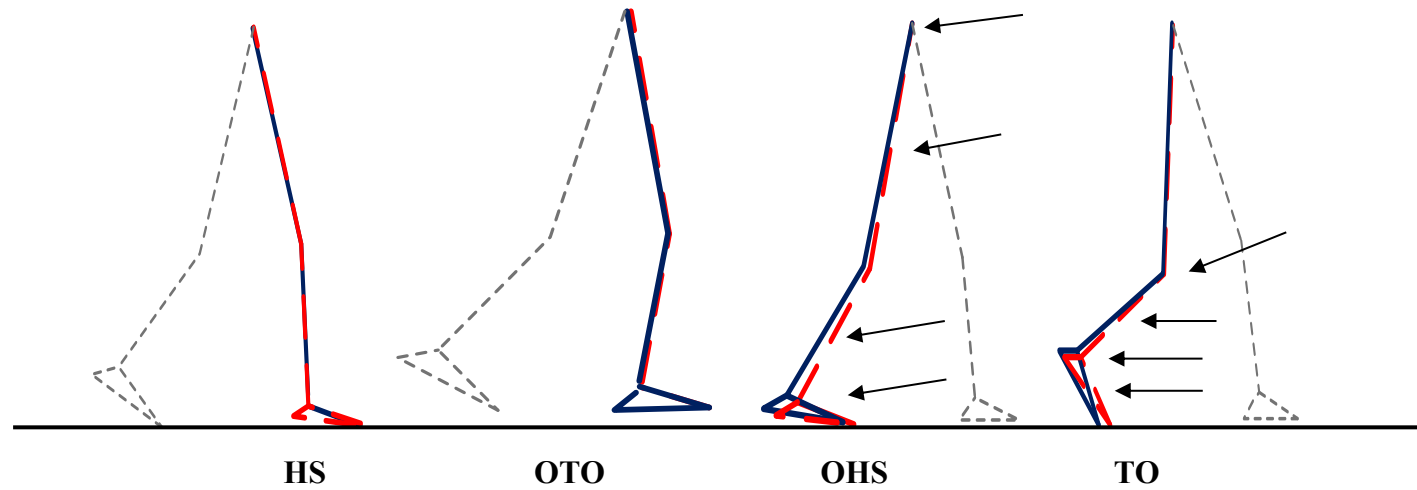


Figure 4.10 *Group effects* - Stick figures of leg configurations at four stages of the gait cycle Heel-strike (HS); Opposite Toe-off (OTO); Opposite Heel-strike (OHS); Toe-off (TO). Solid black line represents TD group and red dashed line represents DCD group. Arrows indicate significant group differences.

Age effects

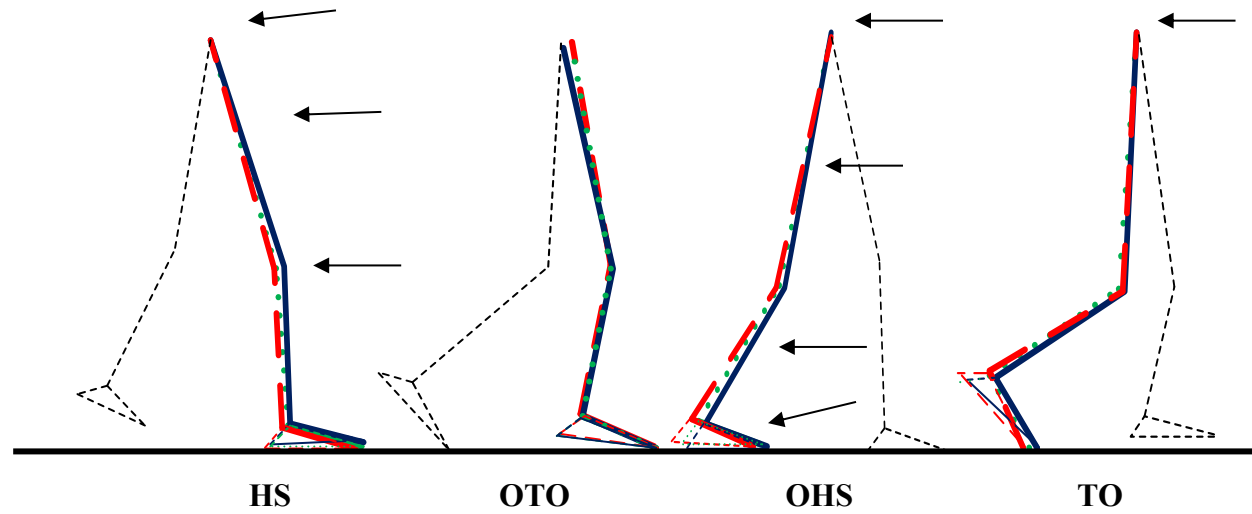


Figure 4.11. *Age effects* - Stick figures of leg configurations at four stages of the gait cycle; red dashed line represents children; solid black line represents teenagers; green dotted line represents adults. Arrows indicate significant age differences.

4.5. Discussion

The purpose of this study was to complete an ecologically valid and robust investigation to characterise the walking patterns of individuals with and without DCD whilst walking on level ground. A comprehensive analysis investigated spatio-temporal measures, and angular kinematics of the head, trunk and legs together with variability. This detailed description provides a deeper understanding of the underlying mechanisms involved in walking than has previously been described. Given the large age range of participants in this study, results will be discussed in terms of group and age effects and group-by-age interactions.

4.5.1. Group effects

The only significant group effects for any of the spatio-temporal measures in this study were for proportional step length, with the DCD group walking with a significantly shorter proportional step length than their TD peers. The lack of group effects for any other spatio-temporal measure (speed, step width ratio, % time in double support, vertical and lateral movement of the trunk) extends previous investigations into gait patterns for children with DCD (Woodruff, 2002; Chenn et al., 2009; Deconinck, et al., 2010) by illustrating that both teenagers and adults with DCD also exhibit walking patterns within the typical range in predictable environmental conditions (Please see Appendix IV for typical stepping parameters). In contrast, there were significant group differences in body configuration as the individuals with DCD inclined their heads further towards the ground than their TD peers as they walked. Additionally, group differences in the angular kinematics of the legs, particularly at Opposite Heel-strike and Toe-off were also identified. Furthermore, the individuals with DCD showed significantly more variability for all spatio-temporal measures except vertical trunk movement. These findings will be discussed in detail below.

The shorter step length found in the current study supports research by Deconinck et al. (2006^a) who showed that children with DCD used a shorter step and greater forward incline of the trunk than their TD peers whilst walking on a treadmill. Deconinck et al. (2006^a) argue that the ‘safer’ walking strategy shown by the individuals with DCD in their study was a strategy to find an optimum compromise between forward propulsion and balance control. Furthermore, as discussed in Chapter 2, a shorter step length is argued to be a strategy used by older walkers to assist with balance constraints (Lord et al, 1996; Winter et al., 1990; Woollacott & Tang, 1997).

The apparent conflict in these findings compared to Woodruff, et al. (2002) who found very little difference in spatio-temporal measurements of walking patterns of individuals with and

without DCD, can be explained by examining the methods employed. Woodruff, et al. (2002) normalised step length by expressing it as a percentage of the gait cycle (to account for any correlation between step length, age and/or leg length) and the lack of group difference can be explained with reference to Deconinck et al.'s (2006^a) study. Deconinck et al. (2006^a) scaled step length to the duration of the gait cycle and found that all group differences disappeared, arguing that the shorter stride length for participants with DCD resulted from a higher cadence (steps/minute). Whilst cadence was not measured, these findings could still be pertinent to the current study. It could be argued that if the individuals with DCD walked with a higher cadence than their TD peers, this might explain how they walked at the same speed but had a shorter Proportional Step length. However, these conflicting results highlight the importance of standard measures across studies to ensure findings are correctly interpreted.

Further similarities between the current study and Deconinck et al.'s (2006^a) study can be found whilst comparing angular kinematics. Both studies found greater flexion about the hip for the DCD group compared to TD controls. However, the participants with DCD in Deconinck et al.'s (2006^a) study adopted a stance of greater flexion about the hip throughout the entire gait cycle, caused by greater forward inclination of the trunk. The authors argue that this strategy results in lowering the Centre of Mass to assist with constraints to stability. In the current study the reduced angle at the hip occurred only at Heel-strike and was caused by greater upward inclination of the thigh (as there were no group differences in trunk angles) whilst walking on level ground. It is difficult to conclude at this stage whether differences in findings between the two studies are related to differences in the ages of the participants and/or differences in methods of data collection (treadmill; overground).

So what is happening at Opposite Heel-strike that could influence these group effects whilst walking on level ground? One of the major functions at Opposite Heel-strike is lateral weight transfer from one leg to the other, and the results from this study may reflect difficulties for the DCD group to accommodate the abrupt weight transfer from the reference leg to the contralateral leg at this point. However, there must be something more happening during the relinquishing of weight at Opposite Heel-strike affecting the DCD group; otherwise there would be group effects during weight acceptance at Heel-Strike too. Perry and Burnfield (2010) explain that at Opposite Heel-strike the reference limb responds to the weight transfer with maximum extension about the hip, in contrast to Heel-strike where there is flexion about the hip.

The results from the current study could therefore highlight difficulty for the DCD group to achieve maximum extension about the hip. This hypothesis is supported by DeVita and

Hortobagyi (2000), who argue that increased flexion about the hip during late stance is an adaptive response, by older participants, to accommodate reduced ankle plantar flexion (extension). However, the reduced extension/increased flexion about the hips for the older population is often associated with a lower range of motion about the hip or reduced step length and speed as they adopt a safer walking style (Kerrigan, Xenopoulos-Oddsson, Sullivan, Lelas, Riley, 2003). Given that that DCD group showed a shorter proportional step length than the controls, it could be speculated that extension of the hip and step length are interrelated particularly as there is no evidence to suggest that individuals with DCD have a lower range of motion than controls.

Causation at this stage is difficult to ascertain, and findings from the current study might just highlight differences in walking strategy. The DCD group might be using a '*hip strategy*' reducing their 'push-off' at the ankle and pulling the leg forward at the hip, whilst the TD group use an '*ankle strategy*' pushing the limb forward from the ankle. Both these strategies are acceptable for typical walking (Mueller, et al., 1994), although as discussed in Chapter 2, an ankle strategy is more energy efficient. The use of a less efficient walking strategy, whilst still functional, will obviously be more tiring, and may highlight why individuals with DCD are less inclined to participate in physical activity (Bouffard, Watkinson, Thompson, Caugrove-Dunn, Romanow, 1996). An intervention study focusing on this area might prove an important addition to the DCD literature.

Further support for a group difference in walking strategy (hip vs ankle) is demonstrated by angular kinematics at Toe-off. Individuals with DCD had more extension about their knees which inclined their shins more forwards, and greater flexion about their ankles which inclined the foot upwards more than the TD group. These results support findings from Deconinck et al.'s (2006^a) study, as both studies found group differences at the foot and ankle with the DCD group significantly more flexed at the ankle with greater upwards incline for the foot than their TD peers.

These angular differences are particularly relevant given that movement around the ankle, whilst small, may be functionally critical. A 5° difference in angular measurements at the ankle equates to one standard deviation from the mean, which, Perry and Burnfield (2010) argue is clinically as well as statistically significant. Using one standard deviation from the mean is a frequently used strategy to identify deviation of joint movement from normality. Several researchers have used these parameters whilst designing indices to clinically evaluate atypical gait (Barton, Hawken, Scott & Schwartz, 2012).

Given the importance of walking to access many everyday activities, clinical significance is an important consideration and could identify a scientific rationale for addressing ankle flexibility during clinical management programmes for individuals with DCD. Although not measured in this study, the group differences at the ankle could illustrate lower neuromuscular strength in the DCD group to propel the body forward (Deconinck et al., 2006^a; Raynor, 2001). It could be argued, that an intervention programme focussing on muscular strength at the ankle could provide a possible strategy to address atypical angular rotations at the ankle for individuals with DCD.

It is interesting to note that, whilst the Deconinck et al. (2006^a) study found significant angular differences at all 4 gait events, these differences (with the exception of foot and ankle angle at TO) were mainly apparent at the top of the legs (knee, thigh, hip) and the trunk. Additionally, the reported angular differences were generally greater than 5°. In contrast, the current study reports group differences of between 2-4° for upper leg angles at just two gait events (OHS & TO). It could be argued that even though the angular group differences for the upper leg reported in the current study are statistically significant and fall beyond the margin of error for VICON (1.5° Richards, 1999), in reality a 2° difference in angular movement of (for example) the shin or thigh may not be meaningful.

Neuromuscular strength is an important factor at Toe-off as it is a period of intense force generation used to propel the foot forward (Whittle, 2012) and to sustain efficient walking patterns (Buczek Sanders, Concha, et al., 2003). Furthermore, work by Nigg et al (1994) illustrated that decreased muscle strength in the older population particularly affected the knee and ankle joints whilst walking. Additionally, DeVita and Hortobagyi (2000) found that the reduced muscular force in the elderly about the ankle caused a corresponding reduction of ankle joint torque with less plantarflexion (extension) during late stance compared to young adults. A recent study by Diamond, Downs and Morris, (2014) investigated the propulsion strategy for children with and without DCD whilst walking and running. Their findings support the hypothesis that reduced strength in the ankle at Toe-off was compensated for with greater hip flexor power. Further research is needed to tease these two variables apart and to investigate whether shorter proportional step length for participants with DCD compared to their TD peers could result from gait adaptations to compensate for problems with balance and/or neuromuscular control as argued by Deconinck et al. (2006^a).

In addition to the impact of lower muscular strength on walking patterns, one of the main functions at Toe-off is preparation for foot clearance during swing, it would follow that if there is more extension about the knee and more forward incline at the shin, then there needs to be

more flexion at the ankle to ensure that the foot clears the floor. Explanations for these significant effects suggest that optimal performance at Toe-off requires that the three segments (and joints; hip, knee ankle) work together to lift the foot ready for swing and to ensure the foot just clears the ground during swing (Whittle, 2012). Given that the hip joint is highly stable, being firmly attached to the trunk, greater angular rotation at the foot compared to the hip and knee may be the result of the location of the foot at the distal end of a kinematic chain (Forczek & Staszkievicz, 2012). Furthermore, lacking the advantage of spatial location of their limbs (Mon-Williams et al., 1999), may further compound the ability for individuals with DCD to control the many different degrees of freedom around the joints needed to produce systematic, coordinated movements (Bernstein, 1967) needed for walking as argued by Rosengren et al., (2009).

Support for the argument above can be found by analysing the head angle data. Head angle was used to infer where the participant was looking whilst walking along the pathway. Inclining the head downwards was interpreted as a need to sample the ground terrain or the whereabouts of the lower limbs; the greater the incline, the greater the focus of foveal attention. Given that the DCD group inclined their heads further towards the ground than their TD peers, this could highlight difficulties for individuals with DCD adjusting to changes in proprioceptive, visual and vestibular information (Wilson & McKenzie, 1998, Wann, et al., 1998; Deconinck, et al., 2007) which, as discussed in Chapter 2, are essential attributes needed for efficient walking (Peterka, 2002). Furthermore, the implications of looking downwards rather than ahead when negotiating a real-life environment may affect the use of feedforward visual information to assist with predictions of motor adjustments needed to negotiate objects in the travel path. These findings could be extended with further research using an eye tracker to investigate where individuals are looking as they walk.

4.5.1.1. Variability of spatio-temporal measures.

Given the sensorimotor constraints of individuals with DCD, discussed above, it is understandable that variability of nearly all spatio-temporal measures was higher (proportional step length, Step width ratio, % double support, lateral trunk movement) for individuals with DCD compared to their TD peers. These findings build upon previous research by Rosengren et al. (2009) who showed greater variability in step length for children with DCD compared to their TD peers. They argue this may result from poorer control of the lower limbs which has a negative effect on the production of consistent movement patterns whilst walking. Additionally, increased variability in walking patterns has also been correlated with balance problems for children with DCD (Rosengren et al., 2009) and for older walkers (Maki, 1997). Furthermore,

variability of lateral trunk movement was also greater for the DCD group compared to the TD controls. Kuo and Donelan (2010) argue that poorer control of lateral balance in older adults may result in increased Step Width Ratio variability and might serve as an indicator of poor sensorimotor control of balance when walking.

Sensorimotor control is therefore a crucial element needed for efficient movement. However, for movement tasks carried out within a dynamic environment (such as walking) the efficiency with which feedforward and feedback information is integrated is essential to ensure safe passage to the desired destination. For example, as we walk any errors made in foot placement must be corrected almost simultaneously by the following foot, but if sensory information is difficult to interpret this will reduce the accuracy of control adjustments manifesting in misplaced and variable foot placement (Kuo and Donelan, 2010). Thus for individuals with DCD it could be hypothesised that the motor control needed for effective error management is sub-optimal because of poor integration of essential sensory information.

It could be argued that if findings from studies investigating goal directed arm movements (Smits-Engelsman, et al., 2003; Hyde & Wilson, 2010) transfer to the cyclic task of walking, then problems accessing an accurate internal representation of the movements required for walking could also affect the variability of gait patterns of individuals with DCD to a greater extent than their TD peers. For example, as discussed in Chapters 1&2, in order to plan a movement the individual needs an accurate internal representation of where the body is in space and an estimation of where it wants to be (*feedforward information*). In order to do this the CNS needs accurate sensory information about the current location of all the different body segments (*feedback information*). Additionally, previous experience is used to allow the CNS to locate the appropriate motor command needed to action the necessary movement. However, the accuracy of information used to inform the previous experience has implications for the movement itself. For example, if the sensory systems provide information that can be assimilated and re-weighted to reflect the specific demands of the task and current environmental conditions then the feedforward information used to inform the motor command will be the 'best fit' to accommodate these constraints. The individual can then alternate between feedforward and feedback information as needed to correct any error, with the frequency of error correction increasing as the task and environmental constraints increase.

If the internal model has not received accurate sensory information then it will not be able to provide a reliable forward model to the motor system and error management will subsequently require greater feedforward-feedback interaction. If this occurs during a repetitive task such as walking, it is easy to see how walking patterns could be more variable, and less efficient

(Rosengren et al., 2009). It could be speculated that for populations such as those with DCD who are known to have difficulties with the integration of sensory information (i.e. feedback) and feedforward information (Wilson et al., 2013) error management is sub-optimal. The attentional cost of poor sensory integration may affect the automaticity of walking for individuals with DCD, as attentional resources are needed to adjust movements to accommodate environmental and task constraints.

Given the interrelated use of feedback and feedforward processes used for movement, and particularly for continuous tasks like walking (Kuo & Donelan, 2010), it is difficult at this stage to hypothesise the separate effects of feedback and feedforward processes. However, for populations such as those with DCD, who are known to have difficulties with the integration of sensory information (i.e. feedback) and feedforward information (Wilson et al., 2013), this presents a problem to know how to implement useful interventions. It is therefore important to investigate this issue further to establish whether the two deficits exist independently or do sensory issues explain both deficits?

The additional cognitive load created by these inefficient walking techniques, and consequent lower levels of automaticity (Shumway-Cook & Woollacott, 2002), could explain some of the anecdotal evidence from individuals with DCD of excessive tiredness whilst walking. Considering the delicate interplay needed between the top-heavy passenger unit and the locomotion unit, to remain upright and propel the body forwards whilst walking, it is understandable that Maki (1997) propose that step length variability can destabilise the trunk and increase the likelihood of falling. However causality is not clear; does step length variability destabilise the trunk or are the demands of stabilising the top-heavy trunk causing step length variability? Identifying where causality lies would be useful to inform professionals developing interventions for individuals with DCD.

4.5.2. Age effects

There were no age effects for speed even after partialling out leg length. This might seem counterintuitive as step length increases during childhood and has a direct, positive relationship to speed. Therefore, in order to walk at a similar speed, the children must have walked at a faster rate (cadence = steps/min) than the teenagers and adults. However, these findings confirm previous research that cadence is at its highest during childhood and decreases with maturation and growth (Sutherland et al., 1988). SWR showed significant age effects with children

showing significantly wider SWR than teenagers and adults. This confirms research highlighting the late maturity of this measure (Sutherland et al., 1988).

There was little expectation of age differences for any other measures of walking patterns as several studies have identified that these gait parameters are mature in typical walkers by 7 years of age (Sutherland et al., 1980; Foley, et al., 1979). Surprisingly, several age effects were found, but they were mainly for the teenage group, who walked with a significantly shorter proportional step length than children and adults and inclined their torsos further towards the ground than adults when walking on level ground. Furthermore, teenagers inclined their thighs more upwards than both children and adults at Heel-strike and Opposite Heel-strike and had more flexion about their knees at Heel-strike compared to children and adults.

All the above strategies have been argued by Deconinck et al. (2006^a) to lower the centre of mass and assist with balance difficulties, particularly during the transfer of weight from one leg to the other at Heel-strike (and Opposite Heel-strike). Significant age effects were also found for variability of proportional step length and SWR with the highest variability for both measures being in the teenage age range. Additionally, there was a significant age-by-group interaction for variability in vertical trunk movement identifying that teenagers with DCD were more variable in this measure than their TD peers. Given that age effects for these measures were observed for the teenage age group only, it could be hypothesised that the rapid growth spurt during the teenage years is responsible for this more variable behaviour (Visser et al 1998). It must be noted, however that this study was not set-up to investigate this matter, so any conclusions drawn are purely speculative.

These results suggest that all the children and adults in this study (in either the DCD or TD group) have similar walking patterns, but the teenagers deviate from this pattern. This is an interesting addition to the literature on gait as most research has concentrated on young children (< 13 years) and the elderly. However, given findings in the current study and those of Visser et al. (1998), Tanner (1978) and Shepard (1981) it could be hypothesised that there may be a U-shaped curve of gait development (seen when previously learnt movements, temporarily regress in the efficiency and accuracy of movement control) as individuals pass through adolescence.

4.5.3 Interaction effects

Findings from the current study failed to support the hypothesis that children with DCD will be significantly more affected by the condition manipulations than teenagers and adults with DCD and their TD peers. These findings suggest that, even though there are several main effects of group and age (discussed above), step patterns for all individuals with DCD were similar to

their TD peers. There was only one age-by-group interaction for vertical trunk variability, which as discussed highlighted a greater variability for the teenagers with DCD compared to children and adults with DCD and their TD peers. Overall, these findings support the null-hypothesis that individuals with and without DCD follow a similar developmental trajectory for the variables discussed above, whilst walking along a very predictable level terrain, and it could be argued that age has very little effect on the outcome of group differences.

4.6. Conclusions

To conclude, group differences in proportional step length and angular rotation about the ankle and hip supports the hypothesis that walking patterns observed on a treadmill carry over to level walking. Furthermore the current study has extended previous research (Rosengren, et al., 2009; Deconinck et al., 2006^a; Losse et al., 1991; Cousins & Smyth, 2003) to suggest that some walking parameters are still sub-optimal during adulthood. It was argued that these group effects could reflect differences between individuals with and without DCD in muscle strength at the ankle (Raynor 2001; De Vita & Hortobagyi, 2000; Nigg et al., 1994; Diamond, et al., 2014), balance difficulties (Deconinck et al 2006^a; Lord et al, 1996; Winter et al 1990; Woollacott & Tang, 1997) or control of coordinated muscle synergies required to move the foot (Forczek & Staszkievicz, 2012).

Measures of variability reveal group differences possibly relating to the mechanisms underlying movement control. These measures highlight the adaptive nature of the acquisition of movement skills within the DCD population as argued by Deconinck et al. (2006^a). It could be argued that group differences may be the result of (unconscious) attempts by individuals with DCD to accommodate difficulties with balance (Deconinck, 2010), sensorimotor information processing or internal modelling (Smits-Engelsman et al., 2003; Hyde & Wilson, 2010). Additionally, this study has developed previous research by Rosengren et al. (2009) and Woodruff et al. (2002) by illustrating that variability in individuals with DCD in the acquisition of movement extends into adulthood.

These results highlight that, even when performing a well-practiced movement such as walking in a very predictable environment, populations with DCD may struggle to perform optimally. They also indicate that analysis of angular gait kinematics may provide some useful information for describing the walking patterns of individuals with DCD.

Chapter 5: Symmetry of gait for individuals with and without DCD

5.1. Introduction

Walking is a highly complex activity involving the inter-segmental organisation of many joints, muscles and limbs. Additionally, the synchronisation, or symmetry, of the two legs is another important consideration when analysing walking patterns. Symmetrical gait is defined by Herzog, Nigg, Read and Olsson (1989) as perfect agreement in the movement patterns of the lower limbs, and is regarded as the most energy efficient way to walk (Draper, 2000; Goble, Marino, & Potvin, 2003). Several authors, including Vaughan, Davis and O'Connor (1992), describe typical walking patterns as smooth, symmetrical and using steps of equal length.

This chapter will discuss why symmetry is an important consideration when analysing gait. It will describe some of the problems with measurement, and therefore interpretation of results of investigations into gait symmetry. A literature review will follow to discuss relevant research into gait symmetry and DCD, together with developmental issues pertinent to this study. Evidence will be presented from both typical and atypical populations to explore the possible underlying mechanisms responsible for the control of symmetrical gait.

5.1.1. Measurement of symmetry in gait

Interest in the symmetry of gait arises because it can indicate the efficiency of gait control by providing a measure of inter-limb coordination for variables such as step length and time spent in swing or stance (Patterson, Gage, Brooks, Black & McIlroy, 2010^{a&b}); muscle moments (Sadeghi, 2003) and kinematic symmetry about the joints (Hannah, Morrison & Chapman, 1984). Inter-limb symmetry is often assumed for the typical population (Eng & Winter, 1995; Hannah, et al., 1984), mainly as a consequence of the symmetrical arrangement of the limbs about the body (Kuo and Donelan, 2010). One of the advantages of this assumption in research is for ease of data collection and analysis. Many studies gather data from one side of the body only (Sutherland, et al., 1980; Eng & Winter, 1995) or average data from the left and right side to give a composite value (Hannah, et al., 1984; Arsenaault, Winter & Marteniuk, 1986). These methods of data collection significantly reduce the amount of data needed and consequently the time taken to collect and analyse it (Kuo & Donelan, 2010).

Although the symmetry of gait is often assumed for the typical population, some studies investigating symmetry of the lower limbs whilst walking have produced mixed results. For example, Claeys (1983) reported symmetry for vertical and horizontal reaction forces applied to

the floor by the feet for 214 typically developing adults, elderly people and children. They argue that one of the principal components of typical gait can be characterised by symmetry of the ground reaction forces from the feet. Patterson, et al. (2010^b) reported symmetry of gait for 81 healthy adults (mean age 64.2 years) using a left/right ratio index for several measures including step length; time spent in swing, stance and double support. Finally, Hannah, et al. (1984) investigated kinematic symmetry of the angular displacements about the hips and knees whilst walking. Symmetry for these variables was measured in the sagittal (left; right), transverse (top; bottom) and coronal (front; back) planes. The authors reported high levels of symmetry at the hips and knees in the sagittal plane and high symmetry at the hip in the transverse and coronal plane. Hannah, et al., (1984) conclude that these findings suggest that symmetry at the hips and knees is an indicator of typical adult walking patterns.

In contrast to the studies discussed above gait asymmetry in typical individuals has also been identified. For example Gundersen, Valle, Barr, Danoff, Stanhope and Snyder-Mackler (1989) reported significant differences between limbs for the amount of time spent in stance and maximum knee extension. Barr, Andersen and Danoff, et al. (1987) reported asymmetries in step length, maximum knee flexion during stance and swing in five healthy men and Hannah, et al., (1984) reported asymmetries in the knee in the transverse and coronal planes of motion. Finally, Wheelwright, Minns, Law and Elton (1993) reported asymmetry in several spatio-temporal measures of the lower limbs of children aged 3-18 years.

In an attempt to scrutinise some of the inconsistencies surrounding the assumption of gait symmetry for the typical population, Sadeghi (2003) investigated lower limb symmetry in adults (mean age 25.3 years). Principal Component Analysis (PCA) was used to analyse both local and global symmetry. Two analyses were performed; firstly the peak muscle moments about each joint (hip, knee and ankle) were analysed separately to determine local symmetry. Sadeghi (2003) reported local asymmetry in the groups of muscles about the ankles, knees and hips. The second analysis investigated movements of the limbs as a whole (global symmetry), but they behaved symmetrically. Sadeghi (2003) argues that this global inter-limb symmetry is achieved using compensatory mechanisms at a local level, citing the example of amputee gait to explain his hypothesis.

To explain this hypothesis Winter & Sienko (1988) argue that below the knee amputees have been shown to use compensatory measures at the hip to assist with a lack of ankle function needed for push-off on the amputated side. Sadeghi (2003) explains that whilst this action causes asymmetry at the local level of the joints, it is related to compensation rather than asymmetry and might occur to a lesser extent in typical gait. It is difficult to postulate whether

these findings can be applied to different populations, but Sadeghi (2003) argues that it is the different functional roles specifically relating to balance that contribute to local asymmetry with each joint able to compensate in order to support global symmetry. It may be hypothesised that in populations with balance or coordination deficits, such as those with DCD, the control needed to coordinate the local asymmetries to accommodate global symmetry may be less sensitive. It appears that the assumption of symmetry for typical participants is dependent to some extent upon the variable being measured (Herzog, et al., 1989), and whether it is measured at a local or global level (Sadeghi, 2003). Additionally, subtle differences in the definitions of gait symmetry may lead to inconsistencies in data interpretation. For example Herzog, et al. (1989) described symmetry in gait as the perfect agreement between the left and the right limb, whereas Griffin, et al. (1995) suggest symmetry is only present when there are no statistical differences in parameters measured bilaterally. A review of the literature on human gait symmetry by Sadeghi, et al. (2000) suggests that the main theme of the different definitions illustrate a common idea that symmetry is achieved when both legs behave identically. Furthermore, as there is no standardised method used to calculate gait symmetry (Patterson, et al., 2010^b), this can affect the interpretation of results across studies, which may compromise the criteria used for further research and clinical interventions.

To investigate this problem further Patterson, et al. (2010^b) used the spatio-temporal parameters of step length; time spent in swing, stance and double support; swing; stance ratio. To evaluate four methods of analysing post-stroke gait symmetry:

Ratio = spatiotemporal parameter of left leg / spatiotemporal parameter of right leg

Symmetry index = [(spatiotemporal parameter of left leg - spatiotemporal parameter of right leg) / 0.5 (spatiotemporal parameter of left leg + spatiotemporal parameter of right leg)] x 100%

Gait asymmetry = 100 x [ln (spatiotemporal parameter of left leg/ spatiotemporal parameter of right leg)]

Symmetry angle = [(45°-arctan (spatiotemporal parameter of left leg/ spatiotemporal parameter of right leg)) x 100%]/90

Findings from Patterson, et al.'s (2010^b) study reveals that for this population no equation was preferable in terms of discriminative ability but they suggest the use of the ratio calculation for ease of interpretation. The authors argue that the most important factor for analysis of gait symmetry is the parameter used in the analysis. They explain that whilst spatial measures (step length) and temporal measures (stance/swing time) are correlated they may provide distinct

information, recommending that step length ratio is supported with a temporal measure for symmetry.

5.1.2. The impact of asymmetrical gait.

There are several consequences to asymmetrical gait patterns for post-stroke patients such as challenges to stability and reduced activity levels (Michael, Allen & Macko, 2005; Platts, Rafferty & Paul, 2006). It is therefore an important consideration whilst assessing those affected by a stroke (Griffin, et al., 1995) or amputees with a prosthetic limb (Skinner, & Effeney, 1985), and commonly addressed during rehabilitation (Wall & Turnbull, 1986). Michael, et al. (2005) investigated the role of balance and cardiovascular fitness on the ambulatory activity for participants affected by stroke. They recruited 50 participants over 45 years old who had experienced a stroke more than 6 months before the study. All the participants exhibited a gait pattern identified as observably asymmetrical with a reduced stance time. The authors identified that reduced levels of activity (measured over 48 hours by an automated stride counter attached to the nonparetic ankle) for post-stroke patients were strongly predicted by the severity of balance deficit (measured on the Berg Balance Scale) as patients with the poorest balance had the lowest activity levels.

