Physical Activity in Adolescents with respect to Movement Quality and Quantity

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A thesis submitted in partial fulfilment of the requirements of Oxford Brookes University for the degree of Doctor of Philosophy

2020

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Abstract

Physical activity is a vital component of overall health and development. It has been widely proven that physical activity has beneficial effects on many aspects of physiological, psychosocial, and cognitive function. However, there is consistent evidence that the recommended physical activity durations and intensities are not being met by children and adolescents of all ages. This is, therefore, having a detrimental impact on health, with increased prevalence of overweight/obesity, diabetes, and other cardiometabolic conditions. This highlights the importance of understanding ways in which physical activity can be increased in this population and identifying which individuals are at risk of low physical activity levels in order to provide targeted interventions. Improving motor competence levels has been indicated as a strategy for improving physical activity levels in adolescents. It has been hypothesised that a certain level of motor competence is required to attain certain levels of physical activity. However, there is less conclusive evidence indicating this in adolescents with large varieties in methodologies used to measure motor competence. The main aims of this thesis were to investigate the differences in physical activity levels in adolescents with low and typical levels of motor competence, explore the interaction in walking performance in adolescents with low and typical levels of motor competence and investigate if walking control and motor competence level could predict physical activity duration and intensity levels.

The first study compared the differences in physical activity levels in adolescents with low and typical levels of motor competence and assessed what motor competence cut-off scores were required in order to perform higher levels of physical activity. The results indicated that adolescents were more likely to perform lower levels of physical activity if they were in the low motor competence group and adolescents with higher motor competence were more likely to perform higher levels of physical activity. Motor competence cut-offs for higher levels of physical activity were at the 15th percentile when the full Movement Assessment Battery for Children 2nd edition (MABC2) was used and the 31st percentile when the balance subsection was used to measure motor competence. The second study examined the interaction between walking control under cognitive-motor interference and motor competence level in adolescents. The results indicated that walking control was exacerbated in adolescents with low motor competence as measured by the balance subsection of the MABC2 than their typically developed peers. Walking speed reduced and stride length variability increased more so in the low motor competence group compared to the typically developed group. Study 3 examined the predictive models of motor competence and walking control on physical activity durations and intensities. Results from this study indicated that both models were able to significantly predict different intensities of physical activity levels in adolescents, with stride length variability significantly predicting overall levels of physical activity and the balance subsection of the MABC2 significantly predicting vigorous levels of physical activity.

These studies provide novel insight into the effects of low motor competence on physical activity durations and intensities, walking control and which measures may be used to predict low levels of physical activity

due to low motor competence. In addition, it provides insight into methods for increasing higher levels of PA intensities through better balance control.

Presentations and Publications Relevant to Thesis

Publications

WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H., INACIO, M., JOSHI, S., SPRINGETT, D., MEANEY, A., DELEXTRAT, A., KEMP, S. & DAWES, H. Differences in Motor Competence and Walking Performance in Adolescents. Gait & posture, (in preparation for submission). Chapters 4.

WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H., INACIO, M., JOSHI, S., SPRINGETT, D., MEANEY, A., DELEXTRAT, A., KEMP, S. & DAWES, H. Exploring Motor Competence and Physical Activity in Adolescents to determine adequate MC cut-offs to promote higher PA durations and intensities. (in preparation for submission). Chapters 5.

Presentations

WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H., JOSHI, S., MEANEY, A., DELEXTRAT, A. & DAWES, H. Motor Competence and Physical Activity in Adolescence. Physiotherapy UK, 1st - 2nd November 2019. (Chapter 4)

WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H., JOSHI, S., MEANEY, A., DELEXTRAT, A. & DAWES, H. Exploring the interaction between motor competence and dual task walking in adolescents. International Society of Posture & Gait Research World Congress, 1st - 4th July 2019. (Chapter 5)

WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H., JOSHI, S., MEANEY, A., DELEXTRAT, A. & DAWES, H. Motor Competence and Physical Activity in Adolescence. EARLI EFG Physical Activity and Rest Conference, 6th June 2019.

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WEEDON, B. D., ESSER, P., COLLETT, J., IZADI, H. & DAWES, H. Exploring Physical Activity in Adolescents Considering both Movement Quality and Quantity. Oxford Brookes University Annual Research symposium. 10th January 2017.

Publications associated with this thesis

ESSER, P., **WEEDON, B. D**., MEANEY, A., DELEXTRAT, A., MAHMOUD, W., SALVAN, P., WASSENAAR, T., JOSHI, S., LIU, Y.-C., KEMP, S., WARD, T., JOHANSEN-BERG, H. & DAWES, H. 2019. Brain plasticity and motor skill competence development in adolescents with poor motor skill acquisition and performance: Trial Protocol for a controlled experimental paradigm. OFS, Retrieved from osf.io/w8gj6.