Whilst the aetiology and constraints to walking for individuals affected with stroke are more overt than for those with DCD, there are parallels to be drawn between the two populations. This is particularly apparent with respect to fitness, ambulatory activity and balance, all of which are inter-related and performed at a lower level for these populations (Hands & Larkin, 2006; Poulsen, Ziviani, Cuskelly & Smith, 2007). Furthermore, for people affected by stroke it is clear that their asymmetric gait is the result of paralysis on one side of the body, which also has a causal effect on balance. However, where does causation lie for populations with balance deficits such as elderly fallers or individuals with DCD; is there a causal relationship between asymmetry and balance deficits, and if so, in which direction?

To investigate this question Yogev, et al. (2007) recruited three groups of participants; individuals with Parkinson's disease; idiopathic elderly fallers, and healthy elderly controls. These groups were chosen to represent populations with a wide range of walking abilities; participants with Parkinson's disease exhibit asymmetric gait with a reduced automaticity. Elderly fallers had an increased risk of falling but are not known for asymmetry in gait. The control group provided comparison data as symmetrical gait and full automaticity were assumed. Participants were asked to walk along a well-lit uncluttered walkway 25m long for 2

minutes. A computerised force-sensitive system was used to measure the amount of time spent in swing for each foot, with gait asymmetry defined as a ratio of right swing time divided by left swing time x100. The authors found that participants with Parkinson's disease and the elderly fallers had an increased gait asymmetry compared to controls in the baseline condition. Results from this study suggest that there is a differential in symmetrical walking between elderly fallers and typical elderly walkers which might indicate that when balance is compromised (as for the elderly fallers) gait is more asymmetric. Whilst the aetiology of the balance deficit affecting gait asymmetry for elderly fallers may be qualitatively different to the balance deficit as described in DCD (Macnab, et al., 2001), findings may still be useful to guide research.

5.1.3. Mechanisms responsible for symmetrical gait

There is very little information available to explain which mechanisms actually contribute to gait symmetry, or how high in the hierarchy of gait control, symmetry is regulated (Yogev, et al., 2007). In order to begin this process we need to look at developmental mechanisms that contribute to walking patterns. As discussed in Chapter 2, hypotheses as to the neural basis of locomotion in humans suggest that the rhythmic activity produced by the central pattern generators underpins the interlimb coordination used whilst walking (Grillner, 1973). Research by Yang, Lamont and Pang (2005) used a split-belt treadmill to investigate the walking pattern of infants (7-12 months old). They argue that human gait is controlled by semi-autonomous pattern generators in each leg, proposing that pattern generators in the legs communicate with each other to alternate the swing phase, one leg at a time. Additionally, Jensen, Prokop and Dietz (1998) found that young adults could move one leg at a very different speed to the other whilst walking on a split-belt treadmill, suggesting that low level spinal centres are used to regulate bilateral coordination in adult human walking, thus assuming some level of automaticity.

The question now arises as to whether this automatic regulatory control extends to symmetrical alternation of the legs to maintain efficiency and balance whilst walking. We know that walking involves some automatic adaptations as evidenced by Klint et al.'s (2008) study reported in Chapter 2. However it isn't a fully automated process either as it needs sensory input to allow the system to negotiate the many inconsistencies in our environment (discussed in detail in Chapter 2). Therefore there is a need for cognition and attention to regulate gait; but is gait symmetry similarly affected by attentional demand, and does it have a differential effect on different populations?

Studies investigating this phenomenon often use a dual task paradigm (Woollacott & Shumway-Cook, 2002; Springer, Giladi, Peretz, Yogev, Simon & Hausdorff, 2006) where participants are asked to walk whilst performing a cognitive task (such as counting backwards in multiples) designed to draw attention away from their walking. One of the few studies to investigate the effects of a dual motor task on gait symmetry was carried out by Yang, Chen, Lee, Cheng and Wang (2007). They found that temporal gait asymmetry (percentage of gait cycle spent in single support) was not affected during a tray-carrying dual task for the control group (mean age 62.7 years) but there were significant effects of this task on participants who had suffered a stroke (mean age 61.2 years). However a second dual motor task, which involved doing up buttons, had no significant effect on gait symmetry for either group. The authors suggest that task difficulty could explain these differences, as their results also identified gait adaptations by the control group whilst doing up buttons such as slower walking pace and decreased cadence and stride length. Spatial asymmetry (step length) was also measured but this was not significantly affected under any of the conditions tested. Conclusions to be drawn from this study suggest that the symmetry of typical older adults is not affected by performing a dual motor task. However when automaticity is compromised, as for those affected by stroke, maintaining a symmetrical gait pattern may require additional cognitive attention.

To assess the contribution of cognitive function and the mechanisms involved in the control of symmetrical gait, Yogev, et al. (2007) asked their participants to perform a dual arithmetic task whilst walking in conditions previously described. They found that gait asymmetry for the participants with Parkinson's disease and the elderly fallers significantly increased whilst walking under the dual task condition compared to the baseline walk. Gait asymmetry was not affected by condition for the control group. The authors suggest that for healthy older adults the mechanisms needed to produce a bilaterally coordinated gait do not need high levels of attention, but for populations such as those with automaticity problems or balance difficulties there is a higher cognitive load which can affect gait symmetry. The results of this study are particularly relevant to the investigation of asymmetry in populations with DCD as this population is known to have difficulties with both balance control and attention (Laufer, et al., 2008, discussed in Chapter 4) which may increase cognitive load and negatively affect gait symmetry.

5.1.4. Development of symmetrical gait

Whilst many of the mechanisms needed for successful walking are reported to be mature by 7 years of age (Sutherland, et al, 1980, discussed in Chapter 2), development of the ability to integrate the inter-sensory information, used to control posture may not be mature until 12

years, (Sparto, et al., 2006). Studies by Sparto, et al. (2006) and Shumway-Cook & Woollacott (1985) suggest that it is the assimilation of proprioceptive information that is late in maturing and therefore constrains maturity in postural control. As the foot is the only link between the body and the ground it is a vital organ in providing proprioceptive feedback from the environment, and therefore plays an important role in postural control (Roll, Kavounoudias & Roll, 2002). However, in order for the system to make sense of this information, feedback from both feet needs to be simultaneously assimilated; failure to do so may cause asymmetry in gait (Bosch & Rosenbaum, 2010). Therefore, if proprioception is late in maturing how does this affect the role of the foot for immature walkers?

Bosch and Rosenbaum (2010) investigated this issue using a longitudinal study investigating the symmetry of foot loading for 62 children aged 1.25 – 5.25 years. The children were measured every 6 months and these data were compared to data collected from 26 adults with a mean age of 31.9 years. The authors used an absolute symmetry index (ASI) to assess asymmetry whereby any value greater than 10% was considered asymmetric. They found that the *area* of the children's feet were in contact with the floor symmetrically (ASI = 4%) throughout the study, as were the adult's feet. However, the ASI of *contact time* decreased significantly over the 4 year period; starting at an ASI of 14% (asymmetric) and progressing to an ASI of 6% (symmetric) at age 5 years. However this still contrasted to the adults who showed an ASI of 3.2%. Therefore whilst symmetry improves, it is not fully mature by 5 years old,

Whilst this study provides useful information on asymmetry of foot loading, it is disappointing that the data reported was restricted to the foot; particularly given the findings from Sadeghi (2003) who argues that global inter-limb symmetry is achieved using compensatory mechanisms at a local level. So it may be that the foot loaded asymmetrically but it may have formed part of a symmetrical limb loading system. However, the findings from this study support those by Wheelwright, et al. (1993) who reported that some asymmetry of gait still exists in temporal and spatial measures for typically developing children aged 3-18 years. Additionally Doipa, Rahmani, Belli, Gautheron, Geyssant and Cottalorda (2004) reported asymmetries in spatial and temporal measures together with asymmetrical ground reaction forces for typically developing children aged 4-10 years.

If, as argued by Bosch and Rosenbaum (2010) proprioceptive feedback from the feet is an important contributor to gait symmetry, then in populations where feedback mechanisms are not optimal (such as for the typical children described here whose sensory systems are not fully mature, Assaiante & Amblard, 1995, 1993; Visser & Geuze, 2000), or populations with DCD whose sensory systems are atypical (Mon-Williams, et al., 1999; Wilson & McKenzie, 1998)

this may affect gait symmetry. Furthermore, the lack of symmetry in children's gait revealed in these studies suggests that the assumption of symmetrical gait needs to be carefully considered when reporting data on children's gait parameters. It also highlights the need for caution when interpreting studies that have not investigated this issue (Sutherland, et al., 1980).

5.1.5. Gait symmetry for individuals with DCD

To date, only one study has investigated gait symmetry for individuals with DCD, and this looked at gait variability for children with a mean age of 7.4 years (Rosengren, et al., 2009). The paradigm for Rosengren, et al.'s (2009) study is described in detail in Chapter 4, but to briefly re-iterate; they used phase portraits of the segmental and joint angles of the legs captured by Elliptical Fourier Analysis (EFA) to investigate possible differences in gait symmetry about the shin and thigh for children with and without DCD whilst walking at a fixed speed on a treadmill. The authors found that there was a greater asymmetry in variability of movement patterns between the left and right leg for the DCD group compared to their TD peers. The authors suggest that these results reflect a lack of consistent inter-limb movement patterns which, over successive strides, affects the efficiency of gait for children with DCD.

The results from Rosengren, et al.'s (2009) study adds quantitative support to the findings of a qualitative study by Larkin and Hoare (1991) who described the gait of children with DCD as asymmetric with uncoordinated limb to limb transitions. However, given that movement difficulties associated with DCD extend to adulthood (Losse et al., 1991; Cousins & Smyth, 2003; Kirby et al, 2010), further research is needed to investigate whether this asymmetry extends to older individuals with DCD whilst walking over ground. Additionally, given the group differences found in segment angles whilst walking, particularly around the distal ends of the limbs (discussed in Chapter 4), this could highlight a difficulty for the DCD group in controlling the degrees of freedom to move in a coordinated way around the environment. Whether these atypical segment movements affect gait symmetry needs to be further explored, as symmetry measures may provide an indication of the control of inter-limb coordination and highlight gait adaptations to biomechanical constraints. Furthermore, data collected within a naturalistic setting will further understanding of the gait adaptations necessary for individuals with DCD to negotiate a real environment.

The aim of this study was to extend previous research by Rosengren, et al., (2009) and Wheelwright, et al. (1993) with an exploratory investigation to examine the bilateral symmetry of the legs for individuals aged 8-32 years with and without DCD whilst walking along a level

uncluttered floor. Furthermore, the wide age range of participants in this study allows an investigation into the developmental nature of gait symmetry.

5.2. Hypotheses

Given the importance of proprioceptive feedback for limb symmetry (Bosch & Rosenbaum, 2010), and findings that proprioceptive feedback for individuals with DCD is sub-optimal (Wann, et al., 1998; Mon-Williams et al., 1999) then it is hypothesised that individuals with DCD will have greater limb asymmetry than their TD peers, in line with findings of Rosengren et al. (2009)

Furthermore, given the developmental nature of sensory maturity in the mechanisms needed for walking (Assaiante & Amblard, 1995, 1993; Visser & Geuze, 2000), then it is hypothesised that children will have greater limb asymmetry than teenagers and adults, in line with findings from Bosch and Rosenbaum (2010) and Wheelwright, et al. (1993).

Given the prediction that children will have greater gait asymmetry than teenagers and adults (Assaiante & Amblard, 1995; Visser & Geuze, 2000; Visser et al., 1998) and the limited evidence suggesting there would be smaller group differences in walking patterns between teenagers (Visser et al., 1998) or adults (Cousins and Smyth, 2003) with and without DCD, it is hypothesised that children with DCD will be affected by both a developmental (Assaiante & Amblard, 1995) and a group (Wann, et al., 1998; Mon-Williams et al., 1999) effect of poor proprioceptive feedback. Therefore an age-by-group interaction is expected, with significant group differences expected between children but not for teenagers and adults.

5.3. Methods

Full details of methods, recruitment and materials employed that are consistent across all chapters can be found in chapter 3. A brief resume is provided below.

5.3.1. Participants

Thirty five individuals with Developmental Coordination Disorder (DCD) aged 8-32 years and 35 typically developing (TD) individuals participated in this study. Participants were divided into 3 age groups; 8-12years ($n=24$), 13-17years ($n=24$) and 18-32years ($n=22$). Details of selection and demographic information for all participants can be found in chapter 3.

5.3.2. Materials and procedures

Materials used and procedures were the same as for the study described in Chapter 4, details of which can be found in chapter 3.

5.3.3. Data collection

Details of data collection can be found in Chapter 3.

The gait symmetry parameters measured in this study were divided into two categories; 1) spatiotemporal measures: 2) segment angles.

5.3.3.1. Spatiotemporal measures

Patterson et al. (2010^b) compared the most common expressions of gait symmetry, and argue that the most useful spatial gait parameter to examine gait symmetry is step length, which should be supported by a temporal measure. Therefore, symmetry was analysed for *Step length* (anterior-posterior distance in meters from lead ankle to lag toe) and the temporal measure of *Step time* (time taken in seconds for one step).

Data were collected separately for each side of the body (Left and Right) and averaged over the total amount of trials. To calculate the symmetry ratio the left and right average values of step length, and step time were used and entered into the following equation; left side/right side. However, following the recommendations of Patterson et al. (2010) the numerator was always the largest value so that results were not skewed by values less than 1.0.

5.3.3.2. Segment angles

Although spatio-temporal parameters (such as stride length and step time) can provide an overall impression of gait, from another perspective they might not be considered informative as they only provide insight into the effect (stride length) of a movement rather than the cause (force, bio-mechanics, Sadeghi et al., 2000). Any causal hypotheses used to explain the atypical walking patterns of individuals with DCD (Parker and Larkin, 2003) need to be developed from a deeper understanding of the underlying mechanisms. Consequently, group and age differences in gait patterns for the angular symmetry of the lower leg *segments* were also analysed. This measure was chosen as there are many degrees of freedom to control at each segment to ensure optimum walking patterns are maintained. Any unnecessary movement at this level may affect the efficiency of walking pattern and increase demands for error management, particularly if segment movement is asymmetric. Data were considered at Heel-strike and Toe-off as these are major points in the gait cycle marking the transitions between stance and swing, and may

increase balance constraints as weight is transferred from one foot to the other. As discussed in Chapter 3 the mean numbers of strides used for analysis were 7.83 for the DCD group and 8.86 for the TD group.

Details of angle definitions are discussed in Chapter 4

The angle of the Thigh, Shin and Foot segment was calculated from the horizontal plane, as illustrated in Figure 5.1.

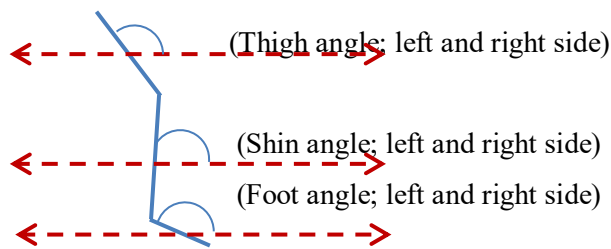


Figure 5.1. Visual illustration of segment angle for legs.

5.3.3.3. Terminology used for limb movement

Terminology used for angular movement of the legs is described in Chapter 2

5.3.4. Statistical analysis

Two-way independent ANCOVA's were used to partial out the effects of order whilst investigating the effects of group (DCD, TD) and age (child, teenage, adult) on the symmetry ratio for step length and step time.

Four-way repeated measures ANCOVA's were used to partial out the effects of order whilst investigating the overall effects of group (DCD, TD), age (Child, Teenage, Adult), Event (Toe-Off and Heel-Strike), and Leg (left; right) on each leg Segment (Thigh, Shin, Foot) individually whilst walking on level ground. This method of analysis was chosen to interpret the subtle differences in angular rotations of the leg segments, which would be lost using the ratio index (for example, detecting a difference between 132° and 127° would provide a ratio of 1.04 which would not be statistically significant, but in real terms a 5° difference would identify a significant difference in angular rotation). Sadeghi et al. (2000) suggest that using statistical approaches to determine similarities or dissimilarities between the lower limbs might

compensate for the insensitivity of the ratio index. This might also provide a better insight into understanding a complex phenomenon as gait, due to the many factors involved which need to be evaluated at the same time. This method of analysis has been previously used by Gundersen, et al. (1989) who used a two-way MANOVA and Allard, Lachance, Aissaoui and Duhaime (1996) who used paired t-tests to determine the presence of gait asymmetry.

It must be noted however, that using different statistical approaches to analysis in a single study is not ideal and care must be given whilst interpreting the results.

Significant interactions found from the ANCOVA's were explored using simple main effects and significant main effects were investigated using post-hoc tests. Bonferroni corrections were applied to protect against Type I error. Statistical significance was set at the 5% level.

5.4. Results

5.4.1. Spatiotemporal measures

Mean scores and standard deviations for the symmetry ratio of step length and step time can be seen in Table 5.1.

For the analyses of the symmetry ratio 1 teenager with DCD and their matched pair had to be removed from the calculations as there were insufficient strides to analyse. This left 68 participants (34 DCD, 34 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 22$.

Results from the ANCOVA reveal that order of walking trial made no difference to the significance of symmetry of step length ($F(1,61) = 1.455, p = 0.232, \eta^2 = 0.023$). For symmetry of step length a significant main effect of group was found ($F(1,61) = 6.754, p = 0.012, \eta^2 = 0.100$), with the DCD group significantly more asymmetric (1.14) than their TD peers (1.06). There was no effect of age ($F(2,61) = 0.704, p = 0.499, \eta^2 = 0.023$), or age-by-group interaction ($F(2,61) = 1.739, p = 0.184, \eta^2 = 0.054$).

Results from the ANCOVA reveal that order of walking trial made no difference to the significance of symmetry of step time ($F(1,61) = 1.303, p = 0.258, \eta^2 = 0.021$). For step time there was no effect of group ($F(1,61) = 1.201, p = 0.277, \eta^2 = 0.019$), age ($F(2,61) = 0.683, p = 0.59, \eta^2 = 0.022$), or age-by-group interaction ($F(2,62) = 1.454, p = 0.241, \eta^2 = 0.045$) was found.

Table 5.1. Means and standard deviations (SD) for symmetry ratio of step length and step time.

Age		DCD			TD			Significance
		Mean (SD)			Mean (SD)			of ratio
		Right	Left	Ratio	Right	Left	Ratio	
Step length (mm)	Child	351.52	345.10	1.11	381.21	375.51	1.06	Group; $p = 0.015$
		(45.02)	(78.74)	(0.13)	(44.24)	(55.66)	(0.06)	
	Teenage	433.08	380.64	1.18	452.87	446.55	1.05	Interaction; $p = 0.187$
		(41.04)	(67.22)	(0.15)	(64.82)	(57.47)	(0.05)	
	Adult	431.88	427.12	1.09	433.29	436.54	1.07	
		(51.35)	(39.96)	(0.12)	(77.29)	(59.43)	(0.09)	
Step time (secs)	Child	0.38	0.39	1.04	0.37	0.41	1.05	Group; $p = 0.245$
		(0.03)	(0.03)	(0.06)	(0.03)	(0.04)	(0.08)	
	Teenage	0.41	0.39	1.10	0.43	0.42	1.03	Interaction; $p = 0.241$
		(0.06)	(0.70)	(0.15)	(0.03)	(0.04)	(0.04)	
	Adult	0.43	0.42	1.04	0.40	0.39	1.03	
		(0.05)	(0.03)	(0.08)	(0.05)	(0.04)	(0.03)	

5.4.2. Segment angles

Mean scores and standard deviations for left and right segment angles at heel-strike and Toe-off can be seen in Table 5.2.

For the analyses of symmetry of segment angles 1 adult and 1 teenager with DCD and their matched pairs had to be removed from the calculations as there were insufficient strides to analyse. This left 66 participants (33 DCD, 33 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 20$.

5.4.2.1. Thigh

Results from the ANCOVA reveal that order of walking trial made no difference to the significance of symmetry at the thigh ($F(1,59) = 15.353, p = 0.379, \eta^2 = 0.013$). There was a significant leg x event x age interaction ($F(2,59) = 7.023, p = 0.002, \eta^2 = 0.192$) indicating that overall symmetry at the thigh is differentially affected by age at the two gait events. Simple main effects and means show that this is due to a significant difference between the angles of the thigh at Toe-off for teenagers ($p = 0.001$), compared to the children and adults, as illustrated in Figure 5.2.

No other significant effects or interactions were revealed (F values ranging from 0.010 for leg x event x group to 2.925 for leg x age).

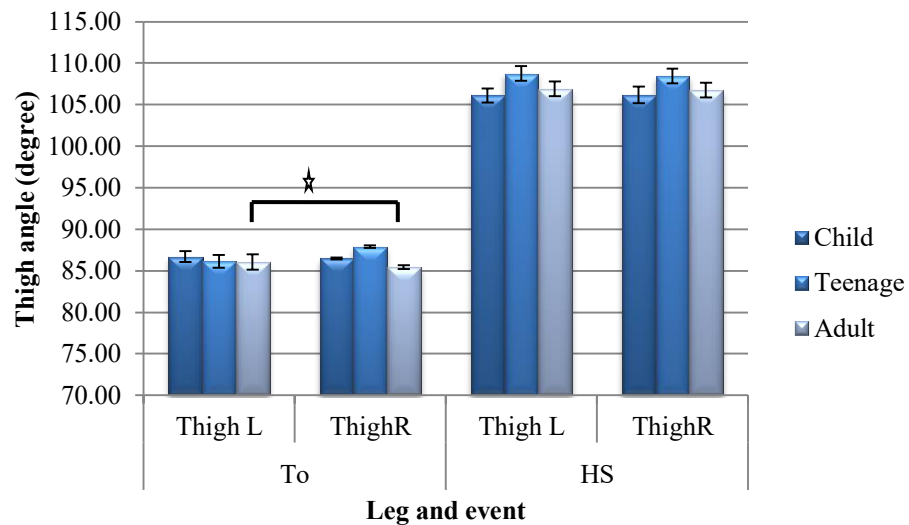


Figure 5.2. Angles of the left and right thighs at Toe-off (TO) and Heel-strike (HS). Error bars represent standard error. **Key*** p = significant to 0.05 level;

5.4.2.2. Shin

Results from the ANCOVA reveal that order of walking trial made no difference to the significance of symmetry at the shin ($F(1,59) = 3.195$, $p = 0.079$, $\eta^2 = 0.051$). There was a significant leg x event x group interaction ($F(1,59) = 5.706$, $p = 0.020$, $\eta^2 = 0.088$) indicating that overall symmetry at the shin is differentially affected by group and gait event. Simple main effects and mean values show that this is due to a significant difference between the angles of the shin for the TD group ($p = 0.028$) at Heel-strike (L94.23°; R92.99° = 1.24° difference), whereas this difference was not significant for the DCD group (L92.65°; R93.49° = 0.84° difference).

Additionally, there was a significant leg x event x group x age interaction ($F(1,59) = 6.201$, $p = 0.004$, $\eta^2 = 0.174$) indicating that overall symmetry at the shin is differentially affected by group, age and gait event. Simple main effects and mean values show that this is due to a significant difference between the angles of the shin for the teenagers with DCD at Toe-Off ($p > 0.001$), illustrated in Figure 5. 3 Leg is also approaching significance for the teenagers with DCD at HS ($p = 0.051$). Finally, there is significant difference between the angles of the shin for the TD teenagers at Heel-Strike ($p = 0.039$), illustrated in Figure 5.4.

No other significant effects or interactions were revealed with F values ranging from 0.022 (leg x event) to 3.884 (leg x group).

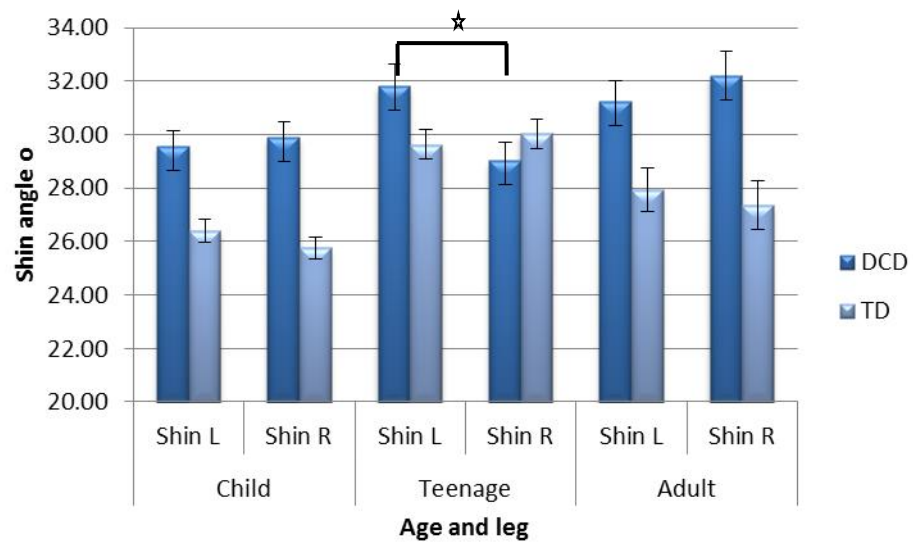


Figure 5.3 Angles of the left and right shins at *Toe-Off*. Error bars represent standard error.

Key* p = significant to 0.05 level;

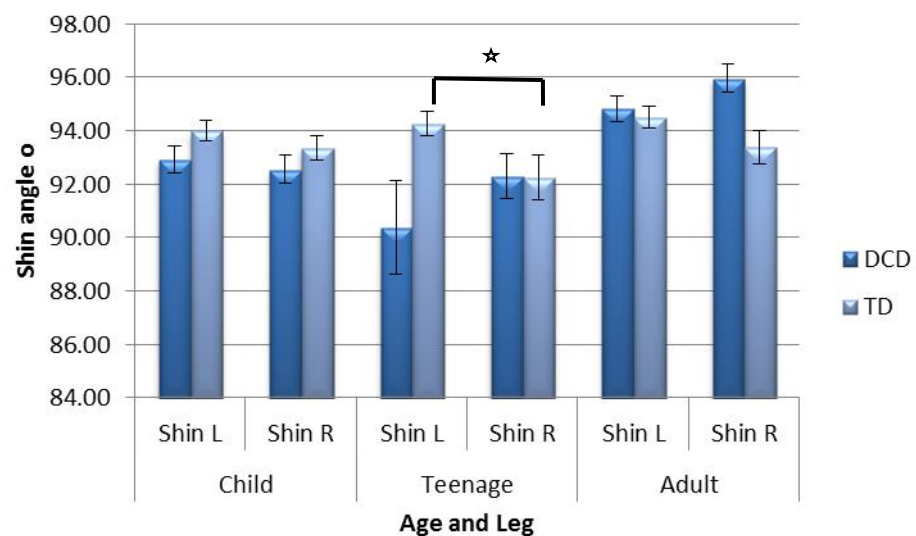


Figure 5.4 Angles of the left and right shins at *Heel-Strike*. Error bars represent standard error.

Key* p = significant to 0.05 level;

5.4.2.3. Foot

Results from the ANCOVA reveal that order of walking trial made no difference to the significance of symmetry at the foot ($F(1,59) = 0.678, p = 0.414, \eta^2 = 0.011$). There was a significant leg x group interaction ($F(1,59) = 6.734, p = 0.012, \eta^2 = 0.102$) indicating that asymmetry at the foot was differentially affected by the two groups. Simple main effects and mean values show that this is due to a significant difference between the angles of the foot for the TD group ($p = 0.001$), whereas this difference was non-significant for the DCD group ($p = 0.964$).

There was a significant leg-by-event-by-group interaction ($F(1,59) = 7.833, p = 0.007, \eta^2 = 0.117$) indicating that symmetry for the angular measurements of the foot was differentially affected for the two groups at each gait event. Simple main effects and mean values show that this is due to a significant difference between the angles of the foot for the TD group at TO ($p = 0.001$) compared to the DCD group as illustrated in Figure 5.5.

Finally, there was a significant group effect ($F(1,59) = 11.009, p = 0.002, \eta^2 = 0.157$) indicating that symmetry for the angular measurements of the foot was differentially affected for the two groups. Mean values reveal greater asymmetry at the foot for the TD (L:R difference = 1.24) compared to the DCD (L:R difference = 0.39) group. There were no other significant effects with F values ranging from 0.014 (leg x event x age) to 2.871 (leg-by-event-by-group-by-age).

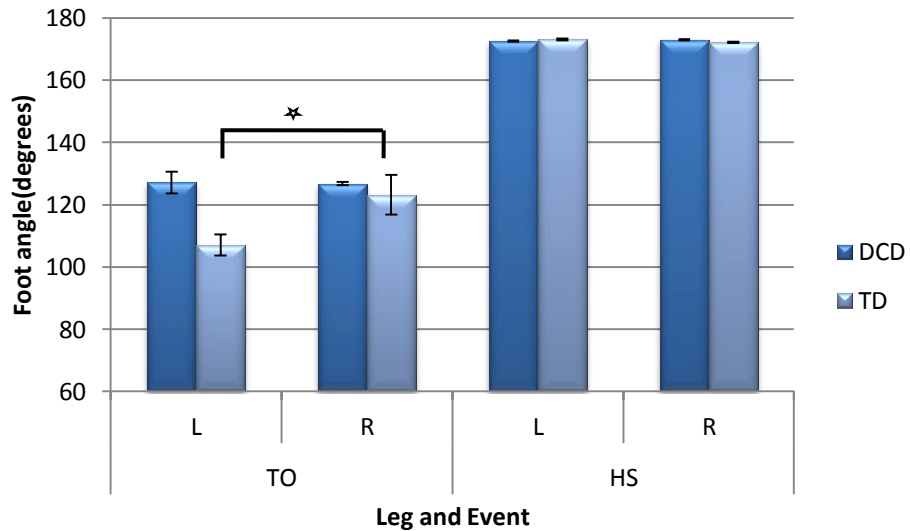


Figure 5.5. Angles of the left and right feet at Heel-strike and Toe-off. Error bars represent standard error. **Key* $p =$ significant to 0.05 level;**

Table 5.2 Mean scores (standard deviations) for left and right segment angles at Heel-strike and Toe-off.

Segment	Age	Heel-strike (HS)				Toe-off (TO)				Significance and
		DCD		TD		DCD		TD		Direction of effect
		Mean (SD)		Mean (SD)		Mean (SD)		Mean (SD)		
		Right	Left	Right	Left	Right	Left	Right	Left	Leg x event x age.
Thigh	Child	106.42	106.30	105.94	105.89	87.31	87.49	85.69	85.94	T > C, A @ TO
	(8-12)	(3.04)	(3.02)	(1.99)	(2.40)	(2.82)	(3.87)	(2.01)	(2.29)	
Angle (degree)	Teenage	108.63	109.58	108.21	107.91	88.09	86.59	87.75	85.65	
	(13-17)	(2.83)	(3.40)	(2.64)	(3.17)	(3.23)	(3.76)	(2.94)	(3.53)	
	Adult	105.46	105.66	108.05	108.15	84.48	85.38	86.44	86.70	
	(18-32)	(3.77)	(3.32)	(4.03)	(3.78)	(5.21)	(4.89)	(3.39)	(3.22)	
Shin	Child	92.55	92.93	93.35	94.00	29.90	29.57	25.76	26.41	Leg x event x group.
	(8-12)	(3.08)	(2.88)	(2.71)	(2.30)	(3.27)	(3.23)	(2.26)	(2.41)	TD>DCD @ HS
Angle (degree)	Teenage	92.29	90.39	92.24	94.25	29.03	31.80	30.04	29.62	Leg x event x group x age;
	(13-17)	(4.83)	(10.07)	(4.75)	(2.65)	(3.79)	(4.73)	(3.18)	(3.14)	T, DCD >TD @ TO
	Adult	95.95	94.82	93.39	94.48	32.19	31.25	27.36	27.94	T, TD >DCD @ HS
	(18-32)	(3.08)	(2.72)	(3.63)	(2.35)	(5.20)	(4.43)	(5.20)	(4.73)	
Foot	Child	171.96	172.85	172.04	173.34	125.00	127.00	114.25	107.03	Leg x group
	(8-12)	(3.44)	(3.52)	(4.32)	(3.47)	(17.40)	(22.96)	(25.49)	(14.05)	Leg x event
Angle (degree)	Teenage	173.49	171.67	171.48	172.82	129.31	131.34	133.96	104.01	Leg x event x group;
	(13-17)	(3.76)	(6.13)	(4.23)	(3.72)	(19.77)	(14.93)	(20.70)	(9.77)	TD>DCD @ TO
	Adult	173.63	173.37	172.95	172.97	128.61	122.83	122.22	114.75	
	(18-32)	(3.92)	(3.92)	(4.15)	(3.86)	(15.51)	(22.59)	(17.37)	(19.62)	

5.5. Discussion

The study discussed in the current chapter attempted to further unpick group differences in variability and angular rotations about the legs and to analyse how they contribute to the efficiency with which individuals with DCD negotiate the environment. Additionally, the aims of the current study were to extend previous research by Rosengren et al. (2009) to investigate inter-leg symmetry for this population. Furthermore, typical gait symmetry was measured to extend the contradictory findings of Sutherland et al., (1980), who argues that typical gait is mature by 7 years of age (assumed to be symmetrical), and Wheelwright, et al. (1993) who argue that for some measures, such as symmetry maturity is not reached until 18 years. Given the importance of consistent and symmetrical interlimb coordination to produce an efficient method of bipedal locomotion (Rosengren, et al., 2009) the mechanisms contributing to the control of symmetrical gait are an important addition to the literature. These investigations are particularly important for individuals such as those with DCD who are known to have difficulties assimilating sensory information needed for efficient walking patterns (Deconinck, et al, 2007; Deconinck et al., 2006^b; Wann, et al., 1998).

5.5.1. Group effects

Given the results from Rosengren, et al.'s (2009) study, who found that children with DCD had greater asymmetry in the variability of movement patterns of the shin whilst walking on a treadmill, it was hypothesised that the DCD group would have greater asymmetry in their gait than their TD peers. This hypothesis was confirmed with the step length symmetry ratios for participants with DCD (1.14) falling beyond the normative range (0.98-1.08) as identified by Patterson et al. (2010), but the same measure fell within the normative range for typically developing participants (1.06). These findings indicate that on a global level the many varying degrees of freedom in the legs work together to produce symmetrical step length for typically developing individuals. However, for individuals with DCD gait patterns have a higher level of asymmetry, illustrating that controlling all the different elements necessary to produce systematic, coordinated and efficient movement is sub-optimal for this population. These findings may provide further explanation for the group differences in variability discussed in Chapter 4, although it must be noted that the group effects found for angular rotations about the joints of the leg does not necessarily affect symmetry.

Causation of this less efficient method of walking for the participants with DCD is difficult to unravel at this stage due to the level of analysis used in this area. However, the correlation between asymmetrical gait patterns, balance constraints and reduced activity levels for stroke patients (Michael et al., 2005) may signpost an area for future investigation. Specifically, further studies could

investigate the strength of correlation between asymmetry and balance difficulties for those with DCD.

As discussed in the introduction, there is little information concerning the hierarchy of control needed to regulate symmetrical gait (Yogev et al., 2007). The hypothesis proposed by Yogev et al., (2007) suggests that if a gait property is fully automatic it does not require cognitive input to operate effectively and **will not** be affected by increased cognitive load. Conversely, a non-automated gait property **will** be affected by increased cognitive load. Yogev, et al. (2007) and Yang et al. (2007) argued that for populations with automaticity or balance difficulties (such as elderly fallers and those with stroke) there is a higher cognitive load required to maintain balance whilst walking which can affect the automaticity of gait symmetry. Similarly, the findings from the current study illustrate group differences in the mechanisms used to control symmetrical gait, resulting in a greater asymmetry for the DCD group compared to their TD peers. Given these findings, it could be hypothesised that the participants with DCD (who are known to have balance and attentional difficulties, Macnab, et al., 2001; Cantell, et al., 1994, Laufer et al., 2008) were more affected by the higher cognitive load needed to regulate these deficits which subsequently affected the automaticity of gait symmetry. This finding supports Yogev, et al.'s (2007) hypothesis that regulation of symmetrical gait uses cognitive input rather than an automatic mechanism controlled by low-level spinal centres.

There were no group differences in the temporal measure of step time supporting Patterson et al.'s (2010^b) recommendation that step length ratio may provide distinct information to temporal ratios such as step time when considering the symmetry of gait. Given the contrasting findings between spatial and temporal measures of gait symmetry it could be hypothesised that the temporal phasing of stepping is controlled automatically, as there was no effect on symmetry for the participants with DCD who may have an increased cognitive load whilst walking (Laufer et al., 2008). Clearly there is more work to be done in this area. It is interesting to note that asymmetry for Yogev, et al. (2007) and Yang et al. (2007) was based on a temporal measure, compared to the spatial asymmetry found in the current study. In fact Yang et al. (2007), who also investigated spatial symmetry, found that only the temporal measures were significantly different between groups. This observation highlights two important points for future research; firstly, it may indicate that there are qualitative differences in walking patterns between the populations investigated and this needs further clarification. Secondly, it emphasises the importance of both a spatial and a temporal measure for the detection of gait symmetry to describe the gait pattern accurately and further investigations are needed to investigate exactly what mechanisms each measure (spatial or temporal) is detecting. Finally these results highlight the need for a gold standard for measuring gait symmetry, which is sadly lacking at present (Patterson et al 2010^b), confusing the interpretation of findings.

For the measures of angular symmetry there were very few group differences (DCD group greater shin asymmetry at TO; TD group greater shin asymmetry at HS; TD group greater foot asymmetry at TO), this was a surprising result given the findings discussed above which would predict asymmetry about the leg segments caused by an increased cognitive load due to balance difficulties. Additionally, given findings from Bosch and Rosenbaum (2010) who argue that asymmetrical foot loading in children was the consequence of immature proprioceptive information from the feet, it could be hypothesised that difficulties for individuals with DCD to assimilate sensory information (Deconinck, et al, 2007; Deconinck et al., 2006^b) would further inhibit symmetrical gait.

Unpicking these seemingly incongruous findings leads to several speculative suggestions; firstly, as proposed by Sadeghi (2003), symmetry of gait may be achieved through a combination of global and local mechanisms, and symmetry in one of these areas does not predict symmetry in the other. Based on this suggestion it could be argued that individuals with DCD can organise each segment symmetrically with the contralateral segment (i.e. local), as evidenced by the findings from angular rotations. However, to organise the whole leg symmetrically with the other leg to produce a symmetrical step length (global) was more difficult for the individuals with DCD to achieve. Secondly, the results highlight how differing methods of measurement may confuse findings. Measurement of the angles took place at static points during the gait cycle (Heel-strike & Toe-off) which cannot relate the limbs together in a continuous fashion. This contrasts with data collection for step length and step time which were taken using a more continuous measure. These findings highlight anomalies that can occur when a 'gold standard' is not available, together with inconsistencies in reporting absolute and/or constant measures, and consequently signposts an important area for future research.

The only group effect for symmetry of the leg segments was at the foot, with the TD group more asymmetric than the DCD group; but only at Toe-off. As discussed in Chapter 2, Toe-off is an important event in the gait cycle as it is a period of intense power generation used to propel the foot forward (Whittle, 2012), and to sustain efficient walking patterns (Buczek et al., 2003). One explanation for this effect is proposed by Sadeghi, et al. (2000) who hypothesise that laterality may have an effect on gait symmetry, arguing that the dominant leg leads the process of achieving the goal whilst the non-dominant leg acts as support. The findings from the current research cannot corroborate these suggestions as laterality was not investigated. However, there is some evidence to suggest that there is a link between lack of laterality and skilled motor performance (Bishop, 1990). This would predict that individuals with DCD who struggle with skilled movement may have less well established laterality. Taken together, the hypothesis from Sadeghi, et al. (2000) and the possible lack of laterality within the DCD population may offer an explanation to the greater absolute asymmetry within the TD group compared to the DCD group. However, this is just an hypothesis,

which as yet has not been validated, so more work is needed in this area to deliver a convincing argument.

5.5.2. Age effects

As discussed Bosch and Rosenbaum (2010) argue that late maturity of sensory assimilation, particularly proprioception, may have a causal effect on gait asymmetry. Furthermore, research by Doipa, et al. (2004) and Wheelwright, et al. (1993) identified asymmetry in children's gait beyond the age of 8 years (youngest participants in this study). To support these findings results from the current study would have identified that any age effects would measure greater asymmetry for children compared to teenagers, who would in turn have greater asymmetry than adults. This was not the case as only the teenagers demonstrated asymmetry in the angular rotations of the leg segments. This asymmetry for the teenage group may be a reflection of the greater variability in walking pattern together with different angular rotations compared to the children and adults (discussed in Chapter 4).

5.5.3. Age-by-group interactions

The developmental constraints to gait symmetry discussed above, together with the additional constraints of sensory integration for children with DCD (Macnab, et al 2001; Wann, et al., 1998; Mon-Williams et al., 1999) predicted significant group differences for this age range. However for the teenagers and adults smaller group differences were expected (Visser et al., 1998, Cousins and Smyth, 2003), thus an age-by-group interaction was hypothesised. Furthermore, results from the studies discussed in Chapter 4, which showed that typically developing teenagers were more variable in their gait pattern with angular rotations of the legs deviating from the patterns exhibited by their DCD peers and typically developing children and adults, also predicted an age-by-group interaction. There is some weak evidence, from the interactions discussed above, to suggest that typically developing teenagers may have a less symmetric gait than the other participants in the current study. It may be that lack of power due to small participant numbers may affect the significance of these results; further studies with larger group numbers would be able to clarify this issue. However support for the null hypothesis for age-by-group interactions suggests that both groups follow a similar developmental progression for gait symmetry.

5.6. Conclusions

Findings from the current study reveal that for the measure of step length the typically developing participants coordinated all the many separate elements in the legs to produce a symmetrical gait pattern, suggesting that for this measure gait symmetry is mature for the typical population by 8 years of age, supporting research by Sutherland et al. (1980). However, assumptions of symmetrical angular rotations of the legs may be misguided, particularly for typically developing participants aged 12-17

years. This is clearly an area of much needed research to unpick these findings and clarify useful parameters to measure symmetry in gait across all ages.

For the participants with DCD step length was significantly more asymmetric than their TD peers. Given the balance difficulties experienced by individuals with DCD (Macnab et al, 2001; Cantell et al., 1994), these findings provide an interesting comparison to the studies of Yogev, et al. (2007) and Yang et al. (2007), who argue that the higher cognitive load for elderly fallers or stroke patients with balance deficits can affect the automaticity of gait symmetry. However, whether this argument can be applied to other populations with balance difficulties such as those with DCD, given differing aetiologies remains speculative and worthy of further investigation. Additionally, Yogev, et al. (2007) and Yang et al. (2007), argue that the mechanisms responsible for symmetrical gait are not controlled by low-level spinal centres, but require some level of cognitive input. Given the sensory difficulties experienced by individuals with DCD (Wilson & McKenzie, 1998), studies investigating gait symmetry within the DCD population provide insight to investigate the contribution of sensory information to gait symmetry.

The findings from this exploratory study investigating symmetry of gait for individuals with and without DCD has signposted an area worthy of further investigation for both groups. Future research would benefit from a more continuous measure of angular data. This would relate the limbs together in a more realistic fashion, and would enhance the findings collected from spatio-temporal parameters.

Chapter 6: Walking on a level and an irregular terrain

6.1. Introduction

The environment we have to negotiate is complex; we constantly encounter different ground terrains in terms of gradient, texture and changing levels. These changing environmental conditions must be seamlessly accommodated by the motor system so that we remain upright and balanced, whilst simultaneously propelling the body towards our destination. The maintenance of dynamic stability is a vital element of locomotion that depends on the efficient integration of visual, vestibular and proprioceptive information (Peterka, 2002). This stream of information from the sensory systems must be efficiently integrated and re-weighted (i.e. change the priority of sensory information to the CNS, reflecting its relative importance) to accommodate the changing demands of environmental constraints (Oie, et al., 2002). However, poor lower limb movement control (Rosengren et al., 2009) and sub-optimal cross modal sensory integration (Wilson & McKenzie, 1998; Deconinck et al, 2007) can place extra demands on populations with DCD, and may affect the efficiency with which they can interact adaptively with a complex environment.

Given the group differences in step-to-step variability and angular rotations about the leg (Chapter 4) whilst traversing a level terrain, it is predicted that these effects will be compounded when walking on an irregular terrain. Given the importance of walking for access to everyday activities, and the lack of uncluttered flat surfaces to walk on; this chapter explores how pedestrians with and without DCD negotiate irregular terrains. Relevant theoretical models are considered, together with an overview of the mechanisms used by typically developing adults and children to traverse irregular terrains. Evidence will be presented from research investigating walking patterns in older adults, who also experience constraints to balance and sensory integration (Marigold & Patla, 2002; Patel, et al., 2009). Findings from this research will be used as a foundation to explore possible constraints for individuals with DCD that may contribute to less efficient movement whilst traversing an irregular pathway. Knowledge of the strategies used by individuals with DCD will broaden and deepen our understanding of the mechanisms used for negotiation of everyday, complex terrains for individuals with and without DCD.

6.1.1. Negotiation of irregular terrain for typically developing adults

As specified by the Ecological Approach (Chapter 1&2) successful locomotion is a prime example of the perception-action link needed to interpret environmental constraints and produce skilled movement; emphasizing the interaction between the individual, the task and the environment (Shumway-Cook & Woollacott, 2012). For example, to meet the demands of the everyday walking task, the individual needs information concerning the changing conditions of the terrain (smooth

tarmac, cobbled, sand or grass), and the ability to predict and respond to any subsequent environmental perturbations (Patla, 1996). This allows the CNS to perform one of its main objectives; to maintain dynamic stability (i.e. keeping the Centre of Mass within the moving base of support) whilst walking (Marigold & Patla, 2005). This change in movement dynamics subtly changes the walking task, and readily available strategies need to be employed that are flexible enough to be useful in a wide variety of contexts (on slippery, uneven, irregular terrains etc.).

As discussed in Chapters 1&2, Wolpert (1996) argues for the use of internal models to assist with the demands of negotiating complex environments, such as those encountered when traversing an irregular terrain. The system uses feedforward information about the upcoming surface terrain to prepare for any motor adjustments needed to negotiate a safe pathway. Similarly, feedback from the sensory systems (visual, proprioceptive and vestibular) is used to identify where the body parts are in relation to each other and to the environment to correct for any errors in the predictive systems. Typically developing adults can access an accurate internal model of the environment, the biomechanical constraints of the body and any possible interactions between the two (Wolpert, 1997). They can also update their internal model, to correct for error, using sensory feedback (Wolpert, 1997; Bair, et al., 2007).

Kluzik Peterka & Horak (2007) argue that integration of proprioceptive and support surface information provides an important frame of reference for postural control and movement. It can be hypothesised that typically developing adults use a combination of internal models and sensory feedback to maintain stability whilst traversing an irregular terrain (Assaiante et al., 2011). However, locomotive adjustments made in a predictive manner are most effective when knowledge about the movement and sensory information are accurate. Thus, the ability to counteract an environmental perturbation relies on prior experience (Marigold & Patla, 2002). These predictive adjustments can therefore serve to reduce the impact of perturbations. In contrast, reactive strategies rely on afferent information travelling from the sensory systems to the CNS. Given the importance of proprioceptive feedback to accommodate the small underfoot irregularities experienced during real-life locomotion (Klint, et al., 2008), the CNS must be able to prioritise, or re-weight, proprioceptive information to reflect its relative importance (Bair, Kiemal, Jeka and Clark, 2012).

MacLellan & Patla (2006) argue that walking on some everyday surfaces such as snow, grass or sand can reduce the reliability of proprioceptive information from the feet. Reliability may be reduced as the ground is compliant rather than firm, so the foot may sink into the terrain and feedback from these surfaces may be more difficult to interpret. They investigated this hypothesis whilst 8 typically developing adults (mean age 21 years) traversed a baseline level walkway, and a visibly compliant surface set into a 5m walkway. Their findings showed that step width and length increased whilst

walking on the compliant compared to the baseline surface, which the authors argue increased the base of support to ensure the stability of the Centre of Mass whilst walking on the compliant surface.

Strategies used to increase the base of support whilst walking have also been reported to be used by older adults to maintain stability. Marigold & Patla (2002) and Patel et al. (2009) argue that the proprioceptive system for older adults operates at a reduced capacity compared to younger adults, and that afferent information may also be degraded. They suggest that these deficits can affect feedforward and reactive adaptations during locomotion. In order to develop this hypothesis, Bierbaum, Peper, Karamanidis and Arampatzis (2010) investigated predictive and reactive locomotion adaptations for old (62-74 years) and young (23-30 years) adults during disturbed walking. Participants walked along a 15m walkway, into which, halfway along, was inserted an exchangeable surface (90x60 cm) which was either firm or compliant. Whilst the compliance of the exchangeable surface was unknown to the participants they were aware of its position; this allowed the authors to investigate both predictive and reactive adjustments.

Results identified that after stepping on the unexpectedly compliant surface both age groups widened their base of support to provide greater stability. The authors argue that this response was a result of feedback information, with the young adults increasing their base of support more than the older adults, perhaps demonstrating a more effective feedback response than the older adults. The predictive abilities were similar for both the old and young adults. Taken together, these results highlight that the strategies used to accommodate unpredictable proprioceptive information, whether it is from the environment (MacLellan & Patla, 2006; Assaiante, et al., 2011) or through sub-optimal sensory input (Bierbaum et al., 2010), focus on maintaining dynamic balance.

As discussed above, typically developing adults use a variety of feedforward, feedback and anticipatory mechanisms (MacLellan & Patla, 2006) to maintain dynamic balance whilst traversing irregular terrains. Previous research investigating adult walking patterns on irregular terrain have had mixed results; largely dependent on the age of the population being studied. For example, Menz, Lord, and Fitzpatrick (2003)^a investigated gait pattern and acceleration of the head and pelvis of typically developing adults aged (22-39 years) to examine how the postural control system responds to challenging environmental conditions. Participants were asked to walk under 2 conditions: along a level corridor where the ground was stable and firm, and on artificial grass, beneath which were foam and wooden blocks placed arbitrarily along the walkway. Results showed that participants maintained their walking speed in spite of the irregular terrain. Menz, et al (2003^a) also found that participants increased their step length as they traversed the uneven ground. The authors suggest this was an attempt by the participants to minimise foot contact with the unstable terrain, and argue that taking longer steps increased the swing phase duration allowing time to plan the limb trajectory of the next step, as argued by Patla, Prentice, Rietdyk, Allard and Martin (1999).

A subsequent study by Marigold and Patla (2005) investigated the strategies used to maintain balance whilst traversing irregular terrain. They invited 8 young adults (mean age 24 years) to walk along an 8m walkway with 4 different levels of surface compliance (one solid/baseline; 3 compliant). The different surfaces were mounted on a force plate and presented individually midway along the walkway. Infra-red markers placed on participant's feet, legs, arms, trunk and head (left side only) were tracked by 3 Optotrak cameras, together with EMG of selected leg and trunk muscles. Participants stepped onto the test surface with their left foot (the 'perturbed foot') and onto a second force plate with their right foot, or 'unperturbed foot'. They were not told when the test surface was compliant, so this study looked at recovery strategies from an unexpected perturbation, and the efficiency of the CNS reaction to maintain stability whilst still walking forwards. The authors found that in response to stepping on a compliant surface, participants lowered their Centre of Mass and inclined their trunks forwards more compared to the baseline condition. This was argued to emanate from an increased difficulty controlling trunk angle, and a need to maintain dynamic stability, when traversing a compliant surface.

Several studies have compared strategies used by older and young populations to traverse uneven terrain. For example Menz, Lord, and Fitzpatrick (2003^b) compared the acceleration patterns and gait characteristics of old (75-85 years) and young (22-39 years) pedestrians under similar conditions to their Menz, et al. (2003^a) study. Results identified that the older adults walked more slowly, and with a shorter step length but greater step-time variability compared to the young adults whilst walking on level ground, but when walking on the uneven terrain group differences were exacerbated. This was illustrated as the young adults maintained their walking speed but increased their step length (supporting their Menz, et al. 2003^a study), but the older group slowed even more with an invariant step length between conditions. The authors argue that this more conservative gait pattern indicates that the older participants perceived the irregular walking surface as a greater risk to dynamic stability, and adapted their gait to accommodate this threat. They also argue that this safer walking style, together with reduced magnitude of acceleration at the head and pelvis, helps to maintain stability and thus reduce the likelihood of falling. These findings extend previous research investigating the walking patterns of older adults on level ground (Menz, 2003^a; Winter, et al., 1990; Woollacott & Tang, 1997) by demonstrating similar strategies hypothesised to assist with dynamic balance, are used both on level and uneven .

6.1.2. Negotiation of irregular terrain for typically developing children

There is little research to-date to investigate the strategies used by children to negotiate irregular terrains, but research discussed in Chapter 2, suggests that although walking patterns are reported to be mature by 7 years old (Sutherland et al., 1980), the successful integration of vestibular, proprioceptive and visual information, takes longer than 7 years to mature. Mechanisms pertinent to

walking on an irregular terrain include proprioceptive sensitivity, which is reported to develop continuously from the age of 5 to 16¹/₂ years (Visser & Geuze, 2000). Additionally, since the housing of both the visual and vestibular systems is in the head, strategies used to stabilise this information (i.e. stabilise the head) are important for successful and adaptive environmental negotiation. However, Assaiante and Amblard, (1993) argue that the skill of head stabilisation does not reach adult levels until about 7 years of age, how this affects children's walking patterns on an irregular terrain has yet to be investigated. Furthermore, McFayden, Malouin and Dumas (2001) argue that anticipatory locomotor adjustments for children aged 7-9 years are lower, when compared to adults, suggesting that anticipatory control strategies are still maturing during middle childhood.

To investigate this further, Vallis and McFayden (2005) compared the strategies used by 5 children (8-11 years) and 6 adults (26 years) to circumvent (to left or right) an obstacle in their travel path. Participants walked at a self-selected pace along a 9m walkway towards a cylindrical object placed 3m from the start of the travel path, which they had to negotiate by walking around it rather than over it. The results from this study need to be viewed with caution as it had a particularly small sample, they do however show that adults and children use different strategies to re-orientate their head and trunk segments, whilst avoiding an obstacle in their path; Adults reoriented their head and trunk, whilst simultaneously altering their medio-lateral sway. However, the children divided the obstacle avoidance into two separate tasks; Firstly, proactive movement of the head and trunk to assist with steering around the obstacle, then just prior to obstacle crossing they reduced their speed and made last minute adjustments to their gait (step length and width) to ensure obstacle clearance.

Vallis and McFayden (2005) argue that this segmental approach used by the children suggests different anticipatory strategies are used by the two groups. They suggest that the children may have a greater dependency on visual information to guide movements, and attempt to stabilise visual information by moving their head and trunk *en bloc* before obstacle avoidance. The immature '*en bloc*' movement of head and trunk reduces the degrees of freedom that have to be controlled during movement and provides a stable frame of reference for visual and vestibular information to be processed. Adults can control their movement using articulated strategies where the head moves freely. The two different strategies may reflect developmental differences in perceptual abilities between adults and children, as argued by Assaiante & Amblard (1995) who investigated the changes in control of the head, arms, and trunk body segments from early walkers to 10 years.

Assaiante & Amblard (1995) illustrated a developmental change in the way children adapt to changes in equilibrium. Initially children organise their responses from the bottom up (feet towards head) controlling the head *en bloc* and using mainly proprioceptive cues to maintain balance. But as control of the hips, shoulders and head stabilises top down organisation of balance starts to become dominant (head towards feet) and the children can adopt the articulated mode of balance control using visual

and vestibular information. Whilst this study isn't directly comparable to an investigation with an irregular terrain, the adaptive strategies to accommodate the balance constraints of the task may be similar.

6.1.3. Walking with DCD on an irregular terrain

Very little research has been conducted to assess how populations with DCD negotiate everyday irregular terrains. However given the importance of predictive, reactive and anticipatory strategies to maintain dynamic balance whilst walking (MacLellan & Patla, 2006), and the constraints to poor lower limb movement control (Rosengren et al., 2009) and sub-optimal cross modal sensory integration (Wilson & McKenzie, 1998; Deconinck et al., 2007) experienced by individuals with DCD, it could be hypothesised that the efficiency with which individuals with DCD negotiate an irregular terrain will be degraded compared to their TD peers.

Several studies have investigated the use of feedforward or predictive information for individuals with DCD, as discussed in Chapter 1. For example, Wilmut et al., (2006), Smits-Engelsman, et al., (2003) and Hyde and Wilson, (2010) argue that children with DCD have problems with the use of feedforward information compared to TD children whilst performing fine motor reach-to-target tasks. Additionally, Johnston, Burns, Brauer & Richardson, (2002) found that anticipatory muscle activity in the trunk was less accurate and efficient for children with DCD compared to their TD peers whilst performing a rapid, goal-directed arm movement. These findings have been supported by Przysucha; et al. (2008) who found that anticipatory postural adjustments for children with DCD differ qualitatively from those of their TD peers during a leaning task, which the authors suggest could be due to sub-optimal processing of sensory information.

In contrast to these findings, Deconinck et al. (2010) found forward planning during a locomotor task, whilst traversing an obstacle in the pathway, was unimpaired for children with DCD, and they argued the primary deficit was that of balance (all the above studies are discussed in detail in Chapter 1). The different strategies used between tasks may reflect a speed of processing deficit, whereby the reach-to-target tasks required fast movement control, needing anticipatory mechanisms to support accurate reaching. In contrast, whilst participating in the Deconinck et al. (2010) study participants would have had time to visually sample the obstacle and make locomotor adjustments whilst walking along the level, uncluttered pathway, negating any need for last minute anticipatory control. However, the studies by Wilmut et al. (2006), Smits-Engelsman, et al. (2003) and Hyde and Wilson (2010) also demonstrate a difficulty in the planning of a movement without ongoing visual information. This contrasts to the task demands in Deconinck et al.'s (2010) study which uses feedforward information to plan in anticipation of a movement. However, walking along an irregular terrain will require a continuous flow of feedforward and feedback information in anticipation of the movement, together with fast responses to maintain dynamic stability which may not include ongoing visual information.

As discussed in Chapter 1, several studies have identified problems integrating visual, proprioceptive and vestibular information for children with DCD (Deconinck et al 2006^b; Deconinck et al, 2007; Wilson & McKenzie, 1998; Geuze, 2003). These difficulties may affect the quality of sensory feedback (afferent information) and subsequent reactive strategies to control balance whilst walking. In fact, Deconinck, et al. (2007) argues that a deficit in the ability to re-weight sensory inputs in response to changing environmental constraints for individuals with DCD may help explain their locomotor difficulties. These difficulties may be particularly apparent when negotiating irregular terrains. For example, Kuo and Donelan's (2010) model of balance deficits, discussed in Chapter 4, suggests that motor output is affected by error which in turn can affect control adjustments. If sensory information is degraded, this will reduce the accuracy of control adjustments manifesting in misplaced and variable foot placement, which will be exacerbated if the ground is uneven, increasing the likelihood of a fall. Research investigating increased variability in walking patterns in typical adults support this hypothesis and indicates that variability in step length may be causally linked to greater risk of falling (Maki, 1997;) and reduced automaticity (Shumway-Cook & Woollacott, 2002).

As previously discussed, a major challenge, whilst walking is to maintain dynamic stability, however, the maintenance of dynamic stability is a common feature of DCD, with 73-87% of children with the condition having issues with balance skills (Macnab, et al., 2001). Geuze (2003) suggests that in challenging situations a sub-group of children with DCD and balance problems (discussed in Chapter 1) have difficulties with postural control resulting in increased postural sway. Changes in posture, particularly movement of the head, may alter the sensory (vestibular and visual) feedback available for the maintenance of postural control which, as discussed, is a fundamental strategy to maintain balance whilst negotiating the environment (Winter, 1995). Thus the need for effective motor planning and control becomes increasingly important whilst traversing more complex, irregular terrains. Additionally, as Assaiante and Amblard (1995) explain, use of this ontogenetic model to explain balance control requires both feedforward and feedback sensory information to work effectively. If there is any early sensorimotor impairment prior to the acquisition of head stabilisation at 3 years of age this can implicate the development of this strategy.

The aim of this study was to examine the control of the head and trunk together with lower limb dynamics whilst traversing an irregular terrain in individuals with and without DCD aged from 8-32 years. The wide age range of participants in this study allows an investigation into the developmental progression of the gait adaptations used to traverse the irregular terrain.

6.2. Hypotheses

In line with research by Deconinck et al., (2007) and Deconinck et al. (2010) it is hypothesised that the DCD group will walk slower, with shorter, wider steps and spend more time in double support compared to the TD group to accommodate the increased threat of destabilisation whilst walking on the irregular terrain

If typical walkers and those with balance difficulties are known to adapt their walking pattern to accommodate balance disturbances from the environment (Marigold & Patla, 2005, Menz et al., 2003^b), then it is hypothesised that all participants are expected to walk slower, with shorter, wider steps and spend more time in double support when walking on an irregular terrain. Additionally, based on the developmental nature of sensory maturity in mechanisms needed for walking (Assaiante & Amblard, 1995, 1993; Visser & Geuze, 2000), it is hypothesised that children will have greater adaptations to negotiate the irregular terrain than teenagers and adults.

Given the developmental hypotheses above (Assaiante & Amblard, 1995, 1993; Visser & Geuze, 2000) and the additional constraints to negotiating an irregular terrain for children with DCD (Hyde & Wilson, 2010; Deconinck et al., 2010; Macnab et al., 2001), it is predicted that children with DCD will show significant differences in walking patterns compared to their TD peers. However, smaller group differences are expected between the teenagers (Visser et al., 1998) and adults (Cousins and Smyth, 2003). Therefore an age-by-group interaction is hypothesised (significant group differences for children, but not for teenagers and adults).

Finally, using previous findings from Rosengren et al. (2009), Deconinck et al. (2010) and the findings reported in Chapter 4 participants with DCD are expected to have significantly more step-to-step variability, compared to their TD peers whilst walking on the irregular terrain.

6.3. Methods

Full details of methods, recruitment and materials employed that are consistent across all chapters can be found in chapter 3. A brief resume is provided below.

6.3.1. Participants

Thirty five individuals with Developmental Coordination Disorder (DCD) aged 8-32 years and 35 typically developing (TD) individuals participated in this study. Participants were divided into 3 age groups; 8-12years ($n=24$), 13-17years ($n=24$) and 18-32years ($n=22$). Details of selection and demographic information for all participants can be found in chapter 3.

6.3.2. Materials and procedures

Details of the materials used and procedures can be found in chapter 3, but to briefly reiterate, participants walked along a 6m x 1m walkway which had ‘Cobbles’ stuck at irregular intervals to make the surface uneven. Two cones were situated directly opposite each other, at either end of the walkway, illustrated in Figure 3.1.

A VICON 3D motion analysis system tracked the motion of small reflective markers attached to the feet, legs, trunk and head. These locations provided measurements including walking speed, stride length, step width ratio, time in double support and the angles of the head and trunk. Additionally, step-to-step variability was analysed using standard deviations (SD) of each individual’s data. Data are reported under three headings; *spatio-temporal measures* (walking speed, (stride length, step width ratio, time in double support); *variability* and *angles of the head and trunk*.

6.3.3. Statistical analysis

Mean percentage differences between walking conditions (level; irregular) were calculated for all spatio-temporal measures for each participant individually (the ‘level’ data is the same as that reported in Chapter 4). This approach was taken as it provides more informative data about the *adaptation* of walking patterns between conditions. For example if a participant from group 1 walked along the level terrain at 1m/s and a participant from group 2 walked at 1.25 m/s, absolute values would identify a group difference, however, if when they walked along the irregular terrain the participant from group 1 reduced their speed to 0.65m/s compared to participant 2 who reduced their speed to 0.81ms, absolute values would still show group differences as they do not take into account the baseline speed. However, the percentage change for both participants is a reduction in speed by 35%, clearly identifying the *adaptive* abilities from one terrain to the other.

Variability was calculated using the mean value differences in standard deviation between walking conditions for all spatio-temporal measures for each participant individually. Value differences were used for this measure rather than percentage differences due to the small values in variability. Analysing percentage change of very low values cannot adequately identify condition effects.