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Public Engagement

Oxford Brookes Science Bazaar, 25th February 2017 and 24th February 2018, interactive stall of Motor Competence and Fitness measures for children. Engaging children from the ages of 4-12 years in scientific measures of health and fitness.

European Researcher's Night, 29th September 2017, interactive stall of Motor Competence and Fitness measures for children. Natural History Museum, Oxford. Introducing scientific measures of motor competence and fitness to children and young adolescents.

As part of this project, we invited classes from the three schools we recruited and provided practical lessons in aerobic capacity using breath by breath analysis in the laboratories at Oxford Brookes University. This was completed for Year 10 students and A-level students undertaking sports science.

I was invited to lecture at the three schools for years 9, 12 and 13. This was to talk about my career path through school, university and work as PhD researcher, giving details on what we do and how we collect data to answer important questions about health, rehabilitation and physical activity. This lead to several students undertaking work experience within our department.

Acknowledgements

Firstly I would like to thank my Director of studies Dr Patrick Esser and supervisor Dr Johnny Collett who have helped me enormously with their vast experience, knowledge and hard work over the last three years. It has been a privilege to work with them as their great sense of humour and overall positivity made it a joy to come to work. More importantly, they have taught me valuable lessons which will continue to greatly affect my development as an independent clinical researcher.

I would also like to thank Prof Helen Dawes and the extended research team from the Centre for Movement, Occupational and Rehabilitation Sciences (MOReS), and Dr Andy Meaney from the Clinical Exercise and Rehabilitation Unit (CLEAR Unit). Without the help from every member, I would not have been able to fully complete such a large study over such a long period. I am unable to name everyone who has helped with screening over the past three years as there have been so many, but I would like to highlight a few PhD students who were unlucky enough to start their PhD alongside me and have therefore been dragged into helping me while also concentrating on their own very complicated projects. Thanasis Tektonidis, Yaomeng Liu, Erin Hannink, and Jon Room thank you very much for all your help, it did not go unnoticed and good luck with your projects. I would like to single out Shaun Joshi who is a completing his medical degree and PhD at Drexel University and spent over a year helping me run the EPIC 2 study and was heavily involved in all screening, assessments and interventions. Thank you very much for your hard work, perseverance and knowledgeable insight.

Finally, I would like to thank my family who have suffered the most from the stresses and strains of me being a PhD student. To my Uncle and Aunt Tim and Debbie Weston and my cousins, Richard and Ellie Weston thank you for your support and ability to keep me grounded while distracting me from my work. To my father Roger Weedon and my brother Chris Weedon I simply could not have got myself to this point without you, the successes I have experienced past and future should also be credited to you both. Lastly, I would like to say a special thank you to my mother Gillian Weedon, who has done everything in her power to help me in any way she can. I will be forever in your debt and cannot begin to describe how much you have meant to me.

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Abbreviations

AP	Anterior-Posterior
AUC	Area Under the Curve
Bal	Balance
BMI	Body Mass Index
BOT2	Bruininks-Oseretsky Test of Motor Proficiency 2nd Edition
cm	centimetre
CMI	Cognitive-Motor Interference
CoM	Centre of Mass
CV	Coefficient of Variation
DCD	Developmental Coordination Disorder
DLW	Doubly Labelled Water
DSM-5	Diagnostic and Statistical Manual of Mental Disorders 5th Edition
HR	Heart Rate
HRF	Health-Related Fitness
Hz	Hertz
IMD	Index of Multiple Deprivation
IMU	Inertial Measurement Unit
kg	kilogram
KTK	Körperkoordinationstest für Kinder
Low MC	Low Motor Competence
m	meter
MABC2	Movement Assessment Battery for Children 2nd Edition
MAND	McCarron Assessment of Neuromuscular Development
MC	Motor Competence
ML	Medial-Lateral
MVPA	Moderate Vigorous Physical Activity
ND	Non-Dimensional
O_2	Oxygen
CO_2	Carbon Dioxide
PA	Physical Activity
ROC	Receiver Operator Characteristics
SD	Standard Deviation
Sed	Sedentary

SLJ	Standing Long Jump
SOP	Standard Operating Procedure
SWT	Single Walk Task
TD	Typically Developed
TGMD2	Test of Gross Motor Development 2nd Edition
V	Vertical
VO_2max	Maximal Aerobic Capacity
VPA	Vigorous Physical Activity
20mSRT	20m Shuttle Run Test
95% CI	95% Confidence Intervals

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Chapter 1 Introduction

Reduced movement quality can impact daily activities, academic achievement and psychosocial health in children and adolescents, resulting in a longitudinally increased socio-economic costs [1]. An increasing concern in the current health literature is the growing evidence that children and adolescents are engaging in low levels of physical activity (PA) [2] resulting in greater health problems and increased morbidity. A significant reduction in movement quality or motor competence (MC) has been cited as a major reason for this decline in PA and health which, tracks into later life [3]. As walking is the primary source of PA [4] and is also reflective in motor problems, understanding the link between MC PA and walking performance is important for current and future health conditions.