This information was entered into statistical analysis using two-way independent ANCOVA’s to partial out the effect of order of trial presentation (discussed in Chapter 3) whilst investigating the effects of group (DCD, TD) and age (Child, Teenage, Adult) on 4 spatio-temporal measures (walking speed, proportional step length, step width ratio, percentage of time in Double support), the percentage changes in the angles of the head and trunk, and step-to-step variability whilst walking on a level and irregular terrain.

Significant interactions found from these analyses were explored using simple main effects and significant main effects were investigated using post-hoc tests. Bonferroni corrections were applied to protect against Type I error. Statistical significance was set at the 5% level.

6.4. Results

Not all data were normally distributed; therefore when transforming (Log10) was successful the transformed data are reported (signified with #). However sometimes the transforming didn't work and the untransformed data are reported (signified with Δ).

All data reported in tables 6.1-6.4 contains both the percentage change (value difference for variability) and also the raw scores. Statistical analysis was completed on the percentage change only.

6.4.1. Spatio-temporal measures

Means, standard deviations and significance values for percentage change in spatio-temporal measures between walking on the Level and Irregular terrains can be found in Table 6.1

For walking speed 1 teenager with DCD and their matched pair had to be removed from the analysis as the chest marker was obscured from the cameras lens, so there was no walking speed calculated in MATLAB. This left 68 participants (34 DCD, 34 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 22$.

For percentage change in walking speed, it is clear from mean values in Table 6.1 that both groups walked more slowly in the irregular condition than in the level walking condition (indicted by a negative percentage change). Results from the ANCOVA revealed that order of walking trial made no difference to the significance of percentage change in walking speed ($F(1,61) = 0.700, p = 0.406, \eta^2 = 0.011$). However, there was a main effect of group ($F(1,61) = 13.069, p = 0.001, \eta^2 = 0.176$) with the DCD group reducing walking speed from flat walking (-36.02%) to a greater extent than their TD peers (-21.20). In addition there was a significant main effect of age ($F(1,61) = 3.862, p = 0.026, \eta^2 = 0.112$). Post hoc tests reveal a significant difference between children and teenagers ($p = 0.021$), with children reducing their walking speed on the irregular terrain more than teenagers. The interaction between age and group was not significant ($F(1,62) = 12.654, p = 0.001, \eta^2 = 0.170$).

For the percentage change in proportional step length, mean values from Table 6.1 indicate that both groups reduced their proportional step length when walking on the irregular terrain compared to level walking (there were no significant group differences for level walking, as reported in Chapter 4). Results from the ANCOVA revealed that order of walking trial made no difference to the significance of percentage change in proportional step length ($F(1,63) = 0.700, p = 0.406, \eta^2 = 0.011$). However, there was a significant effect of group ($F(1,63) = 13.069, p = 0.001, \eta^2 = 0.176$) indicating that the

irregular terrain affected the individuals with DCD more than their TD peers. The DCD group had significantly larger percentage reduction in proportional step length (-15.19%) than the TD group (-5.28%). No effect of age ($F(1,63) = 0.700, p = 0.406, \eta^2 = 0.011$) or interaction between age and group ($F(1,63) = 0.700, p = 0.406, \eta^2 = 0.011$) was found. (Variances were not equal for this data set, even after transformation. Untransformed data is reported but the results need to be interpreted with caution).

For Step Width Ratio 1 teenager with DCD and their matched pair had to be removed from the analysis as the markers at the hip were obscured for several trials. This left 68 participants (34 DCD, 34 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 22$. All other variables had 70 participants.

Results from the ANCOVA revealed that order of walking trial made no difference to the significance of percentage change in Step width ratio ($F(1,61) = 0.475, p = 0.493, \eta^2 = 0.008$). Both groups increased their step width ratio overall when they walked on the irregular terrain, but group effects show that the DCD group increased their step width ratio significantly more than the TD group ($F(1,61) = 10.183, p = 0.002, \eta^2 = 0.143$). There was no effect of age ($F(2,61) = 0.996, p = 0.375, \eta^2 = 0.032$). However, there was a group-by-age interaction ($F(2,61) = 6.802, p = 0.002, \eta^2 = 0.182$). Simple main effects (using the Bonferroni adjustment) show this is due to a larger percentage change in SWR for children ($p = 0.049$) and adults ($p < 0.001$) with DCD compared to their TD controls. This is supported by inspection of Figure 6.1.

Results from the ANCOVA revealed that order of walking trial made no difference to the significance of percentage change in time spent in double support ($F(1,63) = 3.114, p = 0.082, \eta^2 = 0.047$). There were no group ($F(1,63) = 0.600, p = 0.442, \eta^2 = 0.009$) or age effects ($F(2,63) = 1.759, p = 0.181, \eta^2 = 0.053$), or group-by-age interactions ($F(2,63) = 0.555, p = 0.557, \eta^2 = 0.017$).

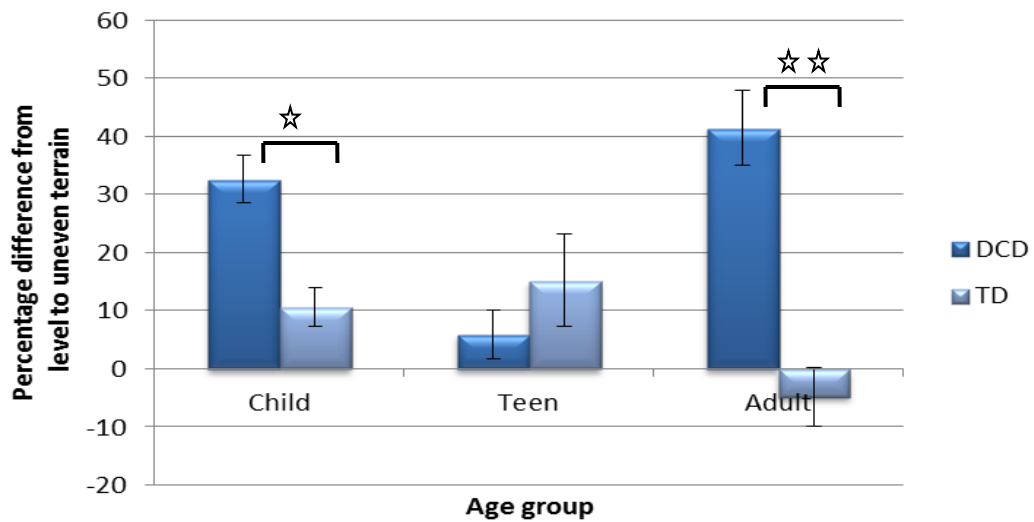


Figure 6.1 Percentage difference in Step Width Ratio from Level to Irregular terrain. Error bars represent standard error. *key** p = significant to 0.05 level; ** p = significant to 0.001 level.

Table 6.1. Means, standard deviations (SD's) and percentage change in Spatio-temporal measures

Level: Irregular terrain.

Measure	Age	DCD			TD			Sig [post hoc]
		Mean (SD)			Mean (SD)			
		Level	Irregular	% change	Level	Irregular	% change	
Speed (m/s)	Child (8-12y)	0.99 (0.20)	0.56 (0.18)	-44.30 (17.44)	1.05 (0.17)	0.74 (0.19)	-29.57 (12.61)	Group ** [DCD < TD] Age * [C < T]
	Teenage (13-17y)	1.06 (0.22)	0.81 (0.20)	-24.02 (9.15)	1.12 (0.12)	0.88 (0.23)	-21.51 (21.82)	
	Adult (18-32y)	1.06 (0.17)	0.64 (0.12)	-38.98 (13.10)	1.10 (0.18)	0.97 (0.16)	-11.75 (24.20)	
Prop step length (SL/Leg length)	Child (8-12y)	0.61 (0.08)	0.52 (0.12)	-14.55 (18.52)	0.66 (0.05)	0.60 (0.08)	-9.38 (10.13)	Group* [DCD < TD]
	Teenage (13-17y)	0.58 (0.09)	0.50 (0.10)	-11.72 (17.43)	0.62 (0.05)	0.60 (0.07)	-2.93 (4.78)	
	Adult (18-32y)	0.63 (0.05)	0.50 (0.07)	-19.69 (7.58)	0.64 (0.07)	0.62 (0.08)	-3.39 (11.30)	
SWR (SW/hip width) (n = 68)	Child (8-12y)	0.83 (0.17)	1.12 (0.25)	32.59 (20.15)	0.92 (0.12)	1.03 (0.19)	10.58 (16.34)	Group* [DCD > TD] Group -by-age Interaction*
	Teenage (13-17y)	0.63 (0.17)	0.65 (0.15)	5.91 (19.45)	0.68 (0.13)	0.75 (0.14)	15.20 (36.95)	
	Adult (18-32y)	0.66 (0.20)	0.92 (0.29)	41.42 (30.58)	0.75 (0.13)	0.71 (0.21)	-4.81 (23.67)	
Percent Double Support (% gait cycle spent in DS)	Child (8-12y)	15.65 (3.05)	22.64 (6.25)	44.60 (28.39)	15.05 (1.39)	20.66 (2.91)	35.08 (19.74)	ns
	Teenage (13-17y)	17.67 (4.46)	19.21 (7.85)	18.01 (46.21)	15.80 (2.19)	19.49 (5.62)	24.10 (17.42)	
	Adult (18-32y)	16.74 (5.66)	20.19 (5.45)	29.74 (49.15)	16.04 (1.13)	18.87 (1.51)	18.22 (12.47)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; ns = not significant.

6.4.2. Variability.

Means, SD's and significance for variability between walking on the Level and Irregular terrain can be seen in Table 6.2.

Results from the ANCOVA revealed that order of walking trial did not affect the significance of results for variability of percentage time in double support ($F(1,61) = 0.687$; $p = 0.411$, $\eta^2 = 0.011$).

There was a significant main effect of group ($F(1,61) = 5.499$; $p = 0.022$, $\eta^2 = 0.083$), with the

percentage change in variability greater for the DCD group than the TD group overall. However, variability for the DCD group reduces (-1.18) on the irregular terrain, whereas the TD group increase their variability (0.93). No effect of age ($F(2,61) = 1.776$; $p = 0.178$, $\eta^2 = 0.055$), or interaction between age and group ($F(2,61) = 0.500$; $p = 0.609$, $\eta^2 = 0.016$), was found.

Results from the ANCOVA revealed that order of walking trial did not affect the significance of results for variability of walking speed ($F(1,62) = 2.210$; $p = 0.142$, $\eta^2 = 0.034$), proportional step length ($F(1,62) = 0.656$; $p = 0.421$, $\eta^2 = 0.011$) or Step width ratio ($F(1,62) = 1.895$; $p = 0.174$, $\eta^2 = 0.031$).

No main effects of age, group or age-by-group interactions were found for walking speed (F values 0.031 age; 0.209 group; 2.269 age-by-group), proportional step length (F values 1.389 age; 1.685 group; 0.393 age-by-group), or step width ratio (F values 1.500 age; 0.437 group; 0.916 age-by-group). This suggests that both the DCD and the TD groups and all age groups demonstrate similar changes in variability when walking on the Level and the Irregular terrain in terms of these variables.

Table 6.2. Means, SD's and significance for variability – Level: Irregular terrain.

Measure	Age	Level	Irregular			Level	Irregular		Significance
		DCD	DCD	Mean	TD	TD	Mean		
		Mean (SD)	Mean (SD)	value difference	Mean (SD)	Mean (SD)	value difference		
$\triangle$ Prop	Child	0.07	0.08	0.01	0.03	0.05	0.02	ns	
Step	(8-12y)	(0.05)	(0.03)	(0.06)	(0.02)	(0.03)	(0.02)		
Length	Teenage	0.13	0.09	- 0.05	0.06	0.06	- 0.003		
variability	(13-17y)	(0.13)	(0.10)	(0.17)	(0.05)	(0.06)	(0.09)		
	Adult	0.06	0.05	0.005	0.04	0.07	-0.02		
	(18-32y)	(0.03)	(0.04)	(0.03)	(0.04)	(0.06)	(0.09)		
SWR	Child	0.23	0.28	0.05	0.14	0.24	0.10	ns	
Variability	(8-12y)	(0.09)	(0.13)	(0.14)	(0.05)	(0.13)	(0.13)		
(n= 68)	Teenage	0.24	0.23	- 0.01	0.16	0.22	0.06		
	(13-17y)	(0.09)	(0.08)	(0.06)	(0.05)	(0.07)	(0.08)		
	Adult	0.13	0.17	0.04	0.14	0.18	0.04		
	(18-32y)	(0.05)	(0.04)	(0.05)	(0.06)	(0.05)	(0.08)		
$\triangle$ Perc	Child	3.60	3.14	- 0.22	1.38	2.51	0.95	Group* [DCD < TD]	
DS	(8-12y)	(4.52)	(1.98)	(3.21)	(0.47)	(0.79)	(0.84)		
variability	Teenage	3.24	3.02	-2.16	1.66	1.96	0.22		
	(13-17y)	(3.02)	(1.40)	(5.84)	(0.75)	(0.63)	(1.23)		
	Adult	3.13	2.34	- 0.79	1.26	1.49	0.23		
	(18-32y)	(3.80)	(1.17)	(4.43)	(0.56)	(0.60)	(0.67)		
#Walking	Child	0.14	0.16	0.03	0.14	0.18	0.04	n/s	
speed	(8-12y)	(0.06)	(0.09)	(0.10)	(0.09)	(0.08)	(0.10)		
Variability	Teenage	0.14	0.14	- 0.008	0.06	0.11	0.05		
(n=68)	(13-17y)	(0.20)	(0.09)	(0.22)	(0.04)	(0.11)	(0.08)		
	Adult	0.05	0.13	0.08	0.09	0.07	-0.02		
	(18-32y)	(0.02)	(0.10)	(0.11)	(0.09)	(0.07)	(0.08)		

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; ns = not significant; # = transformed data; △ = failed transformation.

6.4.3. Angles of the head and trunk

6.4.3.1. Head angle

Means, SD's and significance for change in head angle when walking on the Level compared to the Irregular terrain can be seen in Table 6.3.

Several participants had to be removed from this analysis because the forehead marker was obscured as participants inclined forwards during data collection; 2 x DCD children; 3 x DCD teenagers and 1 TD adult together with their age-matched controls. This left 58 participants (29 DCD, 29 TD group), divided by age into; child $n = 20$, teenager, $n = 18$, adult $n = 20$.

Results from the ANCOVA revealed that order of walking trial did not affect the significance of results for head angle ($F(1,51) = 0.872, p = 0.355, \eta^2 = 0.17$). Mean values from Table 6.3 show that both groups reduced their head angle (i.e. inclined head more towards the ground) when walking on the uneven compared to the level terrain. However, significant group effects ($F(1,51) = 6.151, p = 0.016, \eta^2 = 0.108$) show that the DCD group were more affected by the irregular terrain than the TD group, with the DCD group inclining their head (-32.22°) more towards the ground than their TD peers (-23.14°).

There were no age ($F(2,51) = 1.305, p = 0.280, \eta^2 = 0.049$) or age-by-group interactions ($F(2,51) = 0.219, p = 0.804, \eta^2 = 0.009$).

Table 6.3. Means, SD's and significant values for percentage difference in head angles – Level; Irregular terrain.

Age	DCD (<i>n</i> =29)			TD (<i>n</i> =29)			Significance
	Level (Degree)	Irregular (Degree)	Mean % change (SD)	Level (Degree)	Irregular (Degree)	Mean % change (SD)	
Child (8-12y)	72.63 (4.45)	45.70 (12.11)	-37.46 (14.24)	75.93 (5.35)	55.12 (11.48)	-27.30 (14.44)	Group* [DCD <TD]
Teenage (13-17y)	69.52 (11.04)	48.60 (16.33)	-30.72 (15.07)	72.10 (10.54)	57.86 (9.98)	-18.59 (11.63)	
Adult (18-32y)	72.86 (8.83)	51.20 (9.09)	-28.32 (17.50)	78.83 (9.72)	60.56 (11.82)	-23.06 (11.51)	

Key; * *p* = significant to 0.05 level; ***p* = significant to 0.001 level; ns = not significant

6.4.3.2. Trunk angle

Means, SD's and significance for change in trunk angle when walking on the Level compared to the Irregular terrain can be seen in Table 6.4.

Two teenagers with DCD and their matched controls were removed from this analysis as the chest marker was obscured during data collection. One child with DCD and their matched pair also had to be removed as there were insufficient trials for analysis. This leaves 64 participants (32 DCD, 32 TD group), divided by age into; child *n* = 22, teenager, *n* = 20, adult *n* = 22.

Results from the ANCOVA revealed that order of walking trial did not affect the significance of results for trunk angle ($F(1,51) = 2.084$, $p = 0.155$). There was a significant main effect of age ($F(2,51) = 4.622$, $p = 0.014$, $\eta^2 = 0.153$). Pairwise comparisons (using the Bonferroni correction) show that children reduce their trunk angles (i.e. incline more towards the ground) to a greater extent than the teenagers ($p = 0.039$).

There were no group ($F(1,51) = 0.156$, $p = 0.692$, $\eta^2 = 0.003$) or group-by-age interactions ($F(2,51) = 1.1242$, $p = 0.333$, $\eta^2 = 0.042$) for this measure. This suggests that both groups demonstrate similar changes in trunk angle when walking on an Irregular compared to a Level terrain.

Table 6.4. Means, SD's and significant values for percentage difference in trunk angles – Level; Irregular terrain.

Age	DCD (n=32)			TD (n=32)			Sig.
	Level (Degree)	Irregular (Degree)	Mean % change (SD)	Level (Degree)	Irregular (Degree)	Mean % change (SD)	
Child (8-12y)	90.63 (3.93)	80.83 (7.83)	-12.54 (13.84)	88.82 (4.44)	83.56 (4.13)	-9.34 (6.90)	Age* [C>A]
Teenage (13-17y)	86.62 (3.97)	82.76 (6.10)	-3.96 (4.02)	89.17 (4.17)	85.23 (6.01)	-6.39 (6.55)	
Adult (18-32y)	91.39 (4.15)	85.42 (5.61)	-2.92 (5.06)	92.04 (4.48)	89.42 (6.78)	-5.86 (7.57)	

Key; * p = significant to 0.05 level; C = Child; A = Adult.

6.5. Discussion

The current study investigated the locomotor adaptations of individuals with and without DCD aged 8-32 years whilst traversing an irregular terrain.

Both groups walked more slowly and with shorter, wider steps in the irregular, compared to the even walking condition, demonstrating that when proprioceptive information from the feet is not stable it can be difficult to interpret, and gait adaptations are made to protect stability (MacLellan & Patla, 2006). These adaptations provide a clear illustration of the interaction between the individual, the task and the environment as specified by the Ecological approach (Gibson, 1966) and Newell's constraints model (1986); both groups increased their *individual* adaptations (shorter step length etc.) to the more demanding *environmental* constraints (irregular terrain), which altered the walking task (constraints to stability).

However, it appears that the impact of the irregular terrain was greater for the individuals with DCD compared to the control group, demonstrated by group effects for percentage change in walking speed, proportional step length and step width ratio. This manifested with the DCD group walking slower and with shorter, wider steps, than their TD peers on the irregular terrain.

Walking slower with shorter, wider steps are strategies previously identified to preserve stability when there are environmental and/or internal challenges to balance (Bierbaum et al., 2010; Menz et al., 2003^b; Maki, 1997; Deconinck, et al., 2006^a). However, this profile of walking needs to be unpicked as several strategies can be used to reduce walking speed, but not all assist with dynamic stability. For example, if the pedestrians are moving their limbs more slowly, this will increase time spent in single support which could actually increase balance demands. There is also research to suggest that slower walking speeds increase variability (Dingwell & Marin, 2006), a measure used to predict increased risk of falling in the older population (Verghese, Holtzer, Lipton, Wang, 2009). Alternatively, if the slower speed is due to a longer period in double support, this will aid balance. The results from the current study indicate that the slower walking speed is the result of shorter steps, which, in conjunction with a wider step width ratio is an approach used to assist with dynamic stability whilst walking, (Winter, 2009). This strategy helps to control the Centre of Mass excursion within a moving base of support (Marigold & Patla 2002), by reducing the step length, so that the Centre of Mass has a smaller excursion falling forwards, and the wider step width ratio provides a more stable base. These results compare favourably with those found by Menz et al., 2003^b who identified that older adults walked more slowly and with shorter steps than younger adults whilst negotiating an irregular terrain.

However, the young TD adults in Marigold and Patla's (2008^a) and Menz, et al's (2003^{a&b}) studies maintained their walking speed and increased their step length, in contrast to the current study where both groups walked more slowly and with smaller steps on the irregular terrain compared to level ground. Different methods might explain these differences as Marigold and Patla's (2008^a) study was performed wearing a safety harness, thus highlighting group differences in the *perception* of risk to balance whilst negotiating the irregular terrain. For example, wearing the harness may have reduced the perceived threat to balance for the younger but not the older group whilst negotiating the irregular terrain, resulting in fewer accommodations to gait patterns and speed. However, in the current study where participants were responsible for their own safety strategies, greater gait adaptations were seen for all participants. This is particularly evident as the walking speed of both the level (approx. 1.3 m/s) and irregular terrains (approx. 1.4 m/s) in Marigold and Patla's (2008^a) study are much faster than in the current study.

Group differences in gait adaptation to the irregular terrain can be explained with reference to the relationship between sensory integration and balance control. As discussed in the introduction, the sensory integration problems reported for individuals with DCD (Deconinck et al 2006^b; Deconinck et al, 2007; Wilson & McKenzie, 1998; Geuze, 2003) may affect the quality of sensory feedback (afferent information) and subsequent reactive strategies to control balance whilst walking, as argued by Marigold & Patla (2002), Patel et al. (2009) and Deconinck, et al. (2007). This hypothesis was supported by Bierbaum, et al. (2010) who found that young adults increased their base of support more than the older adults, in response to an unexpected perturbation which they argue demonstrates a more effective feedback response for young compared to older adults. However, in the current study, participants with DCD were found to produce greater gait adaptations to the irregular terrain than their TD peers. Supporting previous research by Tsai et al. (2008) and Deconinck et al. (2010) which argues that problems with dynamic balance is exacerbated for individuals with DCD in more challenging situations

It could therefore be speculated that both groups are able to use appropriate feedforward–feedback strategies to adjust their lower limbs to the changing environmental conditions they encountered on the irregular terrain. But, because the balance constraints for the DCD group are greater than the TD group (Macnab, et al., 2001) their gait adaptations generate a 'safer' style of walking to accommodate this. Support for this hypothesis comes from Deconinck et al (2010) who suggest that feed forward information whilst walking towards an obstacle in the pathway is used appropriately by individuals with DCD. However, conflicting findings from Smits-Engelsman et al, (2003) and Wilson et al. (2013) who argue that feedforward processes for goal

directed arm movements are thought to be impaired in populations with DCD, may highlight different mechanisms used to control a continuous motor activity such as walking compared to the discrete actions involved in goal directed arm movements.

It could be speculated that the individuals with DCD in this study have shown that, even when sensory integration is sub-optimal, the prime concern for the CNS whilst negotiating irregular terrains is the maintenance of dynamic stability, reiterating Marigold and Patla's (2005) argument that dynamic stability is a major priority whilst walking. These findings also emphasise the link between the individual, the environment and the task (Newell, 1986; Shumway-Cook & Woollacott, 2012) illustrating how balance constraints for the individuals with DCD manifest as changes to the walking task to accommodate changing environmental conditions.

Age effects were only observed for percentage change in walking speed, with children reducing their speed on the irregular terrain more than teenagers. This reduced speed may give the children additional time to process the complex environmental information as they are subject to the constraints of maturational processes of the central nervous system involved with the organisation of movement (Duysens & Van de Crommert, 1998). They are also heavily reliant upon perceptual processes, particularly visual, vestibular and proprioception (Hulme & Snowling, 2009), and their reduced speed may give additional processing time to assimilate this information, whilst also assisting with maintaining the stability of the head and pelvis in a similar fashion to the older adults in Menz, et al's (2003)^a study.

There were no age differences for percentage change in step width ratio; so there was no additional impact from walking on the level to the irregular terrain. This was unexpected as previous research suggests that this is another gait measure to mature late (Sutherland et al, 1980), and a wider step width ratio is known to assist with constraints to balance. However there was a group-by-age interaction indicating a greater percentage change in step width ratio for children and adults with DCD compared to their TD controls, but a smaller percentage change in step width ratio for the teenagers with DCD. These results may identify several issues; firstly, it may reflect the late maturational process for the children with DCD who used a wider step width ratio to accommodate these deficits. Secondly, it may reflect that the adult DCD group are more cautious with their walking parameters, using a wider step to protect their balance.

Group differences in variability were only found for the percentage of time spent in double support. However, the direction of the effect was surprising as it was the TD group who

increased their variability to a greater extent than the DCD group for this measure. Analysis of the mean value tables, suggests that whilst the TD group did increase their variability across conditions, this was still substantially below the variability of the DCD group in both level and uneven walking. Given that research with older (Maki, 1997) and younger (McAndrew-Young & Dingwell, 2012) adults suggests that increased variance in time spent in double-support was positively associated with falling; these findings highlight the impact to balance for the TD participants of the irregular terrain. However, for the DCD group, it may be that variability of percentage of time spent in double support was at a maximum whilst walking on the level terrain and could not be increased whilst simultaneously maintaining a rhythmic walk. The analysis of variability is particularly relevant for this measure as analysis of the spatio-temporal changes did not reveal any group differences in the percentage of time spent in double support. Both groups reacted in a similar manner for this measure, increasing time spent in double support on the irregular terrain compared to the level ground. Analysis of variability for this measure highlights that the mechanisms behind the movement, but not the movement itself, differ between groups when adapting to the irregular terrain.

Both groups inclined their heads more towards the ground when walking on the uneven compared to the level terrain, illustrating the additional visual planning needed to negotiate irregular terrains. However, the DCD group inclined their heads towards the ground to a greater extent (-32.16%) than their TD peers (-22.98%). This was apparent even though the DCD group inclined their heads more towards the ground than the TD group whilst walking on a level terrain. However, the *percentage change* in angle for the DCD group between conditions was greater (-32.40%) compared to the TD group (-23.48%), which suggests that individuals with DCD were more affected by the irregular terrain than their TD peers. In the absence of a portable eye tracker, this study used head angle to infer whether the participant needed to use foveal information whilst traversing the irregular terrain. Inclining the head towards the ground was interpreted as a need to sample the ground terrain; the greater the incline, the greater the foveal information available to the participant. As argued by Deconinck, et al., (2007) and Mon-Williams, et al. (1999), individuals with DCD have difficulties integrating visual and proprioceptive information. This difference in head angle could be caused by a greater need for the DCD group to ‘visually sample’ the irregular terrain or foot position more than the TD group, possibly supporting difficulties interpreting ‘unreliable’ proprioceptive information from the feet (MacLellan & Patla, 2006; discussed in Chapter 7). This would support research by Smits-Engelsman, et al. (2003) who argue that individuals with DCD rely on visual information for movement to a greater extent than their TD peers. There were no group effects for angle of

the trunk, indicating a similar postural response for both the TD and the DCD participants whilst traversing the irregular terrain.

The lack of age-by-group interactions for any measure except Step Width Ratio, was a surprising result given the developmental nature of mechanisms needed to negotiate irregular terrains (Assaiante & Amblard, 1995, 1993; Visser & Geuze, 2000) together with additional constraints to negotiating an irregular terrain for children with DCD (Hyde & Wilson, 2010, Deconinck et al., 2010, Macnab et al., 2001). It was hypothesised that these constraints would result in greater gait adaptations for the children with DCD compared to all other participants. The lack of interactions indicates that the effect of walking on an irregular terrain results in a similar developmental trajectory for both groups. Furthermore, these findings may highlight that for a cyclic task such as walking (compared to target focussed movements, Hyde & Wilson, 2010; Smits-Engelsman et al., 2003) children with DCD use feedforward and feedback control to support their primary deficit which, as argued by Deconinck et al. (2010), is balance.

6.6. Conclusions

The results from the current study suggest that there are significant differences in walking patterns for all participants whilst walking on an even compared to an irregular terrain. All participants walked more slowly with shorter, wider steps, and inclined their head more towards the ground when traversing the irregular terrain compared to level ground. These strategies could highlight an adaptive approach used by both groups to preserve stability and increase visual sampling whilst traversing the irregular terrain. However, the DCD group walked more slowly with shorter, wider steps than their TD peers, inclining their heads more towards the ground. This suggests that the DCD group were forced to adapt to a greater extent than the TD group to possibly accommodate motor difficulties.

Chapter 7: The effect of visual occlusion of the feet whilst walking on a level and an irregular terrain

7.1. Introduction

As pedestrians we are continually bombarded with rich visual information that has to be effectively processed to safely forge a path to our destination. To walk around the environment, this perceptual information must be integrated with the motor demands required to move the body forward and keep it balanced, whilst simultaneously adapting to different ground terrains and avoiding obstacles in our path. As discussed in Chapter 2, vision is perfectly suited to assist with locomotion as it provides both near and distant information, which can be used to specify spatial relationships between the environment and the individual. Visual information can be used to regulate walking patterns both locally, on a step-by-step basis, or globally to plan the chosen route (Patla, 1997). Allport (1989) claims that we pay attention only to features in the environment that are relevant toward an intended action, thus vision and action are inextricably linked. Additionally, feedforward visual input is also essential to regulate the proactive motor accommodations necessary to negotiate different ground surfaces such as staircases, slopes or irregular terrain. Patla (1997) suggests that these accommodations demand a change in locomotor strategy that needs to be sustained over several steps, in comparison to the avoidance of obstacles that only influence one or two steps. These examples highlight the perception-action link (discussed in Chapter 2) which allows the pedestrian flexibility to accommodate changes in the environment.

This chapter will discuss the role of vision for effective walking in individuals with and without DCD. This will develop the findings from previous chapters by investigating the effects of visual occlusion of the feet whilst walking along level terrain (developing findings from Chapter 4), and whilst walking along an *irregular terrain* (developing findings from Chapter 6). Ecological validity was an important methodological consideration for both the terrain and the visual manipulation, and the current study was designed to replicate real-life but within the confines of a lab environment. The visual manipulation was designed to replicate loss of vision associated with carrying something in front of the body, such as a tray, whilst maintaining complete availability of visual information from optic flow. The irregular terrain replicated a cobbled walkway that pedestrians may encounter in the real world. The chapter begins with a review of current research investigating the role of vision in walking, together with reported adaptations to walking patterns when visual input is reduced. Evidence will be presented from research investigating the developmental progression in the use of vision for locomotion.

Finally there is a literature review of the few studies investigating how individuals with DCD use visual information whilst walking.

There are two experimental manipulations reported in this chapter; the first (study 1) investigates the effects of visual occlusion of the feet on walking patterns for individuals with and without DCD when traversing a level terrain. The second manipulation (study 2) uses the same sample and visual manipulation to investigate walking patterns on an irregular terrain.

7.1.1. Role of vision in walking

To fully understand the role vision plays in the walking task, it is important to understand what people look at as they negotiate their environment. In addition to the information received from optic flow, which Gibson (1950, 1966) argues is perceived without any need for cognition (discussed in Chapter 2), the visual system also uses information from voluntary eye movements; we can direct our eyes where we choose to look. These ‘choices’ are often controlled by cognitive processes (top down) to maximise the useful information obtained from a scene. Studies investigating top down control of eye movements (Land & Hayhoe, 2001; Land & Lee, 1994) have identified that people use the superior resolution of foveal vision to fixate on targets containing a large amount of task-relevant information, together with information for future action. It could therefore be argued that when walking along a level predictable terrain, people will look ahead at the main target or direction of walk, and use peripheral vision to view closer information, to highlight any hazards which will need foveal attention.

To investigate whether this is the case, Patla and Vickers (1997) explored gaze behaviour of 8 adults whilst stepping over obstacles. The participants wore a mobile eye tracker whilst walking along a 10m walkway, along which was placed an obstacle in one of three different heights (1cm, 15cm, 30cm). Results showed that during the approach, participants fixated the obstacles for, on average, 78% of trials, although the frequency and length of fixation increased as the height of the obstacle increased. These results support previous research suggesting that fixations are made to task-relevant information, as the higher obstacles will be perceived as more threatening to balance, and therefore a more important task to ensure foot clearance during obstacle than the lower ones. They also emphasise the importance of visual information as task constraints increase. Interestingly, participants only fixated the obstacles 2-3 steps before they stepped over them, but not whilst they were traversing the obstacle. The authors suggest that this provides evidence of a feedforward process provided by the visual system to support the planning process of limb movement by identifying ‘anchors’ for the feet to aim at for obstacle

crossing. Feedback information from the vestibular and proprioceptive systems would be used after the movement to correct any error.

To further investigate what people look at as they walk, Hollands, Patla and Vickers (2002) explored gaze behaviour used to change direction whilst walking along a level uncluttered pathway. Seven adults walked along a 9m pathway under two conditions; either in a straight line or a change of direction (30° or 60° left or right). The authors found that participant's gaze was aligned with features lying in the travel path both before and following a change in direction. Hollands et al. (2002) argue that this finding confirms Gibson's optic flow (1950, 1966) hypothesis as the participants manipulated their perceptual input (by aligning eyes and head to a target) such that features in the travel path were positioned straight ahead, providing the focus of expansion for optic flow which was then used to inform the most appropriate direction of travel. These findings show that whilst information from optic flow may be perceived without any need for cognition, top-down processes are used to focus visual input and ensure the most important environmental information is directly ahead, optimizing optic flow in the periphery.

The evidence provided so far suggests that occlusion of foveal vision would severely interfere with skilled action, as it would remove visual information about the target and the focus of expansion for optic flow. However, a Russian physiologist, Krestovnikov (1951, cited by Franchak & Adolph, 2010) observed that athletes are more disadvantaged whilst performing a skilled action when peripheral vision is removed than when foveal vision is removed. The athletes were still able to perform activities such as javelin throwing, slalom skiing and figure skating when foveal vision was occluded. However, without peripheral vision javelin throws fell short, skiers veered off course and skating patterns were erratic.

Franchak and Adolph (2010) further investigated this phenomenon and developed an experiment to assess whether it is *necessary* to fixate on obstacles in the travel path whilst navigating a complex environment. Six children (mean 7.1 years) and 8 adults (20-22 years) were asked to find 30 star stickers intermittently placed around a room filled with obstacles. The participants walked freely around or over the obstacles to reach the stars, whilst wearing a head-mounted eye tracker. Results showed that 41% of the children and 68% of adults did not fixate the obstacles in their path at all to successfully navigate past them. Of the remaining children who did fixate obstacles in their path, 59% of encounters were fixated and the remaining adults fixated 32% encounters.

Whilst these results contradict previous adult studies of obstacle crossing (Patla & Vickers, 1997- objects fixated 78% trials) the different methods used to gather data may provide an explanation for this. Patla & Vickers' (1997) research was conducted under fairly basic conditions where terrain was predictable and there was little else to look at other than the obstacle in the travel path, therefore time spent fixating the obstacle may be overestimated in these experiments.

Franchak and Adolph (2010) argue that findings of reduced fixation to obstacles in the travel path demonstrates that pedestrians can adaptively walk in complex environments without fixating obstacles in their path, and that peripheral vision is sufficient for accurate foot placement in a complex and irregular terrain. Furthermore, research by Hollands et al. (2002) has identified that optic flow from peripheral vision can be used to determine direction of travel and the position of the body, as a whole, in space. Findings from Franchak and Adolph's (2010) study add to this by highlighting the use of peripheral vision for accurate guidance of foot placement in a complex and irregular terrain. It also illustrates the use of top down processes; the use of peripheral vision to traverse the irregular terrain allowed the participants to use foveal vision to scan the environment for the stars, which could be argued to be the most task relevant exercise for the participants in this example. However, this could also be a confound to the results, as previous research has identified that we fixate on task-relevant information (Land & Hayhoe, 2001). If the stars were the most important thing to look at in this scenario, resulting in greater fixation, this may have underestimated normal foveal activity and overestimated peripheral activity. Either way it does demonstrate that previous studies may have overestimated fixation percentage when there is only one obstacle to concentrate on, and that peripheral vision is sufficient to control some aspects of locomotion.

Not only do people fixate on task-relevant objects (object fixation) whilst walking, we also travel fixate, where gaze is anchored 2-3 steps in front of the body (Patla & Vickers, 1997; Land, 2006) allowing the extraction of information concerning self-motion from optic flow to be processed (Gibson, 1966). Patla and Vickers (1997) argue that travel fixations account for approximately 60% of all fixations during locomotion, with object fixations being used to solve complex locomotor problems such as obstacle negotiation and changing direction. However, Patla and Vickers (2003) confirmed the dominant use of travel fixations (>50%) even in a more challenging locomotive situation; whilst stepping on irregularly placed stepping stones. They argue that this indicates the use of visual information obtained from travel fixations is used for planning and control of future steps (i.e. feedforward processes), together with information from optic flow concerning environment and self-motion. They suggest that travel fixations are as

relevant to the task as the need for object fixations to a secure foothold incurred through irregular stepping surfaces.

7.1.2. The effects of reduced visual input on walking patterns

Another way to investigate the use of vision for walking is to reduce visual input and monitor the effect on walking patterns. This paradigm was used by Hallemans, Ortibus, Meier and Aerts (2010) who invited 10 adults (mean age 26.7 years) with a visual impairment and 20 age matched controls with no visual impairment to walk along an uncluttered walkway. The participants with a visual impairment were divided into two sub-groups; low visual acuity and blindness. The control group was tested in full vision and a no vision condition, using swimming goggles masked with black tape to remove visual input. Unsurprisingly, there were group differences in the spatio-temporal measures analysed, with the visually impaired participants taking smaller steps, with less trunk flexion (i.e. leaning backwards) and less plantar flexion at the ankle following heel-strike than their controls in full vision. Interestingly, gait adaptations for the control group in the no vision condition were similar to those of the participant's with a visual impairment. In addition to these modifications the controls walked more slowly, with limited movements about the hip and ankle compared to the full vision condition.

Conclusions drawn from the comparisons between these populations have to be carefully considered, given the different aetiologies of visual deprivation between groups. Additionally, the methods used to manipulate the visual deprivation for the participants with normal sight will not create a comparable condition to that experienced by the visually impaired participants. As explained by Hallemans, et al. (2010) the participants with a visual impairment, who had all lacked visual information from birth, utilise sensory information from other modalities to regulate their walking, but for the control group, for whom walking without visual feedback was novel, the utilisation of information from other sensory modalities was not as readily available and therefore resulted in greater gait adaptation to the visual deprivation. The authors argue that the gait adaptations to visual deprivation suggest a more cautious walking pattern that relies on tactile feedback from the feet and the reduced angular extension at the ankle serves to increase the surface area of the foot in contact with the ground.

The gait adaptations discussed above have been found in other studies investigating the effects of visual deprivation during overground walking (Buckley, MacLellan, Tucker, Scally, and Bennett, 2008). Finally, differences in gait patterns were even seen between the individuals with low vision compared to those with blindness (individuals with blindness show smaller head

incline, larger step width and larger knee flexion at heel-strike than low vision individuals), illustrating that even a small amount of visual input can positively affect gait control.

Conclusions to be drawn from adult data gathered whilst negotiating the environment indicates that people look at targets that are highly relevant to the task in hand, using the higher resolution of foveal vision to support this role. Additionally, as task complexity increases so does the relative importance of visual information (Patla & Vickers, 1997). However, according to the Newell's constraints paradigm (1986, discussed in Chapter 1), task complexity will be personally specified, reflecting experience, size and personal characteristics. For example, ascending a flight of stairs to a typically developed young adult will be an easier task than for a toddler, where the ratio of stair height to leg length will be higher, or an older person who may have additional constraints to joint movement. Therefore fixation on the stairs would reflect the relative difficulty of the stair ascent as perceived by the individual. Thus the use of top-down information is also crucial when trying to understand how humans negotiate the environment as demonstrated by Marigold and Patla (2007) and Franchak and Adolph (2010) who provided evidence of task-relevance significantly affecting fixation rates. Findings from these and Hallemans et al. (2010) study suggests that use of visual information obtained from travel fixations is used for planning and control of future steps (i.e. feedforward processes), together with information from optic flow concerning environment and self-motion (Hollands et al., 2002).

7.1.3. The development of visual skills for walking

Having discussed some of the visuo-motor processes involved in effective navigation of the environment for typical adults, the issue of how relevant these findings are to children is now considered.

As discussed in Chapter 2, effective motor skills evolve gradually over several years (Duysens & Van de Crommert, 1998), but by 7 years of age children are indistinguishable from adults on standard measures of walking skill (Sutherland et al 1980). However, there is evidence to suggest that some of the visual perceptual abilities of children do not reach maturity until much later in life (Wann, et al., 1998; Shumway-Cook & Woollacott, 1985; Sparto, et al 2006). The extra reliance children put on visual input may these make them vulnerable when negotiating irregular terrains as they cannot utilise other sensory inputs from the vestibular and proprioceptive systems as well as adults.

Further evidence to support the developmental role of visual input to motor processes is provided by Franchak and Adolph's (2010) study, discussed previously. They argue that there is

a developmental progression in the use of foveal and peripheral vision for navigating the environment; Infants (14 months) fixated 75% of obstacles when walking unsupported (Franchak, Kretch, Soska & Babcock & Adolph, 2010), children (4-8 years) 59% and adults (20-22 years) 32%. This may illustrate greater efficiency of top down processes in the use of vision by adults, who were more able to guide their navigation peripherally whilst using foveal vision to locate the stars. These results highlight an interesting phenomenon as the infants in this study fixated obstacles for a shorter time than adults in previous studies (Di Fabio, Zampieri & Greany, 2003; Patla & Vickers, 1997). There are several explanations for this phenomenon; firstly, as already discussed, there may have been little else to look at in the previous studies thus overestimating the length of time adults fixate. Secondly, as children use visual feedback to a greater extent than adults for postural control (Cowie, Atkinson & Braddick, 2010; Shumway-Cook & Woollacott, 1985) they may need to fixate relevant obstacles for longer to encode the necessary information to navigate past them.

7.1.4. Visual contribution to movement for individuals with DCD

There is limited research investigating the effects of vision on the walking patterns of children and adults with DCD, however several studies discussed in Chapter 1 have identified problems with information processing (Wilson & McKenzie, 1998; Mon-Williams et al 1999), cross modal sensory integration (Mon-Williams et al, 1999) internal modelling (Wilmot et al. 2006; Smits-Engelsman, et al. 2003; Hyde & Wilson, 2010) and postural control (Geuze et al. 2003) all of which could affect the efficiency with which individuals with DCD walk around their environment. Additionally, there has been conflicting evidence for the role of vision in the control of movement for children with DCD. Several studies argue that children with DCD are more reliant on visual information for movement than their TD peers (Wann et al., 1998; Smits-Engelsman et al., 2003). However in other studies this is not the case (Geuze, 2003; Przysucha & Taylor, 2004). One of the explanations for these differences may be attributed to the heterogeneity of DCD which may affect the use of visual information differentially within the DCD population, but clearly more research is needed in this area.

To-date many of the studies investigating the perceptual contribution to movement for individuals with DCD have concentrated on fine motor, table-top tasks (e.g. Smits-Engelsman, et al., 2003; Wilmot & Wann, 2008) or the control of static balance (Wann et al., 1998; Geuze 2003). The visual contribution to locomotion is an important addition to the DCD literature because the dynamic visual cues experienced whilst walking will provide different sensory feedback to those experienced during a stationary task. Additionally, the continuous nature of the walking task may affect how the pedestrian uses visual information to support error

management whilst negotiating environmental constraints (Kuo & Donelan, 2010). This, together with the constraints to movement for individuals with DCD, discussed above, make this a much needed area for research. During locomotion it is important that we can use visual information to predict outcomes and respond accordingly to ensure successful navigation around obstacles, along different terrains and to assist with safety by correctly estimating the time-to-contact for obstacles in the pathway such as passing cars or other pedestrians.

One of the few studies to investigate the contribution of vision during a walking task was conducted by Deconinck, et al. (2006^b). They invited 24 children aged 7-9 years with and without DCD to walk at their own pace along a 9.6m walkway towards a target. The target (in the guise of a puzzle) was used as a distractor, and participants were asked to look at it as they walked, to focus attention on that rather than their walking patterns. Participants completed this walk in two conditions; in normal light and in darkness, where the only light available was a small LED at the end of the walkway. 3-Dimensional kinematic data were collected from reflective markers attached to the lower limbs, torso and wrists of the participants. The children with DCD walked more slowly, and their upper bodies swayed more in the dark condition than the TD children, whose walking patterns were unaffected by darkness. Deconinck et al. (2006^b) argue that the TD group were able to use the limited light provided by the LED (providing visual information about lateral sway) to assist in controlling balance and velocity whilst walking towards the target. They propose that the TD group adapted to the loss of optic flow using other sensory channels such as proprioception and/or the vestibular system. However, the children in the DCD group seemed less able to adapt to the changing visual conditions and utilise the limited light from the LED.

Additionally, differences in the percentage of the gait cycle spent in double support varied between groups for both conditions, but for the DCD group this increased considerably from the visual to the no vision conditions, contrasting with the TD group where changes in this measure were negligible. Deconinck et al (2006^b) argue that children with DCD cannot easily shift to other sensory channels when vision is removed, supporting previous studies that suggest an over reliance on visual information for movement by individuals with DCD (Rösblad & von Hofsten, 1994; Wilmut & Wann, 2008; Smits-Engelsman et al., 2003). They propose that there is a deficiency in utilising proprioceptive and vestibular input when visual input is difficult to interpret which particularly affects children with DCD. TD children seem more able to flexibly adapt to the different sensory modalities, effectively demonstrated by their ability to control locomotion after the removal of vision. As discussed in Chapter 1, Deconinck et al. (2006^b) postulate that the problems experienced by the DCD group to fully integrate sensory

information may highlight deficits in the assimilation of feedback and/or feedforward information which affects the internal model, exacerbating subsequent movements needed to correct any errors.

As discussed, Deconinck et al. (2006^b) have identified an over-reliance on visual information during walking tasks in children with DCD. However, the visual deprivation condition took place in complete darkness, so it is unclear whether the changes in walking patterns when visual information was removed were due to the loss of optic flow or visual feedback from the limbs as implied in studies which remove visual information during manual aiming movements (Wilmot et al., 2006; Smits-Engelsman, et al., 2003). It is also unclear whether these visual adaptations for the children with DCD persist to adulthood. Although the findings in Chapter 4 suggest that individuals with DCD looked down more than their TD peers as they walked. Given that the pathway was level and uncluttered (i.e. very predictable), this may suggest that visual information concerning the whereabouts of the feet is more important for pedestrians with DCD of all ages compared to their TD peers. Furthermore, there is some evidence to suggest that in challenging situations, such as when walking along a narrow beam, TD adults also rely disproportionately on vision (Assaiante, Marchland and Amblard, 1989).

To further explore the anticipatory planning skills of children with DCD, Deconinck, et al. (2010) invited children aged 7-9 years with and without DCD to traverse an obstacle whilst walking along a pathway. Children walked at a self-selected speed towards a puzzle at the end of the walkway under three conditions; level walking; crossing a low obstacle (5% of leg length); crossing a high obstacle (30% of leg length). The walkway was surrounded by 8 infrared cameras which gathered data from reflective markers placed on the participant's feet, legs, trunk and wrists. The authors found that both groups walked more slowly during obstacle crossing than walking over level ground, and reduced the spatial variability of their foot placements as they approached the obstacle, which was negotiated with a similar strategy; There were no differences in approach distance, length of lead leg and trail step, or lead and trail elevation. However, the DCD group exhibited a greater speed and amplitude in the medio-lateral sway of the Centre of Mass than the TD group whilst traversing the obstacle. The authors argue that these results show that whilst the children with DCD exhibit satisfactory anticipation and visual guidance, they have a reduced ability to control the momentum of the Centre of Mass when crossing obstacles indicating problems with dynamic postural control.

It is interesting to note that both Deconinck et al's (2006^b & 2010) studies used a diversionary puzzle for the children to focus upon. The intention was to avoid over thinking the walking task given that the children might feel self-conscious walking whilst being watched. However, using

a distractor in this way may have created a confound to the results as illustrated by the Constrained Action Hypothesis (Wulf, Shea & Park, 2001).

Wulf et al (2001) argue that directing attention to the effects of a movement on the environment, (external focus of attention), rather than the actual body movements (internal focus of attention) improves motor skill. They argue that this is a robust finding and discuss several studies where they have found this effect. For example, Wulf, Hoss and Prinz (1998) investigated the effect of internal/external focus of attention for learning to perform slalom type movements on a ski simulator. Instructions were provided referring to the force exerted on the platform they were standing on. Participants were divided into three groups, one group (internal focus) received instructions focusing on forces exerted by their feet, another group (external focus) were given instructions focussing on the force exerted on the wheels of the platform, and a third group (controls) were given no focus instructions. The authors found that participants in the external focus group demonstrated more effective performance (as measured by a retention test 3 days later) than those in the internal focus group. Furthermore, they found that internal focus of attention was not more effective in this task than no instruction. In a second study Wulf et al. (1999) repeated these findings whilst participants completed a balance task standing on a stabilometer platform. Participants who were asked to focus on markers attached to the platform in front of their feet (external focus) demonstrated more effective learning (as measured by a retention test 2 days later) than those who were asked to focus on their feet (internal focus). The generalisability of these findings (Shea and Wulf, 1999; Wulf, Lauterbach & Toole, 1999;) have led Wulf et al. (2001) to argue that conscious attempts to control movement can negatively affect the automaticity of motor control. They argue, however, that by focussing on the effect a movement has on the environment (apparatus, implement) the motor control system is more able to self-organise. Thus the use of conscious control on the motor system actually constrains movement skill, interfering with the automaticity of movement.

Therefore, returning to Deconinck et al's (2006^b & 2010) studies, it could be hypothesised that focusing on the puzzle (external focus of attention), rather than on movement, may lead to improved automaticity of walking patterns for both groups of children. The Constrained Action Hypothesis (Wulf, Shea & Park. 2001) predicts that when walking in less constrained conditions, where the pedestrian can focus attention at will, the pedestrian may use an internal focus of attention more than in the above studies. It could be speculated that this strategy may become more apparent in challenging situations such as in reduced visual conditions or when traversing an obstacle in the pathway where movement needs to be more considered to ensure safe passage. The findings from the Deconinck et al (2006^b & 2010) therefore need to be

carefully considered, particularly as it is possible that for populations with movement difficulties, such as those with DCD, an inflated internal focus of attention is used to control movement. Thus group differences discussed above could be the result of differing strategies used to control movement rather than the manipulation effect argued by Deconinck et al (2006^b & 2010). As there has been no research in this area for individuals with DCD it is difficult to make conclusive predictions, but it is useful to interpret the results with these possible confounds in mind.

To summarise, research with TD children suggests an extra reliance on visual information for some areas of movement control in both stationary and dynamic situations. This behaviour has also been found to be exacerbated in children with DCD. Given that for typically developing adults top down processes ensure that visual information is specified to provide task relevant information, the importance of understanding what children and individuals with DCD look at as they negotiate their environment, is increased. Furthermore, given the movement and perceptual difficulties experienced by individuals with DCD (Wann, et al., 1998; Rösblad & von Hofsten, 1994; Wilmut & Wann, 2008; Smits-Engelsman et al., 2003; Deconinck et al., 2006^b), further research is needed to explore the impact this might have on perceptions of task difficulty and therefore personally specified task relevance.

The aim of the two studies presented in this chapter was to extend the work of Deconinck et al. (2006^b), and Deconinck et al. (2010) by designing an experiment to investigate the effects of visual occlusion of the feet on the walking patterns of individuals with and without DCD aged from 8-32 years. However, rather than removing vision completely, as in Deconinck et al.'s (2006^b) study, this investigation developed the work by Wilmut et al. (2006) and occluded the moving limbs only. These manipulations will therefore investigate whether visual feedback from the legs is an important component for the maintenance of efficient walking patterns for children with DCD whilst traversing level and uneven ground.

The two manipulations discussed in this chapter explored the effects of visual occlusion of the feet whilst walking on level ground (study 1) and over irregular terrain (study 2). By applying the hypothesis that the most challenging condition will manifest in the greatest gait adaptations, separating the studies in this way will allow for the identification of the most important mechanisms required to negotiate the environment. For example, if removal of vision of the feet whilst walking on level ground, as in Study 1, caused a large adaptive response in walking patterns, then it might be assumed that this was a challenging environment. Similarly, if gait adaptations are greater in Study 1 (visual occlusion of the feet, level ground) compared to Study 2 (visual occlusion of the feet, uneven ground) then it could be argued that visual information

about the whereabouts of the feet is more important than information about the ground terrain. Conversely if gait adaptations in Study 2 are greater than Study 1 then it could be argued that information about the ground terrain is more important than visual information about the feet.

7.2. Study 1 level ground; Hypotheses

Given that individuals with DCD rely more on vision than their TD peers for the guidance of movement (Deconinck et al., 2006^a; Smits-Engelsman, et al., 2003; Deconinck, et al., 2006^b), and limbs (Wilmut et al., 2006, & results from Chapter 4) it is hypothesised that individuals with DCD will adopt a ‘safer’ walking strategy compared to their TD peers when vision of their feet is occluded. This will manifest as slower walking speed with shorter, wider steps whilst spending longer in double support.

Additionally, given that typically developing adults travel fixate 2-3 steps in front of the body (Patla & Vickers, 1997& 2003) then it is hypothesised that visual occlusion of the feet will have a minimal impact on walking patterns for this population.

However, given the maturational constraints to visuo-perceptual development (Wann, et al., 1998; Shumway-Cook & Woollacott, 1985; Sparto, et al., 2006) it is hypothesised that the effects of visual occlusion of the feet will affect the gait adaptations of children to a greater extent than teenagers and adults.

Finally, children with DCD have shown significant differences in walking patterns compared to their TD peers walking in complete darkness (Deconinck et al. 2006^b), but the limited evidence available suggests there would be smaller group differences in walking patterns between teenagers (Visser et al., 1998) or adults (Cousins and Smyth, 2003) with and without DCD. Therefore an age-by-group interaction is hypothesised (significant group differences for children, but not for teenagers and adults).

7.2.1. Methods

Full details of methods, recruitment and materials employed that are consistent across all chapters can be found in chapter 3. A brief resume is provided below.

7.2.2. Participants

Thirty five individuals with and without Developmental Coordination Disorder (DCD) aged 8-32 years participated in this study. Participants were divided into 3 age groups; 8-12years ($n=24$), 13-17years ($n=24$) and 18-32years ($n=22$). Details of selection and demographic information for all participants can be found in Chapter 3.

7.2.3. Materials and procedures

Participants walked up and down a 6m x 1m flat walkway comprising six 1m² interlocking high density, non-slip sports mats, as described in 3.3.1. Vision of the feet was occluded with a small (20x15cm) light 'tray' which participants were asked to carry against their upper chest (visual illustration in Chapter 3). It was supported by strong ribbon around the neck, and was based on waterproof map carriers; so both hands were free (see Figure 3.3. for illustration).

Two trays were provided; one was clear, and one was opaque with a cardboard insert to block vision of the feet. The clear manipulation was introduced to indicate whether the presence of the tray has any negative effect on gait control. Participants walked around the level walkway, as described in Chapter 3, under two randomly ordered conditions; wearing either the clear or the opaque tray.

Measurements of walking speed, stride length, step width ratio, time in double support and the angles of the head and trunk were taken for this study. Step-to-step variability was analysed using standard deviations (SD) of each individual's data. Data is reported under three headings; *spatio-temporal measures* (walking speed stride length, step width ratio, time in double support vertical and lateral movement of the trunk); variability and *angles of the head and trunk*.

7.2.4. Data analysis

In order to investigate the effects of visual occlusion of the feet, all measures were calculated using percentage changes between (1) level walking (walk data presented in Chapter 4) and level walking carrying a clear tray (Walktray) and (2) level walking (Walk) to level walking carrying an opaque tray (Walkopaquetry). This ensured that any differences in walking patterns are not due to carrying a tray (Walk to Walktray), but rather due to the manipulation of removing vision (Walk to Walkopaquetry). Percentage change was used instead of absolute values to provide information about the *adaptation* of walking patterns between conditions (as explained in Chapter6).

7.2.5. Statistical analysis

Mean percentage differences between walking conditions (level walking with tray compared to level walking and level walking with opaque tray compared to level walking) were calculated for all spatio-temporal measures for each participant individually. This information was entered into statistical analysis using three-way mixed group ANCOVA's to partial out the effects of order of trial presentation (discussed in Chapter 3) whilst investigating the effects of group

(DCD, TD), age (Child, Teenage, Adult) and condition (Walktray, Walkopaquetry) on the spatio-temporal measures of speed, proportional step length, step width ratio, percentage gait spent in double support, vertical and lateral movement of the trunk and the percentage changes in the angles of the head and trunk whilst walking in the conditions described above.

Significant interactions from these investigations were explored using simple main effects and significant main effects were explored using post-hoc tests. The Bonferroni correction was used for all post-hoc tests to control for type I error. Statistical significance was set at the 5% level.

7.2.6. Results

Means and standard deviations for walking speed are shown in Table 7.1. Means and standard deviations for the remaining spatio-temporal measures whilst walking and walking holding a tray plus the percentage difference can be seen in Table 7.2. for the clear tray condition and Table 7.3. for the opaque tray condition.

All data reported in tables 7.1 – 7.5 contains both the percentage change and also the raw scores. Statistical analysis was completed on the percentage change only.

Not all data were normally distributed; therefore when transforming (Log10) was successful the transformed data are reported (signified with #). However sometimes the transforming didn't work and the untransformed data are reported (signified with $\triangle$).

7.2.6.1. Spatio-temporal measures

Results from the ANCOVA revealed that order of walking trial made no difference to the significance of walking speed ($F(1,63) = 3.387, p = 0.070, \eta^2 = 0.051$). There were no significant age ($F(2,63) = 0.897, p = 0.413, \eta^2 = 0.028$) or group effects ($F(1,63) = 0.136, p = 0.714, \eta^2 = 0.002$) or age-by-group interactions ($F(2,63) = 2.613, p = 0.081, \eta^2 = 0.077$) were found when comparing percentage change in speed between level walking and level walking holding a tray; and level walking and level walking carrying an opaque tray. No repeated measures effects for condition were found either (F values ranged from 0.929 for condition-by-age to 0.038 for condition).

Table 7.1. Means (SD) for walking speed (m/s) whilst walking and walking holding a tray (clear and opaque) plus the percentage difference.

		DCD			TD			
		Mean (SD)			Mean (SD)			
Speed		Level	Level	%	Level	Level	%	Signific.
m/s	Age		+tray	change		+tray	change	[Post hoc]
Walk + Clear Tray	Child	0.99	0.93	-6.65	1.05	1.01	-3.58	} n/s
	(8-12y)	(0.20)	(0.22)	(13.26)	(0.17)	(0.19)	(11.55)	
	Teenage	1.02	1.11	9.27	1.12	1.06	-5.81	
	(13-17y)	(0.25)	(0.47)	(3.31)	(0.12)	(0.21)	(16.04)	
	Adult	1.06	0.97	-8.07	1.09	1.10	0.98	
	(18-32y)	(0.17)	(0.25)	(17.85)	(0.18)	(0.14)	(10.15)	
Walk + Opaque tray	Child	0.99	0.96	-2.41	1.05	1.05	0.27	} n/s
	(8-12y)	(0.20)	(0.17)	(8.46)	(0.17)	(0.16)	(5.24)	
	Teenage	1.02	1.01	-0.56	1.12	1.09	-2.41	
	(13-17y)	(0.25)	(0.14)	(19.86)	(0.12)	(0.15)	(16.14)	
	Adult	1.06	0.94	-10.47	1.09	1.07	-2.05	
	(18-32y)	(0.17)	(0.30)	(23.78)	(0.18)	(0.19)	(4.26)	

Key; ns = not significant

Results of the ANCOVA revealed that order of walking trial made no difference to the significance of proportional step length ($F(1,63) = 2.968, p = 0.090, \eta^2 = 0.045$). There were significant group effects ($F(1,63) = 5.352, p = 0.024, \eta^2 = 0.078$) in percentage differences from level walking to walking with a clear tray and level walking to walking carrying an opaque tray. The DCD group increased their proportional step length overall (Clear tray, 5.15%; Opaque tray, 0.82%) more than the TD group (Clear tray = -1.76%; Opaque tray = -1.23%). Illustration of these effects can be seen in Figure 8.1. There were no significant age effects ($F(2,63) = 0.094, p = 0.911, \eta^2 = 0.003$), or any significant group x age interactions ($F(2,63) = 0.725, p = 0.488, \eta^2 = 0.023$) for proportional step length. There were no significant condition interactions (F values ranged from 1.442 condition-by-group to 0.43 condition-by-age).

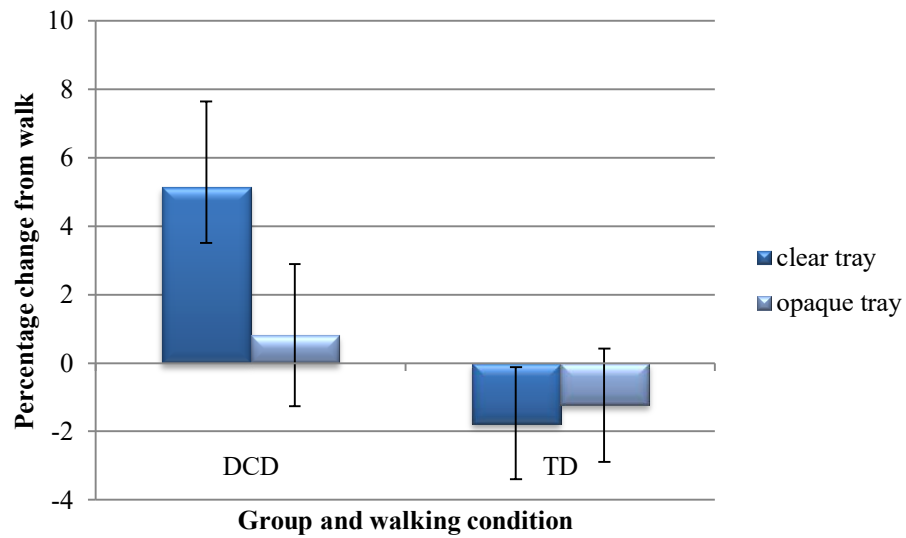


Figure 7.1. Mean of proportional step length percentage difference from walk (clear tray; opaque tray). Error bars represent standard error.

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of *Step width ratio* ($F(1,63) = 0.012, p = 0.914, \eta^2 = 0.00$); *Percentage of time spent in Double Support* ($F(1,63) = 0.034, p = 0.855, \eta^2 = 0.001$) *Vertical movement of the Trunk* ($F(1,63) = 0.414, p = 0.522, \eta^2 = 0.007$) *Lateral movement of the Trunk* ($F(1,63) = 0.039, p = 0.845, \eta^2 = 0.001$).

There were no significant group or age effects, or any interactions for the measures of *Step Width Ratio* (F values ranged from 2.666 for age to 0.141 for condition-by-age-by-group), *Percentage of time spent in Double Support* (F values ranged from 0.137 for group to 1.370 for age), *Vertical* (F values ranged from 0.005 for condition-by-group to 0.776 for condition-by-age) and *Lateral movement of the Trunk* (F values ranged from 0.234 for condition-by-age-by-group to 1.073 for condition-by-group).

Table 7.2. Means (SD) for spatio-temporal measures whilst walking and walking holding a *clear tray* plus the percentage difference.

Measure	Age	DCD Mean (SD)			TD Mean (SD)			Significance [Post hoc]
		Level Walk (SD)	Level+ Tray (SD)	Mean% Change (SD)	Level Walk (SD)	Level+ Tray (SD)	Mean% Change (SD)	
Δ Proportional step Length (SL/leg length)	Child (8-12y)	0.61 (0.08)	0.65 (0.07)	6.12 (11.77)	0.66 (0.05)	0.65 (0.05)	-2.29 (3.50)	Group* DCD > TD
	Teenage (13-17y)	0.58 (0.09)	0.60 (0.09)	6.11 (21.54)	0.62 (0.05)	0.61 (0.11)	-1.27 (20.8)	
	Adult (18-32y)	0.63 (0.05)	0.65 (0.07)	3.04 (8.52)	0.64 (0.07)	0.63 (0.09)	-1.71 (4.53)	
# Step width ratio (SW/hip width)	Child (8-12y)	0.83 (0.17)	0.77 (0.18)	-4.38 (16.22)	0.92 (0.12)	0.86 (0.08)	-3.44 (8.99)	n/s
	Teenage (13-17y)	0.63 (0.17)	0.67 (0.15)	4.96 (28.01)	0.68 (0.13)	0.71 (0.13)	6.75 (12.68)	
	Adult (18-32y)	0.66 (0.20)	0.66 (0.25)	-2.00 (15.82)	0.75 (0.13)	0.72 (0.18)	-3.62 (14.87)	
# % Double Support (% gait cycle spent in DS)	Child (8-12y)	15.65 (3.05)	15.34 (2.13)	-0.88 (9.09)	15.05 (1.39)	15.40 (2.00)	2.79 (7.76)	n/s
	Teenage (13-17y)	17.67 (4.46)	16.89 (1.49)	4.08 (14.43)	15.80 (2.19)	16.04 (2.67)	2.50 (18.73)	
	Adult (18-32y)	16.80 (5.66)	16.77 (1.43)	5.22 (19.03)	16.04 (1.13)	16.43 (1.56)	2.42 (5.55)	
# Vertical trunk Movement (mm)	Child (8-12y)	33.43 (7.75)	32.26 (6.28)	-2.44 (11.91)	38.84 (5.21)	37.54 (5.20)	-2.77 (6.45)	n/s
	Teenage (13-17y)	41.94 (10.16)	52.93 (14.12)	1.28 (17.51)	42.11 (7.88)	41.94 (7.89)	-1.83 (7.54)	
	Adult (18-32y)	42.38 (12.86)	51.79 (20.86)	-0.90 (22.03)	40.03 (8.61)	39.44 (8.92)	-1.61 (7.73)	
# Lateral trunk Movement (mm)	Child (8-12y)	73.69 (22.77)	68.84 (21.92)	-2.95 (24.52)	60.22 (21.95)	62.33 (16.45)	11.36 (35.57)	n/s
	Teenage (13-17y)	57.33 (27.26)	59.76 (15.98)	-11.87 (32.14)	53.82 (20.08)	49.50 (15.27)	-5.01 (30.22)	
	Adult (18-32y)	54.73 (20.08)	56.74 (21.06)	16.43 (67.87)	66.21 (31.90)	64.61 (30.67)	-2.42 (16.65)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant. # = transformed data; Δ = failed transformation.

Table 7.3. Means (SD) for spatio-temporal measures whilst walking and walking holding an *opaque tray* plus the percentage difference.

Measure	Age	DCD Mean (SD)			TD Mean (SD)			Significance [Post hoc]
		Level walk (SD)	Level+ Opaquetray (SD)	Mean % Change (SD)	Level walk (SD)	Level+ Opaquetray (SD)	Mean % Change (SD)	
Δ	Child	0.61	0.63	3.66	0.66	0.64	-2.72	Group* [DCD > TD]
Proportional	(8-12y)	(0.08)	(0.08)	(6.84)	(0.05)	(0.05)	(4.72)	
step	Teenage	0.58	0.59	1.09	0.62	0.61	-1.71	
Length	(13-17y)	(0.09)	(0.11)	(8.29)	(0.05)	(0.13)	(14.37)	
(SL/Leg	Adult	0.63	0.61	-2.55	0.64	0.65	0.93	n/s
length)	(18-32y)	(0.05)	(0.10)	(12.98)	(0.07)	(0.84)	(8.05)	
Step width	Child	0.83	0.77	-5.78	0.92	0.88	-0.94	
Ratio	(8-12y)	(0.17)	(0.16)	(11.61)	(0.12)	(0.13)	(12.10)	
(SW/hip	Teenage	0.63	0.65	3.56	0.68	0.71	6.17	n/s
width)	(13-17y)	(0.17)	(0.20)	(23.02)	(0.13)	(0.13)	(8.58)	
	Adult	0.66	0.73	11.42	0.75	0.72	-4.27	
	(18-32y)	(0.20)	(0.23)	(22.77)	(0.13)	(0.21)	(20.06)	
#	Child	15.65	15.09	-0.88	15.05	15.11	2.79	n/s
% Double	(8-12y)	(3.05)	(2.00)	(9.09)	(1.39)	(1.29)	(7.76)	
Support	Teenage	17.67	13.25	0.13	15.80	16.65	1.40	
(% gait cycle	(13-17y)	(4.46)	(4.34)	(21.04)	(2.19)	(2.32)	(11.30)	
spent i DS)	Adult	16.74	14.21	11.81	16.04	16.58	2.43	n/s
	(18-32y)	(5.66)	(3.45)	(14.13)	(1.13)	(1.60)	(5.55)	
#	Child	33.43	32.47	-1.54	38.84	36.40	-5.15	n/s
Vertical trunk	(8-12y)	(7.75)	(5.82)	(13.83)	(5.21)	(5.48)	(7.35)	
Movement	Teenage	41.94	55.31	-4.97	42.11	41.26	-3.68	
(mm)	(13-17y)	(10.16)	(18.29)	(12.09)	(7.88)	(9.93)	(13.58)	
	Adult	42.38	52.98	0.72	40.03	39.21	-1.84	n/s
	(18-32y)	(12.86)	(19.60)	(16.11)	(8.61)	(8.15)	(6.99)	
#	Child	73.69	66.38	-2.95	60.22	59.51	11.36	n/s
Lateral trunk	(8-12y)	(22.77)	(21.85)	(24.52)	(21.95)	(13.16)	(35.57)	
Movement	Teenage	57.33	49.77	-11.87	53.82	53.99	-5.01	
(mm)	(13-17y)	(27.26)	(29.28)	(32.14)	(20.08)	(23.33)	(30.22)	
	Adult	54.73	52.71	16.43	66.21	65.78	-2.42	n/s
	(18-32y)	(20.08)	(23.90)	(67.87)	(31.90)	(37.78)	(16.65)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant. # = transformed data; Δ = failed transformation.

7.2.6.3. Angles of the head and trunk

As there was no significant difference in the angle of the head and trunk over the four phases of gait, this factor has been collapsed for the following analysis.

7.2.6.3.1. Head angles

Two participants from the teenage age group (1x DCD and their matched TD control) had to be removed from this analysis because the forehead marker was obscured. This left 68 participants (34 DCD, 34 TD group), divided by age into; child $n = 24$, teenager, $n = 22$, adult $n = 22$.

Results from the ANCOVA revealed that order of walking trial made no difference to the significance percentage difference in head angle ($F(1,61) = 1.537$, $p = 0.220$, $\eta^2 = 0.025$). There was a significant main effect of age ($F(2,61) = 3.779$, $p = 0.028$, $\eta^2 = 0.110$) for percentage difference in head angle. Post hoc tests reveal significant differences between teenage and adult age groups ($p = 0.029$), with the adults increasing their head angle (i.e. inclined upwards) more, (Clear tray, 4.02, Opaque tray = 6.32) for both tray carrying conditions than teenagers (Clear tray, -0.15 Opaque tray = -0.99) compared to walk condition. Figure 7.2 illustrates this effect. There were no group or age-by-group interactions for percentage difference from walk (F values ranged from 2.792 for group to 0.154 for condition-by-group).

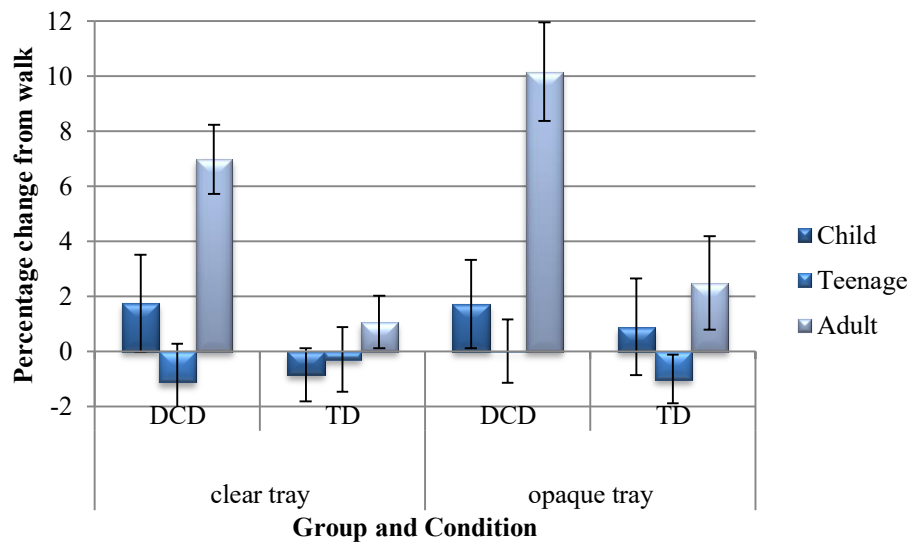


Figure 7. 2. Mean percentage change in head angle from level walking (clear tray, opaque tray). Error bars represent standard error.

Table 7.4. Means, (SD) for head angle between walking and walking holding a tray (clear and opaque), plus the percentage difference.

Measure	Age	DCD (n=29)			TD (n=29)			Significance
		Level walk (SD)	Walk + tray (SD)	Mean % change (SD)	Level walk (SD)	Walk + tray (SD)	Mean % change (SD)	
Walk + Clear Tray (Degree)	Child (8-12y)	72.66 (4.85)	73.76 (7.64)	1.75 (10.34)	76.86 (5.35)	76.09 (7.08)	-0.85 (5.67)	Age* [A > T]
	Teenage (13-17y)	69.88 (9.92)	67.66 (10.56)	-1.12 (8.14)	73.83 (10.86)	73.47 (10.74)	-0.29 (6.84)	
	Adult (18-32y)	71.77 (9.14)	77.03 (7.25)	6.98 (7.36)	78.38 (9.38)	77.45 (7.28)	1.07 (5.58)	
Walk + Opaque tray (Degree)	Child (8-12y)	72.66 (4.85)	73.59 (5.37)	1.73 (9.63)	76.86 (5.35)	76.54 (7.11)	0.89 (10.27)	
	Teenage (13-17y)	69.88 (9.92)	71.82 (8.97)	0.02 (6.73)	73.83 (10.86)	73.46 (11.25)	-1.01 (5.16)	
	Adult (18-32y)	71.77 (9.14)	78.90 (8.92)	10.17 (10.40)	78.38 (9.38)	79.82 (9.46)	2.48 (9.91)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant

7.2.6.3.2. Trunk angles

Results from the ANCOVA revealed that order of walking trial made no difference to the significance of percentage difference in trunk angle ($F(1,61) = 0.036, p = 0.851, \eta^2 = 0.001$). There were no group or age effects or any interactions for percentage difference from walk in trunk angles (F values ranged from 0.513 for group to 0.115 for condition-by-group-by-age).

Table 7.5. Means, (SD) for trunk angle between walking and walking holding a tray (clear and covered), plus the percentage difference.

Measure	Age	DCD ($n=29$)			TD ($n=29$)			Significance
		Level walk (SD)	Walk + tray (SD)	Mean % change (SD)	Level walk (SD)	Walk + tray (SD)	Mean % change (SD)	
Δ	Child	90.63	90.35	-0.70	88.82	89.54	1.87	n/s
Walk +	(8-12y)	(3.93)	(4.11)	(4.68)	(4.44)	(5.02)	(3.71)	
Clear	Teenage	86.62	88.57	2.41	89.17	87.42	-0.96	
Tray	(13-17y)	(3.96)	(5.15)	(4.32)	(4.17)	(5.44)	(3.85)	
(Degree)	Adult	1.39	92.12	-2.71	92.03	88.55	0.21	
	(18-32y)	(4.15)	(4.61)	(12.15)	(4.48)	(9.85)	(1.48)	
Δ	Child	90.63	90.52	-0.23	88.82	90.44	2.05	
Walk +	(8-12y)	(3.93)	(4.53)	(3.69)	(4.44)	(3.68)	(4.23)	
Opaque	Teenage	86.62	89.71	2.81	89.17	87.45	0.59	
tray	(13-17y)	(3.96)	(4.81)	(5.23)	(4.17)	(3.88)	(3.22)	
(Degree)	Adult	1.39	92.19	-3.40	92.03	87.88	0.15	
	(18-32y)	(4.15)	(4.16)	(13.17)	(4.48)	(10.65)	(2.08)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant.. Δ = failed transformation

7.2.7. Study 1. Discussion

Study1 investigated the role of visual occlusion of the feet on the locomotor adaptations of individuals with and without DCD whilst walking along level ground. This was achieved by comparing the percentage change from a *baseline measure* of level walking (discussed in Chapter 4) to a *visual manipulation* which occluded the feet whilst walking on level ground.

Visual occlusion of the feet did not impede the walking speed of any age or group. This outcome was surprising considering the results from Deconinck et al.'s (2006^b) study which reported that children with DCD walked more slowly than TD children when visual input was removed. However, Deconinck et al.'s (2006^b) study involved the removal of visual input completely for the walking task, with only a small LED target remaining visible, whereas the current study only occluded the feet. Additionally, the walking task differed slightly between studies as in the current study participants walked continuously for 2 minutes along a 6m walkway whereas in Deconinck et al.'s (2006^b) study participants walked along a 10m walkway and were instructed to look straight ahead. These differences would suggest, that when all visual information is removed, children with DCD are affected to a greater extent than their TD peers, but when only the feet are occluded there is little impact on walking speed for children, as well as teenagers and adults.

The only spatial measure in Study1 to exhibit significant effects were for proportional step length, with the DCD group showing an increase from level walking to walking with a tray compared to the TD group who marginally reduced their proportional step length. This was a surprising result, as previous research (Deconinck et al. 2006^b; Mon-Williams et al., 1999; Wilson & McKenzie, 1998) has identified that children with DCD are more reliant on visual information than their TD peers for movement. So one might expect the individuals with DCD in this study to be more affected by the loss of visual information about the whereabouts of their feet and adopt a 'safer' walking strategy using shorter steps. Initially it might appear that the longer stride length may have been an adaptive response to try and gather visual information about the whereabouts of the feet beyond the extremities of the tray. This would support research by Rösblad and von Hofsten (1994) and Smits-Engelsman et al. (2003) who argue that individuals with DCD rely on visual feedback from their limbs to a greater extent than typical individuals for the execution of movement. However this adaptation only occurred in the clear tray condition where they could see their feet anyway.

An explanation for why the DCD group would use a longer proportional step with the clear tray and not the opaque tray could be interpreted using the Constrained Action Hypothesis (Wulf, et

al., 2001). It could be speculated that the individuals with DCD used visual information about the whereabouts of their feet in the clear tray condition (visual information was available) increasing their internal focus of attention about the feet. However, during the covered tray condition, when visual information about the feet was not available, the individuals with DCD were forced to attend to the environmental constraints (i.e. external focus of attention) which resulted in more typical walking patterns.

The negligible findings from the current study provide an interesting comparison to the Hallemans, et al. (2010) study which suggested that the removal of vision, even on an uncluttered level terrain, can significantly affect dynamic stability and walking patterns for typically developing adults aged 26 years. Given the developmental contribution of vision to the mechanisms needed for locomotion such as the postural control system (Shumway-Cook & Woollacott, 1985; Hatzitaki, Zisi, Kollias, & Kioumourtzoglou 2002) maintenance of static balance (Wann et al., 1998), and efficient use of foveal and peripheral vision to negotiate the environment (Franchak & Adolph, 2010) it would be counterintuitive to consider the children in the current study having more mature sensory adaptations than the adults in the Hallemans, et al. (2010) study.

These seemingly conflicting findings may be the result of different methods as the Hallemans, et al. (2010) study removed all visual input for the typically developing participants and it could be hypothesised that the gait adaptations, argued to assist with dynamic balance, may be a manifestation of the total removal of vision. This was not the case in the current study and the different findings may therefore highlight the importance of optic flow to provide information on self-motion, together with feedforward information for planning and control of future steps.

It was hypothesised that for study 1, there would be a minimal impact on walking patterns for typically developing participants whilst walking on the level terrain, so this hypothesis was supported. However, it was also hypothesised that children with DCD would be differentially affected by the visual occlusion even whilst walking on the level terrain compared to their TD peers and other group members. This would predict that children with DCD would be additionally affected due to the maturational constraints on visual development (Wann, et al., 1998; Shumway-Cook & Woollacott, 1985; Hatzitaki, et al., 2002) coupled with a greater reliance on visual information for movement than their TD peers (Deconinck et al., 2006^a; Wilmut, et al., 2006; Deconinck, et al, 2006^b). As discussed this was not the case, and this age-by-group hypothesis cannot be supported. These findings support earlier findings from chapters 4, 5 & 6 that the developmental trajectory for individuals with and without DCD follows a similar route, even when visual information about the feet is occluded.

Study 1 has therefore failed to provide evidence to suggest that visual occlusion of the feet affected the walking patterns of children to a greater extent than adults, or individuals with DCD to a greater extent than their TD peers whilst walking on level terrain. However, it has provided useful information to add to previous research. For example, given the maturational constraints to visuo-perceptual development (Wann et al., 1998; Shumway-Cook & Woollacott, 1985), the effects of visual occlusion of the feet would predict a differential effect on gait adaptations of children compared to teenagers and adults. Additionally, studies that have investigated the effects of visual input on movement for children with DCD have identified that there is a disproportionate reliance on vision rather than proprioception or vestibular information during movement through the environment.

Deconinck et al. (2006)² illustrated that important visual information for guidance of the body through the environment came from peripheral vision. Wilmut et al. (2006) demonstrated that the important visual information to guide the arm to a target came from foveal vision. These findings would again predict greater gait adaptations from the children with DCD compared to their typically developing peers. However, this study has demonstrated that foveal vision of the feet was no more important for typical children or individuals with DCD for guidance of the body around this particular environment, where the terrain was stable.

Research by Land and Lee (1994) and Land & Hayhoe (2001) may provide some answers as they have illustrated that people use visual input to provide relevant information about the task in hand. Therefore foveal visual information of the feet may not have provided any information necessary to successfully negotiate the level and uncluttered walkway for any participants in the current study. These findings provide an interesting comparison with those of Chapter 4, where participants with DCD inclined their heads more towards the ground compared to their TD peers, which was hypothesized to highlight a greater need for the DCD group to ‘visually sample’ the terrain compared to the TD group to support their visual and proprioceptive deficits (Wilson and McKenzie, 1998; Wilmut, et al., 2006; Deconinck, et al., 2007).

Explanations for these seemingly contrasting findings may be provided by suggesting that it is the ground terrain, rather than information about the feet, that provides relevant information for the individuals with DCD. The lack of effect when visual information about the feet was occluded also suggests that participants were travel fixating as they walked along, optimising the use of optic flow. The fact that the DCD group looked down more may highlight they were fixating 1-2 steps in front rather than 2-3 steps identified by (Patla & Vickers, 1997) in TD adults. This may indicate a greater reliance on feedforward information, available through visual input, to accommodate less well coordinated movement patterns.

It is interesting to compare the results of this visual manipulation to the terrain manipulation in Chapter 6 which investigated differences in gait adaptations from walking on a level terrain to walking along an irregular terrain. Findings showed that both groups exhibited significant adaptations to the irregular terrain, walking more slowly using shorter, wider steps. However, group differences also revealed that the DCD group walked significantly more slowly and with shorter, wider steps, and inclined their heads towards the ground even more than their TD peers. These adaptations were argued to assist with stability when there are environmental and/or internal challenges to balance (Bierbaum et al., 2010; Marigold and Patla, 2008^b; Maki, 1997; Deconinck, et al., 2006^a). Additionally, both groups inclined their heads more towards the ground when walking on the irregular compared to the level terrain, but the DCD group inclined their heads towards the ground to a greater extent than their TD peers, indicating a greater need to visually sample the terrain for the DCD group.

Given the importance of encoding task-relevant visual information (Land & Lee, 1994; Land & Hayhoe, 2001) and the adaptations shown when proprioceptive information is less reliable (as the feedback from the irregular terrain is less predictable therefore more difficult to interpret) it could be argued from the findings of this study, that on-line visual sampling of the terrain and/or the position of the feet is more important when proprioceptive information is challenged (traversing an irregular terrain) than when visual feedback from the limbs is occluded but proprioceptive information is stable (traversing a level terrain). This is investigated in study 2.

7.3. Study 2 walking on irregular terrain

Given the lack of level terrains in the real environment, and the importance of fixating task-relevant information (Patla & Vickers, 1997 & 2003) to ensure safe navigation of the environment, the aim of Study 2 was to examine the effect of visual occlusion of the feet for individuals with and without DCD whilst walking on an irregular terrain. This manipulation extends the findings from Study 1, investigating the contribution of visual input from the feet to level walking, and those of Chapter 6, which investigated the differences in walking pattern whilst walking on an even compared to an irregular terrain in full vision, by investigating the contribution of proprioceptive and visual input from the feet to walking whilst traversing an irregular terrain. Findings from these investigations will deepen understanding concerning the visual planning skills for individuals with and without DCD when proprioceptive information from the feet is less reliable (as the ‘cobbles’ are compliant) and therefore harder to interpret.

There is a paucity of research exploring the use of visual information to traverse everyday irregular terrains for individuals with DCD. However, a few studies have investigated where typically developing adults look whilst negotiating complex ground terrains and the findings may be used to inform some predictions for individuals with DCD when negotiating irregular terrains. For example, Marigold and Patla (2007) invited seven TD adults to walk along an 8.5m x 1.5m walkway. The middle portion comprised six different 0.5m squares; 2xsolid, 3xrock, 1xslippery, 3xcompliant, 3xtilt, and 3xirregular surfaces. Gaze fixations were recorded using a head mounted eye tracker. This study has some limitations as the terrain was very complex, and not typical of everyday life, possibly contributing to an overestimation of object fixation when transferred to everyday life. Notwithstanding these limitations, the results contradicted previous research by Patla and Vickers (1997 & 2003) illustrating that less than 1% of all fixations were travel fixations. Instead, eyes fixated on objects relevant to safe foot placement. Whilst the disparity in task difficulty between studies is large, these studies highlight that as the terrain becomes more complex, frequent task relevant object fixations are necessary to ensure safe navigation through the environment. It must also be noted that the conditions in Patla and Vickers (1997 & 2003) studies were very stable and there was very little challenge to dynamic stability. In contrast traversing the terrain in Marigold and Patla's (2007) study may have challenged stability more and fixations may have been used to support balance.

This is a relevant point to the current study, given that foveal vision is used for areas within a scene which have a high proportion of relevant information, and peripheral vision to provide relevant information for future foveal attention (Rayner & Pollatsek, 1992; Land & Hayhoe, 2001). Where people look is, to some extent dependent upon the relative importance placed on visual information about the whereabouts of the feet to negotiate the terrain.

Marigold and Patla (2008^b) further explored the importance of vision for negotiating multi-surface terrain, by designing a study to remove vision from the lower visual field. Ten typically developing young adults (mean 26 years) and 10 older adults (mean 74 years) walked along a wooden walkway (8.5m x 1.5m) similar to the one used in the Marigold and Patla (2007) study, under two visual conditions; with and without special glasses that blocked vision from the lower visual field. Spatio-temporal gait parameters were measured together with head pitch angle which was used to indicate where participants were looking. The results show that when the lower visual field was occluded all participants walked more slowly and with shorter steps, thus demonstrating a more cautious gait pattern often observed in challenging situations (Menz, et al., 2003^b). Additionally, both young and old participants increased their head pitch downwards,

which the authors suggest demonstrates adaptive behaviour to increase the amount of visual information from the lower visual field when traversing an irregular terrain.

7.3.1. Study 2 Hypotheses

Given that individuals with DCD rely on vision more than their TD peers for movement (Discussed in 7.2) and the findings discussed in Chapter 6, where individuals with DCD adopted a ‘safer’ walking strategy to traverse the irregular terrain compared to their TD peers it is hypothesised that individuals with DCD will walk slower with shorter, wider steps and greater trunk inclination than their TD peers when walking on an irregular terrain without visual feedback from the feet.

Additionally, given that typically developing adults travel fixate 2-3 steps ahead (Patla & Vickers, 1997, 2003), it is hypothesised that visual occlusion of the feet will have little effect on gait parameters for this population whilst walking on irregular terrain.

Furthermore, given the maturational constraints to visuo-perceptual development (Wann, et al., 1998; Shumway-Cook & Woollacott, 1985; Sparto, et al., 2006), and the reliance of information from the supporting surface processed through the feet (Assaiante & Amblard, 1993 & 1995) it is hypothesised that the effects of visual occlusion of the feet will affect the gait adaptations of children more than teenagers and adults.

Finally, children with DCD have shown significant differences in walking patterns compared to their TD peers walking in complete darkness (Deconinck et al. 2006^b), this together with the ‘safer’ walking strategy used by individuals with DCD compared to their TD peers to traverse the irregular terrain (discussed in Chapter 6), predicts that there will be significant group differences between children, but group differences will be smaller for the teenage and adult age ranges (Visser et al., 1998, Cousins and Smyth, 2003). Therefore an age-by-group interaction is hypothesised.

7.3.2. Methods

The methods, participants and materials used were identical to those described in Study 1, with the exception of the walkway which was the same length and width but was uneven with ‘flat cobbles’ (9cm wide x 10cm long x 2cm high) stuck at irregular intervals to make the pathway irregular to walk along (a detailed description is provided in Chapter 3).

7.3.3. Data analysis

In order to investigate the effects of visual occlusion of the feet whilst walking along an irregular terrain (as reported in Chapter 6), all measures were calculated using percentage changes between (1) walking along an irregular terrain (irregular walk) and walking on an irregular terrain carrying a clear tray (irregular walktray) and (2) walking along an irregular terrain (irregular walk) and walking on an irregular terrain carrying an opaque tray (irregular walkopaquetray). This ensured that any differences in walking patterns are not due to carrying a tray (irregular walk to irregular walktray), but rather due to the manipulation of removing vision (irregular walk to irregular walkopaquetray).

7.3.4. Statistical analysis

Mean percentage differences between walking conditions (1. Irregular walk; Irregular walk with tray; 2. Irregular walk; Irregular walk with opaque tray) were calculated for all spatio-temporal 'measures for each participant individually. This information was entered into statistical analysis using three-way repeated measures ANCOVA's to partial out the effect of order of trial presentation (discussed in Chapter 3) whilst investigating the effects of group (DCD, TD) and age (Child, Teenage, Adult) and condition (irregular walktray; irregular walkopaquetray) on the spatio-temporal measures of walking speed, proportional step length, step width ratio, percentage gait spent in double support, vertical and lateral movement of the trunk together with the percentage changes in the angles of the head and trunk whilst walking in the conditions described above. Significant effects were explored as for study 1.

7.3.5. Results

Means and standard deviations for walking speed are shown in Table 7.6. Means and standard deviations for spatio-temporal measures whilst walking and walking holding a tray plus the percentage difference can be seen in Table 7.7. for the irregular walktray condition and Table 7.8. for the irregular walk opaquetray condition.

All data reported in tables 7.6 – 7.8 contains both the percentage change and also the raw scores. Statistical analysis was completed on the percentage change only.

Not all data were normally distributed; therefore when transforming (Log10) was successful the transformed data are reported (signified with #).

7.3.5.1. Spatio-temporal measures

For walking speed one teenager with DCD and their matched pair had to be removed from the analysis as the chest marker was obscured from the camera lens, so there was no speed calculated in MATLAB. This left 68 participants (34 DCD, 34 TD) divided by age into child $n = 24$, teenage $n = 22$, adult $n = 22$.

Results from ANCOVA revealed that order of walking trial not did make a difference to the significance of walking speed ($F(1,61) = 0.436$, $p = 0.511$, $\eta^2 = 0.007$). No significant age, group or age-by-group interactions effects were found when comparing percentage change in walking speed between walking along an irregular terrain and walking along an irregular terrain holding a clear tray; and walking along an irregular terrain and walking along an irregular terrain holding an opaque tray (F values ranged from 0.113 for group to 2.131 for condition-by-group).

Table 7.6. Means (SD) for speed (m/s) whilst walking and walking holding a tray over irregular terrain plus the percentage difference.

Speed m/s	Age	DCD Mean (SD)			TD Mean (SD)			Signific. [Post hoc]
		Irregular Walk	Irregular Tray	Mean % change	Irregular Walk	Irregular Tray	Mean % change	
Uneven walk + Clear Tray	Child (8-12y)	0.56 (0.18)	0.49 (0.21)	-7.77 (33.80)	0.74 (0.19)	0.73 (0.19)	-1.18 (16.69)	n/s
	Teenage (13-17y)	0.81 (0.20)	0.73 (0.23)	-7.85 (24.18)	0.88 (0.23)	0.88 (0.21)	7.47 (35.73)	
	Adult (18-32y)	0.64 (0.12)	0.64 (0.27)	-3.18 (37.48)	0.97 (0.16)	0.87 (0.18)	-6.96 (5.24)	
Uneven walk + Opaque tray	Child (8-12y)	0.56 (0.18)	0.54 (0.15)	7.09 (42.38)	0.74 (0.19)	0.76 (0.17)	5.82 (23.00)	n/s
	Teenage (13-17y)	0.81 (0.20)	0.81 (0.24)	1.59 (17.69)	0.88 (0.23)	0.86 (0.25)	0.73 (23.44)	
	Adult (18-32y)	0.64 (0.12)	0.64 (0.16)	0.71 (14.58)	0.97 (0.16)	0.87 (0.16)	-6.30 (5.37)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant # = transformed data

Results from ANCOVA revealed that order of walking trial not did make a difference to the significance of **Percentage time spent in Double Support** ($F(1,63) = 1.378, p = 0.245, \eta^2 = 0.021$). There were significant condition effects ($F(1,64) = 8.920, p = 0.004, \eta^2 = 0.122$) in percentage differences from walking on an uneven terrain compared to walking on an uneven terrain with a clear tray, and from walking on an uneven terrain compared to walking on an uneven terrain with an opaque tray. Mean values reveal that for the clear tray condition percentage time spent in double support increased marginally by 1.5%, but for the opaque tray condition this increased to 5.9%. Results from ANCOVA revealed that order of walking trial not did make a difference to the significance of **Proportional step length** ($F(1,63) = 1.215, p = 0.275, \eta^2 = 0.019$); **Step width ratio** ($F(1,63) = 1.818, p = 0.182, \eta^2 = 0.028$); **Vertical movement of the Trunk** ($F(1,63) = 0.463, p = 0.499, \eta^2 = 0.007$); **Lateral movement of the Trunk** ($F(1,63) = 0.002, p = 0.964, \eta^2 = 0.000$).

There were no significant group or age effects, or any interactions for the measures of **Proportional step length** (F values ranged from 0.155 for condition-by-group to 2.505 for condition-by-age), **Step Width Ratio** (F values ranged from 0.093 for condition-by-age-by-group to 2.517 for group-by-age), **Vertical** (F values ranged from 0.032 for group-by-age to 3.862 for group) and **Lateral movement of the Trunk** (F values ranged from 0.092 for age to 2.334 for condition-by-group-by-age) for percentage differences between walking on an uneven ground compared to walking on an uneven ground carrying a clear tray or an opaque tray.

Table 7.7. Means (SD) for spatio-temporal measures whilst walking and walking holding a *clear tray* over irregular terrain plus the percentage difference.

Measure	Age	DCD Mean (SD)			TD Mean (SD)			Significance [Post hoc]
		Irregular Walk	Irregular cleartray	Mean% change	Irregular Walk	Irregular cleartray	Mean% change	
Prop step Length (SL/Leg length)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	0.52 (0.12) 0.50 (0.10) 0.50 (0.07)	0.51 (0.10) 0.53 (0.09) 0.51 (0.11)	-0.88 (11.95) 7.99 (19.81) 1.60 (21.81)	0.60 (0.08) 0.60 (0.07) 0.62 (0.08)	0.61 (0.06) 0.62 (0.09) 0.61 (0.09)	2.22 (541) 3.14 (12.01) -0.31 (8.90)	n/s
# Step width ratio (SW/hip width)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	1.12 (0.25) 0.65 (0.15) 0.92 (0.29)	1.05 (0.29) 0.76 (0.26) 0.73 (0.26)	2.04 (9.36) 16.04 (19.41) -10.54 (25.50)	1.03 (0.19) 0.75 (0.14) 0.71 (0.21)	1.00 (0.14) 0.78 (0.10) 0.73 (0.25)	2.37 (16.14) 7.53 (34.81) 4.52 (10.65)	
% Double Support (% gait cycle spent in DS)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	22.64 (6.25) 19.21 (7.85) 20.19 (5.45)	25.21 (7.68) 16.37 (7.52) 20.67 (6.73)	10.87 (12.56) -6.89 (19.81) 1.14 (18.36)	20.66 (2.91) 19.49 (5.62) 18.87 (1.51)	20.92 (2.78) 19.38 (1.80) 20.67 (3.61)	1.70 (8.82) -1.99 (6.81) 4.72 (9.93)	Condition* [opaquetray >cleartray]
# Vertical trunk Movement (mm)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	36.34 (12.99) 52.32 (12.82) 47.56 (15.97)	36.18 (7.99) 56.66 (19.30) 49.52 (19.50)	8.35 (36.61) 8.76 (26.99) 13.92 (46.34)	40.53 (5.50) 44.16 (10.52) 41.56 (10.74)	40.38 (7.32) 43.93 (10.11) 39.53 (9.43)	-0.66 (8.98) -0.11 (12.98) -6.72 (10.84)	
# Lateral trunk Movement (mm)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	90.29 (27.99) 57.52 (28.96) 86.37 (33.69)	101.09 (16.13) 61.48 (28.70) 88.29 (40.41)	26.32 (60.1) 14.06 (45.79) 4.39 (27.60)	74.73 (16.85) 77.26 (17.26) 84.22 (29.49)	70.53 (11.78) 74.76 (25.60) 87.72 (30.73)	-1.93 (24.05) -0.46 (37.88) 5.05 (13.34)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant

= transformed data

Table 7.8. Means (SD) for spatio-temporal measures whilst walking and walking holding a *opaque tray* over irregular terrain plus the percentage difference.

Measure	Age	DCD			TD			Significance [Post hoc]
		Irregular Walk	Mean (SD) Irregular opaqtray	% change	Irregular Walk	Mean (SD) Irregular opaqtray	% change	
Prop step Length (SL/leg length)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	0.52 (0.12) 0.50 (0.10) 0.50 (0.07)	0.53 (0.10) 0.52 (0.10) 0.48 (0.10)	3.67 (19.45) 6.04 (23.09) -3.04 (18.73)	0.60 (0.08) 0.60 (0.07) 0.62 (0.08)	0.62 (0.06) 0.59 (0.08) 0.60 (0.07)	3.87 (6.38) -1.22 (8.60) -3.36 (5.95)	n/s
Step width ratio (SW/hip width)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	1.12 (0.25) 0.65 (0.15) 0.92 (0.29)	1.02 (0.29) 0.77 (0.20) 0.80 (0.21)	2.35 (14.31) 10.06 (24.43) -7.11 (26.04)	1.03 (0.19) 0.75 (0.14) 0.71 (0.21)	1.02 (0.15) 0.79 (0.13) 0.78 (0.21)	3.01 (15.19) 6.05 (21.92) 12.56 (21.47)	
% Double Support (%gait cycle spent in DS)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	22.64 (6.25) 19.21 (7.85) 20.19 (5.45)	24.28 (5.84) 18.00 (7.87) 21.79 (6.12)	8.46 (10.06) 0.16 (23.61) 8.42 (22.89)	20.66 (2.91) 19.49 (5.62) 18.87 (1.51)	21.57 (3.46) 20.50 (2.50) 20.89 (3.70)	4.74 (11.94) 6.11 (9.93) 7.82 (8.67)	Condition* [opaquetray >cleartray]
# Vertical trunk Movement (mm)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	36.34 (12.99) 52.32 (12.82) 47.56 (15.97)	37.97 (9.23) 54.29 (23.00) 42.87 (11.44)	12.91 (40.28) 9.94 (32.28) -3.24 (21.23)	40.53 (5.50) 44.16 (10.52) 41.56 (10.74)	41.16 (8.55) 44.28 (6.59) 39.27 (8.42)	1.71 (16.94) -1.62 (25.52) -7.47 (10.01)	
# Lateral trunk Movement (mm)	Child (8-12y) Teenage (13-17y) Adult (18-32y)	90.29 (27.99) 57.52 (28.96) 86.37 (33.69)	90.09 (21.12) 62.03 (35.31) 87.01 (37.30)	9.15 (47.28) 18.14 (61.33) 1.14 (19.74)	74.73 (16.85) 77.26 (17.26) 84.22 (29.49)	74.72 (16.06) 69.54 (15.03) 88.62 (25.58)	1.31 (14.61) -8.43 (17.89) 11.41 (31.59)	

Key; * p = significant to 0.05 level; ** p = significant to 0.001 level; n/s = not significant.

= transformed data

7.3.5.3. Angles of the head and trunk

Head angles

Four participants, (1x Adult; 2x Teenager; 1x Child and their matched controls) had to be removed from this analysis, as the forehead marker was obscured from the cameras. This left 62 participants (31 DCD, 31 TD group), divided by age into; child $n = 22$, teenager, $n = 20$, adult $n = 20$.

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of percentage change in head angle ($F(1,55) = 0.956, p = 0.905, \eta^2 = 0.000$). However, There were significant condition effects ($F(1,56) = 6.102, p = 0.017, \eta^2 = 0.098$) indicating that overall the percentage change in angles of the head were differentially affected by the two tray carrying conditions (clear and opaque tray). Illustration in Figure 8.4 reveals that, whilst all groups increased their head angle (look up) from walking on an uneven to walking whilst carrying a tray, it is more evident in the opaque tray condition.

There were no other significant age, group or age-by-group-by-condition interactions effects for percentage differences between walking on an uneven ground compared to walking on an uneven ground carrying a tray or an opaque tray (F values ranged from 0.019 for condition-by-age to 1.852 for condition-age-by-group).

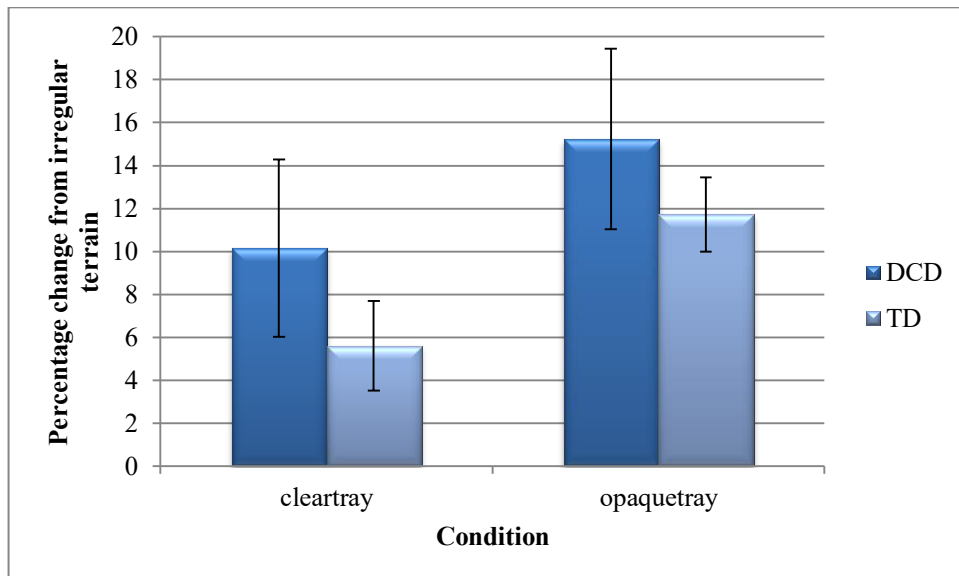


Figure 7.4. Condition effects for change in angle of the head whilst walking on irregular terrain carrying a clear tray and an opaque tray. Error bars represent standard error.

Trunk angles

Results from the ANCOVA revealed that order of walking trial did not make a difference to the significance of percentage change in trunk angle ($F(1,59) = 2.113, p = 0.151, \eta^2 = 0.035$)

There were no significant group, age or interaction effects for percentage change in trunk angle (F values ranged from 0.022 for age to 1.827 for condition-by-age-by-group), indicating that both groups and all three ages adapted to the experimental manipulations in a similar manner.

7.3.6. Discussion of Study 2

Study 2 developed the findings of study 1 by investigating effects of visual occlusion of the feet whilst traversing an *irregular terrain* on the walking patterns of individuals with and without DCD aged 8-32 years. This was achieved by comparing the percentage change from a *baseline measure* of walking along an irregular terrain (discussed in Chapter 7) to a *visual manipulation* which occluded the feet whilst walking along an irregular terrain.

Results from the current study reiterated those found in study 1, as visual occlusion of the feet did not impede the walking patterns of any age or group whilst traversing the irregular terrain, thus indicating that the visual manipulation affected all participants similarly. This is a surprising result given the findings from Chapter 6 and research with individuals with and without DCD. Both groups show the additional need for visual feedback to support balance whilst negotiating a complex environment (Marigold and Patla, 2007 & 2008^b; Deconinck, et al., 2007; Deconinck, et al., 2006^b). These additional demands would predict greater accommodations to the visually deprived condition possibly manifesting in a ‘safer’ walking strategy to preserve dynamic stability (Marigold & Patla, 2007). Additionally, individuals with DCD have shown a specific need for visual feedback from the limbs when making reaching movements directed towards a target, as in the Wilmut et al. (2006) study and the Smits-Engelsman, et al., (2003), although this was not replicated in the Rösblad and von Hofsten (1994) study, where the target was not as precisely defined.

These contrasting results, and those from the current study, may highlight different strategies used by individuals with DCD to reach for a specific target with the hand (as in Wilmut et al., 2006 and Smits-Engelsman, et al., 2003) compared to the continuous movement requirements of walking. Therefore, for individuals with DCD, guiding a limb towards a specific target requires a greater reliance on visual information, than for TD controls, but to guide the body whilst walking around the environment does not require greater reliance on visual information of the whereabouts of the feet, even on an irregular terrain.

It could be speculated that these results highlight ceiling effects whilst walking on the irregular terrain (Chapter 6) where both groups (DCD & TD) inclined their heads more towards the ground when walking on the uneven compared to the level terrain. For example, group differences showed that the DCD group were more affected by the irregular terrain than the TD group, inclining their heads towards the ground to a greater extent than their TD peers. Thus there may come a point where any further head incline would destabilise the whole 'system' as it walks over the irregular terrain. Alternatively, it could be a protective mechanism for the vestibular system which, as it is situated in the inner ear, makes it very sensitive to movement of the head as it provides a stable frame of reference for interpretation of environment information (Assaiante & Amblard, 1993; Berthoz, and Pozzo, 1994). Any unnecessary increase in head movement can affect head stabilisation (Assaiante et al., 2011), which may add noise to sensory information making interpretation difficult. Noisy sensory information may subsequently negatively affect the feedback/feedforward model (Pozzo, et al., 1990; Berthoz & Pozzo, 1998), and subsequently the effectiveness of motor responses (Assaiante, et al., 2011). This explanation can only be hypothesised at this stage but further research would be useful to unpick these effects.

Comparing the findings from the study in Chapter 6 to the current study, may expand upon this hypothesis. When visual information about the feet/terrain was available, individuals with DCD relied on it to a greater extent than their TD peers, as evidenced by greater incline in the head towards the ground. However, in the current study where visual information concerning the feet/terrain was occluded the individuals with DCD did not incline their heads towards the ground to try and visually sample the immediate environment, but utilised the same strategies as their TD peers.

There are two possible hypotheses to explain this phenomenon. Firstly, a more upright head angle may assist with the assimilation of sensory information and explain why group differences in gait patterns were not apparent. This would suggest that the DCD group looked further ahead to gather visual information about the upcoming environment and were therefore 'forced' to utilise this information in the same way as the typically developing individuals, again perhaps supporting typical movement adaptations to environmental constraints. Secondly the Constrained Action Hypothesis (Wulf, et al., 2001) would predict that for the DCD group the use of visual information when available, as in Chapter 6, increased the internal focus of attention (whereabouts of the legs) which had a detrimental effect on walking pattern. However, when the individuals with DCD were 'forced' to attend to environmental features, due to visual occlusion

of the feet, the increased external focus of attention resulted in better self-organisation of the motor system, manifesting in typical walking patterns.

Study 2 did show some condition effects as all participants spent longer in double support during the opaque compared to the clear tray condition. These findings suggest that the removal of visual information from the feet whilst traversing the irregular terrain did cause some instability as this is an adaptive strategy to assist with balance difficulties (Menz, et al., 2003^b). However it is surprising that there were no group differences in this gait adaptation, as previous evidence has shown that some individuals with DCD have issues with balance and rely on visual input to a greater extent than their TD peers (Wann et al., 1998; Macnab et al., 2001). The results from this study contrast with Deconinck et al.'s (2006^b) study where they found an increase in percentage of the gait cycle spent in double support for the DCD group from the visual to the no vision condition, but changes for the TD group between conditions were negligible. The different methods used in these two studies, discussed in section 7.1.4., highlights the importance of information from optic flow for maintaining dynamic balance, particularly for individuals with DCD. It is encouraging that individuals with DCD adopted the same strategy as their TD peers to stabilise their walk on the irregular terrain when their feet were occluded, as it shows a typically adaptive response. However, comparisons with Deconinck et al.'s (2006^b) study suggest that this appears only to occur when all visual information from optic flow is available.

As for study 1 an age-by-group interaction was hypothesised, however findings from the current investigation support the null-hypothesis that individuals with and without DCD follow a similar developmental trajectory for the variables discussed above, even whilst walking along an irregular terrain. It could be argued that it is group membership, rather than age, that affects the outcome of significant differences in the current study.

One final condition effect from study 2 showed that all participants looked up more in the opaque tray compared to the clear tray condition whilst walking along the irregular walkway. This suggests that the participants travel fixated as they walked. These results support the findings from Patla and Vickers (2003) and Franchak and Adolph (2010) who argue that typical adults travel fixated even when traversing challenging terrains and that peripheral vision can be used to successfully negotiate complex and irregular terrains. Conversely, these results provide an interesting comparison to the Marigold and Patla (2008^b) study which suggested that removal of vision from the lower visual field significantly affected the gait of adults whilst negotiating multi-surface terrain. Participants walked more slowly and used shorter steps, which the authors argue demonstrates a more cautious gait pattern often observed in challenging situations.

Furthermore, the greater head pitch downwards in the Marigold and Patla (2008^b) study was argued to demonstrate an adaptive behaviour to increase the amount of visual information from the lower visual field. However, the glasses used to remove vision from the lower visual field had a completely blocked lower portion thus limiting optic flow as well as obscuring the lower visual field. Therefore the contrasting results may signpost a confound as when only information from the feet was obscured and optic flow left intact, as in the current study, then participants were able to use peripheral vision to negotiate the irregular terrain. Alternatively, given that the tray was only 15cm deep it only covered information from the feet, which, as discussed may not be relevant enough to the task to affect walking patterns. However, a slightly larger tray, occluding information about ground terrain just beyond the extension of the foot trajectory, may conceal relevant information and better replicate real life situations when carrying items at the front of the body.

7.4. General conclusions of study 1 and 2

The two manipulations discussed in this chapter explored the effects of visual occlusion of the feet whilst walking on level ground and over irregular terrain. This design enabled the investigation of the visual planning skills needed to traverse both a level and an irregular terrain, together with the efficiency of feedback strategies used when proprioceptive information from the feet may be difficult to interpret. By applying the hypothesis that the most challenging condition will manifest in the greatest gait adaptations, separating the studies in this way allowed for the identification of the most important mechanisms required to negotiate the environment. However, findings from these two studies have shown that adaptations to the visual manipulation for both groups and all ages are negligible, when walking on a level and an irregular terrain. Furthermore, the lack of interaction effects shows a similar developmental progression for both groups. The findings suggest that when visual information about the feet is occluded individuals with and without DCD can traverse everyday terrains anchoring their gaze a few steps ahead (travel fixate) as they walk (Patla & Vickers, 1997).

To conclude, the findings from the current two studies show that visual occlusion of the feet has a minimal impact on the walking patterns of individuals with and without DCD when walking on a level and an irregular terrain. However, analysing the results alongside those from Chapter 6 tentatively shows that the way in which visual information is used can hinder as well as support motor control (Wulf et al 2001); depending upon the area of focus. For example, the findings from Chapter 6 show that gait adaptations were greater when traversing an irregular terrain (compared to a level surface) in *full vision*, compared to negotiating either a level or an

uneven with the feet occluded (compared to full vision, Chapter 7). Taken together, these findings suggest that for both groups walking on an irregular terrain is more challenging than having vision of the feet occluded. Furthermore, these findings suggest that the task was perceived as more difficult by the DCD group given the greater gait adaptations shown by the DCD group compared to their TD peers. However, when the DCD group were ‘forced’ to look ahead, as in the current study, gait adaptations were comparable to those of the TD participants.

It may therefore be speculated that for individuals with DCD to successfully negotiate the environment, they need to ‘*look up*’ and focus visual attention on external constraints. At this stage it is unclear whether this benefits movement due to (1) travel gazing (Patla & Vickers, 1997); optimising information from *optic flow* (Gibson, 1966), (2) the use of *feedforward processing* to regulate movement accommodations (Patla, 1997) or (3) the use of an *external focus of attention* to assist with the automaticity of walking (Wulf, et al., 2002). However, given the importance (and reliance upon) of visual information for access to everyday activities, this it is an area worthy of future research.

These results indicate that when negotiating a fairly predictable every day, irregular terrains, individuals with DCD adopt similar strategies to those applied by typically developing individuals, *as long as they travel gaze, optimising information from optic flow*. They would also suggest that the DCD group can use appropriate feedforward information strategies to adjust their lower limbs to the changing environmental conditions they encountered on the uneven, when ‘forced’ to look ahead.

Chapter 8: General Discussion

8.1. Introduction

Competence in walking must be considered a core skill necessary for many activities of daily living, and although a mundane skill it is not a simple task. As discussed, walking involves the ability to correctly interpret different environmental conditions and to produce simultaneous, coordinated motor responses. Given the findings from research identifying difficulties in areas such as poor lower limb movement control (Rosengren et al., 2009), the use of feedforward information (Wilmot et al., 2006; Smits-Engelsman, et al., 2003; Hyde & Wilson, 2010), and sub-optimal cross modal sensory integration (Wilson & McKenzie, 1998; Deconinck et al., 2007), it is not surprising that Wilson, et al.'s (2013) meta-analysis identifies gait as one of the areas of pronounced difficulty for individuals with DCD. However, to-date there is a paucity of research in this area, the importance of which cannot be underestimated.

Efficient walking patterns provide the individual with the basic movement skills to participate in many activities of daily living, such as walking to school, work or social activities. However, even-though DCD is a lifelong condition (Losse et al., 1991; Cousins & Smyth, 2003; Kirby et al., 2010) there are no studies investigating the walking patterns of adults with DCD.

Furthermore, the implications for poor walking skills for adults are serious as for many adults with DCD walking is the only form of transport they can independently access, as driving and cycling are particularly difficult tasks for this population to master (Cousins & Smyth, 2003). Investigating walking patterns with this age group is therefore an area of much needed research.

The principle aim of this thesis was to characterise gait patterns in children and adults with DCD and, by comparing these patterns to typically developing peers it endeavoured to identify factors linked to poor locomotor ability for this population. An important element of this study was to address some of the methodological limitations of previous work in this area. These issues were addressed by using stringent inclusion criteria for the participants with DCD, and data were collected within a realistic, but controlled laboratory environment. This thesis builds upon the small number of previous studies that have investigated the walking patterns of children with DCD (under 12 years of age) as it was conducted across a broader age range of individuals (aged 8-32 years), to identify both group differences and developmental trends.

In order to consider the control of gait in individuals with DCD it was important to start by looking at level walking, where the task constraints are minimal. An initial study was conducted to quantify the gait pattern parameters in individuals with and without DCD during *level*

walking. However, walking within such a simplistic environment is not fully representative of real life, as it is rare that we walk on an uncluttered flat terrain. Therefore this thesis further examined gait adaptations for individuals with and without DCD to two distinct manipulations, namely: walking along an *irregular terrain* and walking with *reduced visual feedback*. Thus examining the planning skills required to maintain functional walking patterns under different sensory conditions. This final chapter collates the key findings and discusses the theoretical and practical implications of atypical walking patterns for individuals with DCD.

This research addressed the following questions:

1. Are there differences in gait patterns between individuals with and without DCD whilst walking on level ground?
2. Given any differences in gait pattern for the two groups observed in relation to Question 1, are these exacerbated when walking over an irregular terrain?
3. Does visual occlusion of the feet differentially affect gait patterns between individuals with and without DCD
 - i) Whilst walking on level ground?
 - ii) Whilst walking on irregular terrain?
4. Are there significant age effects or interactions between individuals aged 8-32 years with and without DCD for any of the above questions?

These questions will now be addressed in turn;

8.2. Overall findings

8.2.1. Question 1.

Are there differences in gait pattern between individuals with and without DCD whilst walking on level ground?

Initial findings from study 1, discussed in Chapter 4 investigated gait patterns for individuals with and without DCD whilst traversing a level, uncluttered terrain. Findings showed that, after controlling for the effect of order of trial presentation, a group effect for proportional step length was revealed, with the DCD group walking with a significantly shorter proportional step length than their TD peers. As discussed these findings support previous research by Deconinck et al. (2006^a) who found that children with DCD used a shorter step whilst walking on a treadmill.

To further describe gait patterns analysis of angular rotations of the lower limbs was performed. This extended previous research by Deconinck et al. (2006^a) and Rosengren, et al. (2009) investigating how individuals with and without DCD coordinate the joints and limb segments of the lower limbs, as they walk over level ground, rather than on a treadmill. Findings from the current study support those of Deconinck et al. (2006^a) as both studies revealed differences at the foot and ankle with the DCD group significantly more flexed at the ankle with greater upwards incline for the foot than their TD peers. Deconinck et al. (2006^a) argues that the ‘safer’ walking strategy shown by the shorter step length for individuals with DCD compared to controls suggests an adaptive gait pattern designed to support problems with balance or neuromuscular control.

Whilst causality at this stage cannot be confidently assigned as further analysis is needed, evidence from Deconinck et al (2006^a), Raynor (2001) and Diamond, et al. (2014) support the hypothesis of lower muscular strength in the DCD group negatively affecting walking patterns. The emerging evidence, from the current study suggests that individuals with DCD may adopt a less efficient ‘hip strategy’, pulling the leg forward at the hip rather than pushing the leg from the ankle. This compensatory use of the hip has been reported in elderly gait and is attributed to lower muscle strength at the ankle (DeVita and Hortobagyi, 2000). Additionally, this strategy has been seen in children with Down syndrome and in this case is attributed to muscle hypertonia (Galli, Cimolin, Patti, Heaney, Albertini, et al., 2010). Hypertonia, a lack of elastic tension and resistance in the muscles, has previously been associated with decreased strength and hypermobile joints (Martin, Inman, Kirschner, Deming, Gumbel, and Voelker, 2005), a condition also associated with DCD (Kirby & Davies, 2007).

An alternative hypothesis could explore the effect of balance constraints on walking patterns of individuals with DCD, with a reduced step length used as an adaptive response to difficulties in this area. This hypothesis would be supported by findings from research with older walkers who use a shorter step to assist with balance constraints (Lord et al, 1996; Winter et al 1990; Woollacott & Tang, 1997) and several studies by Deconinck et al. (2006^a; 2010).

Finally, the results may show how individuals with DCD have more difficulty controlling their limbs to successfully negotiate the environment (as argued by Deconinck et al., 2009). Support for this argument came from analysing the head angle data, as individuals with DCD inclined their heads further towards the ground than their TD peers. This was argued to support previous research by Deconinck, et al. (2007) and highlights a greater need for the DCD group to ‘visually sample’ the terrain/feet compared to the TD group. It was argued that this could highlight difficulties for individuals with DCD adjusting to changes in proprioceptive, visual

and vestibular information (Wilson & McKenzie, 1998, Wann, et al., 1998; Deconinck, et al., 2007). Additionally, the increased forward head incline may illustrate that individuals with DCD travel fixate only 1-2 steps in front compared to the 2-3 steps identified by Patla and Vickers (1997) for typically developing adults.

Measures of variability revealed group differences, supporting Woodruff et al. (2002), Cherg et al. (2009) and Deconinck et al. (2010) who have shown significant group differences, with the DCD group being more variable than their TD peers. The implications of increased variability whilst walking are serious, Maki (1997) propose that step length variability can destabilise the trunk and increase the likelihood of falling. Kuo and Donelan (2010) argue that environmental noise can affect error management, which may reduce the accuracy of reactive adjustments manifesting in misplaced and variable foot placement.

The construction of poor internal models can explain how step-to-step variability can increase for populations such as those with DCD whose integration of essential sensory information for individuals is sub-optimal. If the internal model has not received accurate sensory information then it will not be able to provide a reliable forward model to the motor system and error management will subsequently require greater feedforward-feedback interaction. If this occurs during a repetitive task such as walking, it is easy to see how walking patterns will be more variable, and less efficient. The attentional cost of this may affect the automaticity of walking for individuals with DCD, as attentional resources are needed to adjust movements to accommodate environmental and task constraints. Furthermore, this hypothesis may support anecdotal evidence that individuals with DCD complain of tiredness when performing gross movement tasks.

Exploring these findings within an Ecological systems approach, incorporating Newell's constraints model (Newell 1986) it can be argued that even within a very safe and predictable *environment* (level and uncluttered terrain) where the *task* constraints are minimal; the *individual* constraints for people with DCD severely inhibit the efficiency with which they can negotiate the environment. These results provide a novel addition to the DCD literature as it shows the increased variability that individuals with DCD have to contend with in very predictable situations. Findings that show increased step-to-step variability continues to adulthood for individuals with DCD suggest that the variability cannot just be attributed to immaturity of the perceptuo-motor system.

Finally, inter-leg symmetry between the three leg segments (thigh, shin and foot) was investigated to further explore the mechanisms controlling the gait patterns of individuals with and without DCD. . It was hypothesised that there would be some asymmetry in the gait patterns of individuals with DCD, in line with Rosengren et al. (2009) This hypothesis was confirmed as the individuals with DCD had a significantly more asymmetric proportional step length ratio than their TD peers. This was argued to illustrate sub-optimal control of all the different elements necessary to produce systematic, coordinated walking patterns. Several studies have investigated the relationship between balance difficulties and asymmetrical gait for elderly fallers and stroke patients (Yogev, et al., 2007 and Yang et al., 2007; Michael et al 2005) leading Yogev, et al. (2007) and Yang et al. (2007), who argue that the higher cognitive load for elderly fallers or stroke patients with balance deficits can affect the automaticity of gait symmetry. However, whether this argument can be applied to other populations with balance difficulties such as those with DCD, given differing aetiologies remains speculative but worthy of further investigation.

In answer to Question 1, the findings from this study show that there *are differences in gait pattern between individuals with and without DCD whilst walking on level ground*; manifesting in shorter proportional step length, step-to-step variability, greater head incline and some angular rotations about the joints and segments of the lower limbs. Exact aetiology of these differences can only be hypothesized at this stage. From a biomechanical perspective, group differences could be the result of poor proprioceptive processing at the hip, causing subsequent compensatory adaptations from the lower limbs. Alternatively, if the reduced extension at the ankle is indicative of lower muscle strength this could result in compensatory flexion about the hip. Given the heterogeneity of DCD (Hoare, 1994) these biomechanical adaptations may emanate from different sources. For example, for some individuals problems may be the result of poor information processing and error management (Wilson & Mackenzie 1998; Mon-Williams, et al., 1999; Kuo & Donelan, 2010), for others motor coordination may be inhibited by difficulty controlling posture and balance whilst walking (Deconinck, et al., 2008; Macnab, et al., 2001), or self-organisation of the synergies used to control the degrees of freedom (Bernstein, 1967). Alternatively difficulties may be the result of disorders such as joint hypermobility (Kirby & Davies, 2007).

8.2.2. Question 2.

Given any differences in gait pattern for the two groups observed in relation to Question 1, are these exacerbated when walking over an irregular terrain?

The aim of the second question was to examine lower limb dynamics together with control of the head and trunk under increased environmental (and therefore task) constraints, whilst traversing an irregular terrain. As discussed, this manipulation examined gait adaptations to proprioceptive information from the feet that were more difficult to interpret as participants traversed an irregular terrain (more representative of everyday life). The successful negotiation of this manipulation demanded efficient and adaptive integration of visual, proprioceptive and vestibular information to traverse the irregular terrain whilst remaining upright and balanced, and simultaneously propelling the body forwards. As discussed, this manipulation was expected to affect walking patterns of the individuals with DCD to a greater extent than their TD peers given the additional constraints to movement for the DCD group (Rosengren, et al., 2009; Wilmut, et al., 2006; Smits-Engelsman, et al., 2003; Hyde & Wilson, 2010; Wilson & McKenzie, 1998; Deconinck et al, 2007).

The findings showed that both groups walked slower and with shorter, wider steps in the uneven, compared to the level walking condition, which is a common gait adaptation used to provide a safer walking strategy when balance is compromised. However, the impact of the irregular terrain was greater for the individuals with DCD compared to the control group, demonstrated as the DCD group walked even more slowly and with shorter, wider steps, than their TD peers on the irregular terrain. This ‘safer’ walking strategy suggests that the individual constraints to balance for the DCD group found this terrain a greater threat to dynamic stability than their TD peers. Group differences were explained with reference to the relationship between sensory integration and balance control.

Previous work has shown that individuals with DCD have difficulties with the integration of sensory information (Deconinck et al., 2006^b; Deconinck et al., 2007; Wilson & McKenzie, 1998; Geuze, 2003), which can subsequently affect the interpretation. This, coupled with poorer limb movement control, as identified in Chapter 4 and Rosengren, et al. (2009), may affect any subsequent reactive strategies to correct error and control balance whilst walking on an irregular terrain (Marigold & Patla, 2002; Patel et al., 2009; Deconinck, et al., 2007; Kuo and Donelan, 2010). Therefore, given the greater gait adaptations to the irregular terrain by the DCD group compared to their TD peers, it could be argued that *both* groups accurately perceived the

feedforward environmental information, but the individuals with DCD had to adopt a ‘safer’ style of walking to accommodate problems either with balance constraints (Macnab, et al., 2001). or the integration of feedforward and feedback information, which as discussed in Chapter 2 are essential elements for effective walking patterns (Donelan & Pearson, 2004). Additionally, the DCD group inclined their heads towards the ground to a greater extent than their TD peers. It was argued that this difference in head angle could be caused by a greater need for the DCD group to ‘visually sample’ the irregular terrain compared to the TD group. Thus when proprioceptive feedback from the feet became more difficult to interpret, the TD participants were able to re-weight the importance of proprioceptive information to accommodate the underfoot irregularities whilst walking on the irregular terrain (Klint, et al., 2008). This meant that they could still travel fixate to gather feedforward visual information to assist in preparing the motor system for future moves. However, the DCD group seem unable to do this and looked down to utilise additional visual information to help interpret the changing environmental constraints. This behaviour further supports the argument that individuals with DCD have difficulties integrating feedforward and feedback sensory information which can subsequently affect efficiency with which the CNS can prioritise, or re-weight, proprioceptive information to reflect its relative importance (Hulme, et al., 1982; Wann et al., 1998; Bair, et al, 2012).

Therefore in answer to Question 2, *Walking patterns were exacerbated in several ways when walking over an irregular terrain*, particularly with regard to interpreting environmental information to maintain dynamic stability. However, the group differences in gait pattern illustrate the adaptive nature of gait for individuals with DCD who adjusted their gait pattern to accommodate the environmental conditions within the constraints (balance and sensory interpretation) of their characteristics.

The behaviours exhibited by individuals with DCD when traversing the irregular terrain highlight several implications for everyday life. For example, the need to look down to visually sample the terrain may affect their ability to focus on the wider aspects of the environment, and negate the benefit of feedforward visual information to predict ongoing movement accommodations necessary to negotiate the dynamic environment. Conversely, individuals with DCD may not use feedforward information as the information it provides is sub-optimal. For example, given the previous arguments that individuals with DCD have a poor internal representation of movement (Smits-Engelsman, et al 2003; Hyde & Wilson, 2010), previous experience may dictate that, for individuals with DCD, predicting the outcome of a movement that is not well represented internally is less helpful in a dynamic environment than the feedback

information that can assist with stability. Whatever the aetiology of this behaviour, a reliance on feedback rather than feedforward information is a less efficient method of negotiating the environment (Schellekens, Scholten & Kalverboer 1983) and as Patla (1997, p55) hypothesises this is not an ideal way to plan locomotion.

“Imagine the potential damage to tissues, not to speak of the state of your mind, should a trip followed by successful recovery be the only way we could accommodate obstacles in the travel path”

8.2.3. Question 3.

Does visual occlusion of the feet differentially affect gait patterns between individuals with and without DCD;

- i) Whilst walking on level ground?**
- ii) Whilst walking on irregular terrain?**

The findings from these two studies together, have shown that adaptations to the visual and proprioceptive manipulation for both groups and all ages are negligible for both walking conditions (level and irregular terrain).

Furthermore there were no group effects for the angles of the head and trunk in either walking condition (No change from level walking to level walking with a clear/opaque tray or from walking on an irregular terrain to walking on an irregular terrain with a clear/opaque tray), so whilst the DCD group still looked down more than their TD peers they didn't increase their head angle when vision was occluded.

This was a surprising result particularly for study 2 which involved traversing the irregular terrain, as it was predicted that the removal of visual information from the foot would affect the DCD group more than their TD peers because of the greater reliance on visual information for movement control (Wann et al., 1998; Smits-Engelsman et al., 2003; Deconinck et al., 2006^b). However, as discussed the impact of the visual manipulation depended upon the relative importance the individual placed upon visual information about the whereabouts of the feet to negotiate the terrain (Rayner & Pollatsek, 1992; Land & Hayhoe, 2001). The findings therefore suggest that the future path was considered most important, by both groups, and participants focused on the main direction of travel (Patla & Vickers, 1997, 2003), rather than the position of the feet. These findings also suggest that when information from optic flow is difficult to assimilate in some way as in Deconinck et al.'s (2006^b) and Wann et al.'s (1998) studies, this

affects the gait patterns or postural sway of children with DCD to a greater extent than their TD peers. However, when optic flow remained constant and only the feet were occluded this did not interrupt normal rhythm of gait.

These findings need to be considered alongside the results from Chapter 6 which found that the DCD group inclined their heads towards the ground to a greater extent than their TD peers when traversing the irregular terrain. Therefore, results from the second study in Chapter 7, which failed to identify any group differences in head angle when vision of the feet was occluded, seem to contradict previous findings. However, they suggest that individuals with DCD will use visual information *when it is available* concerning the whereabouts of their limbs to assist with challenging environmental conditions (irregular terrain) as in Chapter 6. But if visual information about the feet is not available (as in Chapter 7) and they are forced to rely on proprioceptive information, then individuals with DCD can, and do. Two suggestions were discussed to explain this phenomenon. Firstly that individuals with DCD adopted a more upright head angle for this condition to assist with feedforward information being ‘forced’ to utilise feedforward information in the same way as the typically developing individuals. The second suggestion discussed the Constrained Action Hypothesis (Wulf, et al., 2001) which argues for improved self-organisation of the motor system when the focus of attention attends to environmental factors rather than internal movement of, for example, the legs.

Therefore in answer to Question 3, *visual occlusion of the feet does not result in significant differences in gait pattern between individuals with and without DCD either while walking on level ground or on irregular terrain*. Furthermore, by ‘forcing’ the individuals with DCD to look ahead this may have improved the feedforward visual information used to assist with the predictions to generate anticipatory gait adaptations needed for successful environmental negotiation. At this stage conclusions are only speculative and further research is necessary to discover how looking ahead supports movement (whether it is due to travel gazing, Patla & Vickers, 1997; *optic flow*, Gibson, 1966; *feedforward/feedback processing* Patla, 1997; Kuo, 2005; Donelan & Pearson, 2004; or an *external focus of attention*, Wulf, et al., 2002). However, the findings presented here may offer a strategy to individuals with DCD when walking about the real environment, by looking ahead, rather than down at their limbs or the terrain, they may have longer to process visual information which could improve adaptive motor adjustments.

8.2.4. Question 4.

Are there significant age effects between individuals aged 8-32 years with and without DCD for any of the above questions?

Given the findings from Sutherland, et al.'s (1980) seminal paper that, with the exception of step width ratio, gait pattern is mature by 7 years of age there was little expectation that the gait patterns of children would differ from those of teenagers or adults whilst walking along the level terrain. Findings from the current study support Sutherland et al.'s (1980) research as age effects were found for step width ratio, with children having a wider step width ratio than teenagers and adults. As a wider step width is thought to assist with balance constraints, these finding also support Assaiante's (1998) argument that many of the mechanisms underlying balance and postural control mature after 7 years of age. However, given the developmental nature of sensory processing, children's gait pattern was hypothesised to differ from teenagers and adults gait when they traversed the irregular terrain. Age effects were also found for walking speed with the children walking slower than both teenagers and adults. This adaptation was argued to allow additional time to re-weight the proprioceptive information from the feet to ensure safe passage along the walkway.

For the teenage age group, however, several unexpected age effects were found even as they walked on the level terrain. They walked with greater variability in proportional step length and step width ratio. Interestingly, this affect was more apparent in the typical teenagers than the DCD group who improved their motor competence during this time (however, their motor competence still remained significantly worse than their TD peers). Additionally, whilst walking on the irregular terrain there were several angular measures that were different for the teenage age group as they inclined their torsos further towards the ground than adults, and had a smaller hip flexion, thigh flexion and knee flexion. These adaptations were argued to be to lower the Centre of Mass which is a strategy used to assist with balance constraints (Deconinck et al., 2006^a). Explanations for this phenomenon were suggested to be due to a U-shaped curve of development as individuals pass through adolescence (Visser et al et al, 1998).

Finally, it was hypothesised that given the constraints to movement experienced by individuals with DCD there would be several age-by-group interactions, with differences expected between the children from each group, but not teenagers or adults. However, findings showed a lack of age-by-group interactions throughout the thesis, the developmental trends for individuals with and without DCD seem to progress along a similar pathway. This was a surprising result given the importance of efficient integration of vestibular, proprioceptive and visual information, and the difficulties experienced by individuals both children and individuals with DCD in this area. However, findings show that participants with and without DCD follow a similar developmental trajectory and apply similar strategies to negotiate a number of different environmental conditions.

8.3. What does this tell us about DCD?

It is clear from the recent meta-analysis by Wilson et al. (2013) that there are several constraints for individuals with DCD which affect the efficiency with which they can interact with the environment. These include sensori-perceptual function, internal (forward) modelling, postural control and gait, all of which are pertinent to this thesis. The current study has advanced our understanding of DCD whilst walking in a real-life environment, in several ways.

Firstly, it has confirmed previous evidence (Deconinck et al 2006^a, Rosengren, et al., 2009) suggesting that whilst walking on level terrains children with and without DCD have significant differences in walking patterns. These findings have been extended to show that group differences are still apparent during adulthood, with increased variability for the individuals with DCD a consistent finding throughout this thesis, supporting research by Rosengren, et al., 2009. Increased variability was argued to suggest difficulties for individuals with DCD with the underlying mechanisms controlling movement.

Analysis of the angular rotations of the lower limbs highlights group differences in the control of the degrees of freedom needed to move the limbs efficiently about the environment, with the DCD group seemingly having less control. It was argued that these group differences could be the result of error management due to a poor sensory integration system, affecting the ability to create an accurate internal model for movement. Additionally the hypothesis that reduced muscular strength, particularly about the ankle may affect the efficiency of the biomechanics of walking for individuals with DCD. This study also showed that whilst the angular rotations of the leg segments are coordinated symmetrically when walking for individuals with DCD the spatial measure of step length was significantly more asymmetric for the DCD group compared to their TD peers. These findings may highlight differences in global versus local symmetry as argued by Sadeghi (2003), or may highlight how differing methods of measurement may confuse findings, further research is needed to explore this area.

Secondly, whilst walking on irregular terrain (discussed in Chapter 7) the DCD group adapted their walk to a greater extent than their TD peers. These measures highlight the adaptive nature of the acquisition of movement skills within the DCD population as argued by Deconinck et al. (2006^a). These differences may be the result of (unconscious) attempts to accommodate difficulties such as poor balance (Deconinck, et al., 2010), and/or poor sensorimotor information processing.

Finally, whilst this study failed to provide any evidence to suggest that visual occlusion of the feet affected the walking patterns of children with DCD to a greater extent than TD children, it has provided useful information to add to previous research. For example, studies that have investigated the effects of visual input on movement for children with DCD have identified that there is a disproportionate reliance on vision rather than proprioception or vestibular information during movement through the environment. Deconinck et al., (2006^b) illustrated the important visual information for guidance of the body through the environment came from peripheral vision. Wilmut et al., (2006) demonstrated that the important visual information to guide the arm to a target came from foveal vision. However, these studies have investigated vision in either a stationary task or with the total removal of vision.

The visual contribution to locomotion in an everyday environment is an important addition to the DCD literature because the dynamic visual cues experienced whilst walking will provide different feedforward and feedback information to those experienced during a stationary task. This, taken together with the constraints to movement for individuals with DCD, discussed above, make this a much needed area for research. During locomotion it is important that we can use visual information to predict outcomes and respond accordingly to ensure successful navigation around obstacles, along different terrains and to assist with safety by correctly estimating the time-to-contact for obstacles in the pathway such as passing cars or other pedestrians. This study has demonstrated that visual information about the feet was only important in more challenging environmental conditions and only when vision was available. The results suggest that when visual information is available it is relied upon disproportionately by the individuals with DCD to support movement, but when ‘forced’ to rely on other sensory modalities, the DCD group were actually less constrained in their walking patterns. These findings lead to the suggestion that when vision is available during a walking task, this may cause unnecessary head movements as individuals with DCD look at their feet for movement support. However, this additional head movement may add noise to sensory information and subsequently devalue motor responses.

One of the most significant findings from this research is that the persistence of movement difficulties into adulthood for individuals with DCD. This is a valuable addition to the literature on DCD as it highlights an area of difficulty for adults to independently negotiate the environment. This is particularly specific to this population given the difficulties previously discussed in learning to drive or ride a bicycle, which may subsequently affect access to many activities of daily living such as shopping for food or getting to work.

8.3.1. Implications of this body of work

Assessment of the spatio-temporal gait parameters (such as stride length, speed, duration of double support) in the current study has identified significant differences between individuals with and without DCD. This is particularly apparent in complex environments such as when negotiating irregular terrains; however there is some evidence of differences even in a very simplistic environment where step length was significantly shorter for individuals with DCD. Additionally variability was significantly greater for individuals with DCD and this seems to be a robust finding across studies investigating gait for this population. Thus it could be argued that gait assessments would be a useful tool to provide quantitative information to differentiate between individuals with and without DCD.

One of the main implications for this body of work is to recognise the impact of both internal and external constraints on the ability of individuals with DCD to successfully interact with the environment. The findings from the current study show some of the difficulties that individuals with DCD experience even with a mundane and frequently performed task such as walking. From a theoretical perspective, findings from the current study suggest that research and clinical interventions for individuals with DCD need to be considered within an ecological systems framework (Gibson, 1979) which importantly incorporates Newell's constraints model (Newell, 1986). Thus the individual's sensitivity to information from the environment is considered alongside personal constraints that may affect how that information is used to inform movement. Furthermore, as discussed throughout this thesis, the importance of top-down processing needed for goal-directed tasks such as walking cannot be ignored. It is only when DCD is considered within this 'blended' framework that acknowledges the importance of input from several systems (motor, perceptual, biological, and cognitive) that we can begin to unravel the complexities of this condition.

Findings from the studies discussed in Chapters 6 and 7 may be particularly useful to inform clinical practice as they show how visual information can have a positive but also a negative effect on movement depending upon how it is used (Wulf et al 2001). If clinical interventions for individuals with DCD could be designed to focus, not only upon the movement difficulties per se, but taking a wider perspective to improve environmental interaction this would greatly improve access to many everyday activities. For example, simple techniques such as *looking where you are going* or *looking up* may enhance environmental interaction during locomotion by optimising the use of visual information. As discussed, it is unclear whether this benefits movement due to travel gazing (Patla & Vickers, 1997); *optic flow* (Gibson, 1966), the use of *feedforward processing* (Patla, 1997) or an *external focus of attention* (Wulf, et al., 2002).

8.4. Limitations of the empirical studies

There are a number of limitations with these series of studies. Firstly, as with any empirical study it could be argued that the participants altered their gait pattern because of the laboratory conditions, and they might perform differently in a real environment. This was an important consideration for this series of studies as individuals with DCD may be more vulnerable than their TD peers to environmental manipulations because of difficulties with the integration of sensory information (Wilson & McKenzie, 1998). In order to protect against this confound the participants were asked to walk at their own pace along a 6m pathway continuously for 2 minutes for each condition, allowing them to 'settle' into a normal, comfortable rhythm.

It could be also argued that the dimensions of the walkway, at 6m x 1m were adequate although not ideal, and a longer, wider walkway would have been preferable to ensure a more realistic walking pattern. This was particularly apparent at the end of the walkway where participants had to negotiate a 360° turn around the cones. Had a wider walkway been used this would have reduced the disruption to walking rhythm, taking a few steps to return to rhythmic walking patterns. Given that individuals with DCD are reported to be awkward in their gait, frequently stumbling and bumping into things (Parker & Larkin, 2003) it could be argued that the impact of this experimental design could be greater for individuals with DCD than their TD peers. In fact, visual observations during testing revealed that the individuals with DCD knocked into the cones as they walked around them more than their TD peers. To accommodate this disruption data were only collected in the middle 4m of the walkway to enable normal momentum to be regained. However, given the frequency with which participants had to negotiate this obstacle, it could highlight a confound to the results affecting the walking patterns for the DCD group to a greater extent than their TD peers. Another possible confound to the findings of the current study was that the size of the tray carried to occlude the feet was the same for all participants, regardless of height. This may have differentially affected individuals taking part in the study as the area covered by the tray would be proportionally greater for smaller compared to taller participants. Possibly affecting feedforward information gained from travel fixations, as illustrated in Figure 8.1;

Predictions from this confound would suggest that children would be negatively affected by a tray which is not only occluding the feet but a considerable area in front of the feet as well. Given the lack of any age effects for children during the tray carrying conditions in the current study it can be assumed that the size of tray was not a confound. However, future studies using this method of occlusion should consider the relative effects of tray size on differing heights of participants.

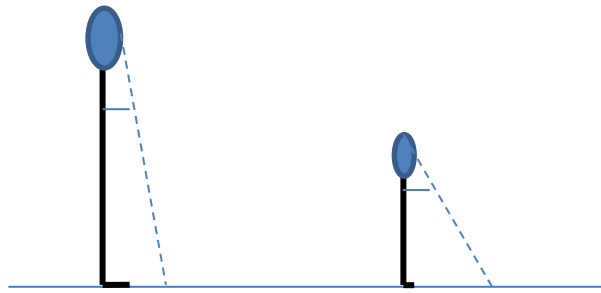


Figure 8.1 Effect of same tray size on occluded area for differing heights of participants.

It could be argued that another limitation of this study was the absence of investigations into arm movements. However, given that arm swing is not a prerequisite for walking, it has been argued that arm movements are a passive element of the walking task (Webb, Tuttle, Baksh 1994) and much of the gait literature ignores any contribution from the arms (Vaughan, et al 1992; Whittle 2012). Therefore, for the exploratory nature of this study it was decided to focus upon leg, trunk and head movements allowing a direct comparison with the other walking studies with individuals with DCD. However, several studies have shown a rhythmic relationship between the legs and arms whilst walking (Wannier et al 2001; Webb & Tuttle, 1989). Furthermore there is some evidence to suggest that perturbations whilst walking can produce muscle activity in the arms (Dietz, et al 2001; Delwaide & Crenna, 1984), which are hypothesised to assist with balance control (Donker, Mulder, Nienhuis & Duysens, 2002). Given the balance difficulties experienced by individuals with DCD (Geuze, 2003; Rosengren et al., 2009), the use of the arms as a strategy to assist with these difficulties might present an area worthy of future study to gain a complete description of the walking task for this population. However, Woodruff et al. (2002) excluded reciprocal arm swing from their analysis to classify gait patterns in children with DCD as the discriminative power was too low to differentiate between individuals with and without DCD.

The small number of strides, averaging 7.23 for the DCD group and 8.79 for the controls (averages per condition in figure 3.7) could be considered a weakness of this study and more strides to analyse would add authority to the conclusions. However, this current study is in line with several other studies investigating walking patterns for individuals with DCD such as Deconinck et al. (2006^a) who analysed 8 strides; Rosengren et al., (2009) analysed 7 strides; Diamond et al. (2014) analysed 6 steps per condition.

Perhaps the most important limitation of this current study was lack of comparison between the first walk vs later walks, which together with the quasi-randomised presentation of the walking

trials may have presented a major confound to the results. Whilst the perturbations were designed to examine participants planning skills required to traverse the pathway with different sensory constraints (discussed in Chapter 3), the level of sensory processing required whilst traversing the terrains, (with or without occluded vision of the feet) changed with each perturbation. The effect of this design meant that participants had different levels of experience based on the order in which the experimental manipulations were presented. In order to account for these order effects statistically an ANCOVA was run for each experiment with 'order' as a covariate investigating the effect of the level walk trail first (1) or not (2). Findings from these investigations are provided within the results and discussion sections of each chapter.

Finally, as for most research with clinical populations, the relatively small sample size for each age group, together with high levels of variability for the DCD group may have affected the significance of some results. Notwithstanding this limitation, nearly all significant measures show medium effect sizes in spite of the relatively small sample. In order to improve statistical power, it could be argued that in some cases it would have been better to drop the developmental hypotheses and concentrate on comparing DCD to TD at each age group. However due to the paucity of walking research, particularly for teenagers and adults with DCD, it was important that for a preliminary study a developmental hypothesis was investigated to inform and direct future research. Furthermore, the lack of interactions in the current study show that for a cyclic task such as walking, individuals with DCD follow a similar developmental trajectory to their typically developing peers. However group differences highlight adaptive walking patterns to support their primary deficit, which, as argued by Deconinck et al. (2010), is balance.

8.5. Suggestions for future research

Further research needs to be conducted to unpick cause and effect of the variability shown by individuals with DCD as they walk in a real environment. As discussed, the emerging evidence suggests that angular rotations of the lower limbs are differentially affected between groups, even within very predictable environments. However, it is not clear at this stage whether the differences in gait patterns are caused by lower muscular strength about the ankle, or a poor feedforward model of the walking movement caused by noisy sensory information, or difficulty controlling the many degrees of freedom needed to walk efficiently. Designing an experiment to discriminate between these possible causal elements needs careful consideration. However, the most important consideration is that any experiment designed to assess walking patterns in this

group of individuals needs to be conducted within a realistic environment. Therefore the walkway would need to be over ground rather than on a treadmill.

To explore the accuracy of movement, and therefore control of the limbs, participants with and without DCD could be asked to traverse a series of stepping stones. Surface EMG recordings of leg muscle activity about the hip and ankle would provide information concerning how and when muscles are activated. The use of a mobile eye tracker would allow the investigation to analyse where the participants are looking, and further our knowledge about the use of sensory information to traverse the walkway. One element of this study would be to record the order of walks so that walking patterns on the first walk could be compared to those on later walks. This would enable the analysis of learning effects and to see if participants refined their gait adaptations with subsequent walks. This information would help investigate the internal modelling abilities of the participants and to see if sensory feedback from the initial walk informs future motor adjustments.

Additionally, given that the legs form an interrelated, segmented system, future research needs to consider the coordination of the joints and limb segments together rather than analysing them separately. Previous studies into walking patterns for individuals with DCD have not done this, but findings from analysis of the dynamic relationship between the limbs whilst walking would be informative, and reflect the theoretical approaches relevant to motor control. As Biryukova and Brill (2008) suggest, individual joint and limb segment kinematics may not provide sufficient information to fully investigate how the body organises the coordinated movement necessary during locomotion. Barela Whittall, Black, and Clark (2000) argue that it is the *relationship* between joints and segments that allows us to investigate this coordinated organisation. This logical suggestion reiterates the ecological approach and Bernstein's (1967) hypothesis that the sub-systems (i.e. joints and segments) cooperate with one another to produce systematic and coordinated movement. Therefore full evaluation of the coordinated movement of the legs needs to consider the inter-limb (leg-to-leg) coordination together with the intra-limb (thigh, shin, foot). Whether this is achieved using statistical analysis or in the methods of the experimental set-up provides a challenge for future research.

Finally, given that much of the interpretation relating to walking patterns for individuals with DCD relate to balance deficits (Rosengren, et al., 2009; Deconinck et al., 2006^a), there is a need for further research to unpick the impact of balance whilst walking for this population. A follow-up study to investigate balance for individuals with and without DCD would extend our understanding. Individuals could be assessed using a battery of tests based on the Berg Balance Scale. This is a 14 item list designed to measure static and dynamic balance in the elderly

population with balance impairments (Berg, et al., 1992) in a number of everyday activities. Whilst the Berg balance scale is recommended for the elderly population it can be adapted to suit participants with DCD with the omission of two items not appropriate for the DCD population (Standing unsupported, sitting unsupported). The participant's balance score is objectively measured using a 5-point scale (from 0-4) with 0 indicating the lowest level of performance and 4 the highest. The Berg Balance Scale takes approximately 20 minutes to administer. The Fukuda stepping test could be used to investigate dynamic balance in participants whilst stepping on the spot (50 steps) with their eyes closed. The degree of movement from the start position will be measured, with any deviation greater than 30° considered abnormal (Honaker, et al., 2009).

8.6. Conclusions

Several novel features of the methodology of this study improve upon previous work in the field and have provided information on walking for individuals with DCD that has not previously been reported. These features include robust selection criteria, employment of a more ecologically valid walking task (rather than treadmill walking), measurement of both spatio-temporal measures and step-to-step variability, together with static angular rotations of the lower limbs. This has allowed for a detailed description of walking parameters and putative underlying control mechanisms, with results that may be generalised to everyday life performance.

The study design has allowed for the novel description of not only group differences in walking patterns (DCD & TD) whilst walking on a level terrain but also whilst traversing an irregular terrain and with reduced visual feedback. Additionally developmental trends into adulthood, which haven't previously been reported, have uncovered some findings applicable to future research with typically developing populations, particularly teenagers, as well as for those with DCD. Group differences in variability reflect possible developmental differences in the control mechanisms underlying walking in DCD. However, given the importance of walking for access to everyday activities, one of the most pertinent findings from this study is the persistence of movement difficulties into adulthood, which, as discussed could have a severe impact on access to activities of daily living such as shopping for food, walking to work or participating in recreational activities.

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Appendices

Appendix I. UREC approval

Dear Dr. Kate Wilmut, Dr, Anna Barnett and Professor Angus Gellatly

UREC Registration No: 110561 – “The effects of sensory feedback on walking patterns”

Thank you for your email of the 30th June outlining your response to the points raised in my previous letter about the PhD study of your research student Judith Gentle, and attaching the revised documents.

I am pleased to inform you that, on this basis, I have given Chair's Approval for the study to begin.

The UREC approval period for this study is two years from the date of this letter, so the 30th June 2013. If you need the approval to be extended please do contact me nearer the time of expiry.

In order to monitor studies approved by the University Research Ethics Committee, we will ask you to provide a (very brief) report on the conduct and conclusions of the study in a year's time. If the study is completed in less than a year, could you please contact me and I will send you the appropriate guidelines for the report.

The attached letter confirms this full approval status. I will send a signed, hard copy to the Director of Studies in the internal post for their file records.

It just remains for me to wish Judith Gentle all the best with the research study and to commend how thoroughly she has responded to the Committee's feedback process,

Yours sincerely

Dr Elizabeth T Hurren

Chair of the University Research Ethics Committee

cc Judith Gentle, Research Student

Morag Maclean, School Research Ethics Officer

Jill Organ, Graduate Office

Louise Wood, UREC administrator

Appendix II Chapter 3. Order of walking trials

Ppt	Group	Walk	WT	WOT	C	CT	COT		W first
34	DCD C	2	1	3	6	5	4		*
35		1	3	2	6	4	5		*
36		6	5	4	3	2	1		
38		1	3	2	6	5	4		*
39		5	4	6	3	1	2		
40		1	3	2	5	6	4		*
41		1	2	3	5	6	4		*
42		4	5	6	3	1	2		
46		1	3	2	5	4	6		*
50		5	6	4	2	3	1		
67		1	3	2	6	4	5		*
55		6	5	4	2	1	3		
									7*
44	TD C	6	4	5	3	1	2		
47		1	3	2	5	6	4		*
52		1	2	3	6	5	4		*
54		5	6	4	2	3	1		
60		1	2	3	5	6	4		*
61		2	3	1	6	5	4		*
62		2	3	1	5	6	4		*
63		6	4	5	1	3	2		
58		1	2	3	6	5	4		*
65		1	2	3	6	5	4		*
68		6	5	4	2	1	3		
69		4	6	5	2	1	3		
									7*
1	DCD T	6	5	4	3	1	2		
3		4	6	5	3	2	1		
4		5	6	4	2	1	3		
5		1	3	2	5	4	6		*
8		4	6	5	3	2	1		
11		4	5	6	2	3	1		
12		2	1	3	6	5	4		*
17		2	1	3	6	5	4		*
21		6	4	5	1	2	3		
22		1	2	3	4	6	5		*
32		2	3	1	6	5	4		*
37		1	2	3	6	5	4		*
									6*
13	TD T	1	2	3	6	4	5		*

15		2	3	1	6	4	5		*
33		1	3	2	5	4	6		*
43		6	5	4	3	1	2		
45		2	1	3	5	4	6		*
48		4	6	5	3	1	2		
49		1	3	2	6	4	5		*
51		1	2	3	5	6	4		*
56		6	4	5	3	1	2		
64		4	6	5	3	2	1		
66		2	3	1	6	4	5		*
70		4	5	6	2	3	1		
									7*
2	DCD A	4	6	5	1	3	2		
7		4	6	5	1	3	2		
9		4	6	5	1	3	2		
10		5	4	6	2	3	1		
14		1	2	3	4	6	5		*
18		2	3	1	4	6	5		*
19		2	3	1	6	4	5		*
20		4	5	6	2	1	3		
23		6	5	4	1	2	3		
24		1	2	3	6	5	4		*
29		6	4	5	3	2	1		
									4*
16	TD A	3	1	2	5	6	4		*
25		1	3	2	4	5	6		*
26		1	3	2	5	4	6		*
27		5	6	4	1	3	2		
28		4	5	6	1	3	2		
53		6	5	4	1	2	3		
30		4	5	6	3	1	2		
31		1	2	3	5	4	6		*
71		4	6	5	3	2	1		
57		5	6	4	2	1	3		
59		1	2	3	4	6	5		*
									5*

Appendix III. Chapter 4 Means, standard deviations segment angles at four gait events

		Opposite				Opposite			
Age		Heel-strike		Toe-off		Heel-strike		Toe-off	
		DCD	TD	DCD	TD	DCD	TD	DCD	TD
		Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
		(SD)	(SD)	(SD)	(SD)	(SD)	(SD)	(SD)	(SD)
Foot Angle (^o)	Child	165.06	163.86	154.77	152.41	161.94	160.15	126.48	107.39
	(C)	(3.05)	(2.50)	(2.21)	(1.71)	(5.15)	(4.75)	(12.63)	(14.96)
	Teenage	169.31	165.51	154.84	154.40	166.67	162.72	130.04	118.99
	(T)	(3.88)	(2.90)	(1.60)	(2.87)	(3.20)	(2.28)	(7.54)	(15.37)
	Adult	165.32	165.44	154.17	153.95	165.65	163.33	124.89	120.73
	(A)	(7.77)	(3.21)	(2.26)	(1.68)	(3.69)	(3.53)	(12.83)	(11.73)
Shin Angle (^o)	Child	92.69	93.68	79.98	78.66	50.66	47.36	29.87	26.09
		(2.80)	(2.44)	(2.44)	(2.05)	(4.69)	(2.99)	(3.17)	(2.28)
	Teenage	91.46	93.25	78.73	79.40	53.05	51.19	30.43	29.83
		(7.03)	(3.62)	(3.08)	(2.97)	(3.69)	(2.49)	(3.98)	(2.73)
	Adult	94.99	93.94	79.91	78.94	52.91	50.56	31.47	27.66
		(2.53)	(2.79)	(1.67)	(2.55)	(6.65)	(3.37)	(4.12)	(4.85)
Thigh Angle (^o)	Child	106.36	105.92	99.24	99.29	75.31	72.81	87.33	85.82
		(2.99)	(2.15)	(3.96)	(2.76)	(3.04)	(2.31)	(3.27)	(2.00)
	Teenage	109.11	108.07	102.55	101.20	78.32	74.34	87.35	86.70
		(2.85)	(2.88)	(4.30)	(4.77)	(3.83)	(2.28)	(2.74)	(3.06)
	Adult	105.58	108.10	98.48	100.65	74.70	74.79	84.90	86.58
		(3.51)	(3.89)	(5.02)	(5.24)	(3.56)	(2.98)	(4.96)	(3.28)

Table A4.1 Means, standard deviations segment angles at four gait events

Appendix III. Chapter 4 Means, standard deviations joint angles at four gait events

	Age	Heel-strike		Opposite Toe-off		Opposite Heel-strike		Toe-off	
		DCD	TD	DCD	TD	DCD	TD	DCD	TD
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Ankle Angle (°)	Child	107.63 (4.98)	109.83 (3.49)	105.21 (3.41)	106.25 (2.48)	68.72 (3.19)	67.22 (2.95)	83.40 (12.88)	98.70 (13.88)
	Teen	111.32 (22.83)	107.26 (6.02)	102.48 (5.83)	104.72 (2.32)	65.27 (5.78)	68.02 (2.20)	79.52 (7.51)	93.14 (13.20)
	Adult	109.67 (9.69)	108.50 (5.37)	105.75 (2.65)	104.99 (2.74)	67.26 (4.34)	67.23 (1.94)	86.59 (10.56)	86.93 (9.31)
Knee Angle (°)	Child	166.33 (4.27)	167.76 (2.03)	160.74 (4.81)	159.37 (3.33)	155.35 (5.26)	154.56 (3.03)	122.55 (3.49)	120.27 (2.45)
	Teen	162.37 (8.94)	165.19 (2.31)	156.18 (5.28)	158.20 (3.84)	154.73 (5.22)	156.84 (3.21)	123.09 (5.32)	123.13 (4.42)
	Adult	169.41 (3.13)	165.84 (3.62)	161.43 (5.57)	158.29 (6.88)	158.21 (6.79)	155.77 (1.88)	126.57 (6.00)	121.08 (3.25)
Hip Angle (°)	Child	163.77 (5.07)	162.05 (6.29)	172.60 (6.49)	170.62 (6.63)	195.80 (5.72)	197.55 (3.48)	182.53 (6.82)	181.21 (4.99)
	Teen	157.32 (4.99)	161.94 (4.20)	164.59 (6.31)	168.92 (7.74)	188.65 (5.27)	195.27 (4.78)	178.71 (5.65)	182.08 (6.61)
	Adult	164.60 (6.43)	163.82 (6.73)	172.38 (6.91)	172.54 (8.11)	196.32 (2.65)	197.56 (4.52)	187.60 (4.96)	185.80 (5.63)

Table A4.2 Means and standard deviations for joint angles at four gait events

Appendix IV typical stepping parameters

Speed; (Whittle, 2012)

Children 8-12 years = 0.82-1.60m/s

Teenagers 13-17 years = 0.95-1.75m/s

Adults 18-49 years = 1.10-1.82m/s

Stride length (Whittle, 2012) halve for step. .

Children 8-12 years = 0.75-1.54m

Teenagers 13-17 years = 1.06-1.75m

Adults 18-49 years = 1.25-1.85m

Step width ratio (Whittle, 2012)

Children 8-12 years =
Teenagers 13-17 years =
Adults 18-49 years =

} . . 30%/70%

% DS (Winter, 1991)

Children 8-12 years =

Teenagers 13-17 years =

Adults 18-49 years = 16-22%

Vertical movement (Thorstensson et al, 2008).

2.5 – 9.5cm

Lateral movement (Thorstensson et al, 2008)

2-6cm