This thesis explores motor competence, walking and levels of physical activity. This research aims to determine the relationship of MC and walking quality on PA duration and intensity. The overall question of this thesis is to what extent movement quality effects movement quantity in adolescents with and without MC deficiencies.

1.1 Motor Competence

1.1.1 Definitions and Terminology

A recently adopted definition of motor competence (MC) has been described as the quality of movement coordination when performing different motor tasks, such as fine and gross motor skills, for goal-directed human movement [3, 5-10]. Terminology has varied substantially over previous years, with many different terms used interchangeably to define an overall aspect of MC [3, 8, 11]. These have included, but are not limited to motor coordination, motor proficiency, motor performance, and motor ability [3, 5, 8]. This has caused some confusion when categorising deficits in MC, understanding the effects of interventions designed to improve MC and developing clear models of MC throughout the lifespan [8]. Work completed by Robinson *et al.,* [3] and Logan *et al.,* [8] have highlighted the need to unify terminology within this area of research and clarify these definitions. They suggest MC should be used to define global movement quality, and include specific details of movements. Therefore, this definition will be used throughout this thesis.

Low MC has been defined in different ways over previous years. The nomenclature has varied across the literature with many studies adopting the terms “clumsy children”, “developmental dyspraxia”, and “developmental coordination disorder” to describe low MC. More recently, developmental coordination disorder (DCD) has become most widely used [11, 12]. The most recent definition from the World Health Organization [13] defines low MC as a “Specific Developmental Disorder of Motor Function” with deficits in the acquisition of fine and gross motor skills, which can present as “clumsiness”, “slowness” or “movement inaccuracy”. These deficits result in MC that is significantly below that of age and cognitive ability matched children. These movement difficulties cannot be explained by conditions of the nervous, musculoskeletal or sensory systems, or reduced intellectual progression. This definition of DCD is similar to that of the DSM-5 [14], which states four criteria used for DCD diagnosis.

Diagnostic Criteria

A

The acquisition and execution of coordinated motor skills are 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 scissor or cutlery, handwriting, riding a bike, or participating in sports).

B

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

The onset of symptoms is in the early developmental period.

D

The motor skills deficits are not better explained by intellectual disability (intellectual development disorder) or visual impairment and are not attributable to a neurological condition affecting movement (e.g. cerebral palsy, muscular dystrophy, degenerative disorder [14].

Work by the Leeds Consensus [15], which aimed to standardise research into DCD, formally adopted the DSM-5 [14] criteria as the most appropriate diagnostic definition for DCD [11]. However, limitations with the DSM-5 [14] criteria, which is cited in the Sugden [15] indicates that the use of DCD in this thesis may be inappropriate. These recommendations suggest the use of valid, norm-referenced and culturally appropriate movement battery tests to assess criteria A. Many of these tests use the lowest 15th percentile as a cut-off point to highlight low MC. These cut-off points are arbitrary and have little theoretical underpinning, and therefore recommendations suggest it may not be suitable to use this method independently to clinically define DCD [15]. Furthermore, Criterion B would require the assessment of MC affecting activities of daily living and academic performance [16], with a full assessment of each participant's neurological, musculoskeletal and cognitive health to fully address criteria D [17]. This would require an assessment from a multidisciplinary team and as such would be impractical for this research. Therefore, the term low MC will be used to describe participants performing scoring at or below the 15th percentile on a validated movement battery test.

1.1.2 Prevalence

A substantial increase in the research of low MC in children and adolescents has led to a large variation in reported prevalence [11, 18-20]. Studies have cited ranges between 1.4% -19% of school-aged children with low MC [21, 22] and studies assessing fundamental movement skills (FMS) have indicated a much larger prevalence. With only 40% acquiring mastery of one FMS [19, 20]. However, the DSM-5 [14] reported that the prevalence of low MC in 5-11 year olds is between 5-6%. This variation in reported prevalence can be attributed to the selection criteria used to assess MC, with differences in age, sex, and culture between studies [22, 23]. This is highlighted in a study by Lingam *et al.,* [21] who reported that low MC in 7 year old UK children was 1.8%. This lower reported prevalence may be explained by the methodology used by Lingam *et al.,* [21]. They adopted a strict MC assessment as defined by Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-4) which defines mental disorders including ones affecting MC. However, due to the large sample size, a full valid measure of MC was not achieved. This study used a reduced number of test items from a valid motor assessment, whereby one test item was chosen from each sub-section. Even though evidence indicates these single measures had good concurrent validity to the overall sub-section score, there are limitations when non-validated tests are used in the assessment of criteria A and this may explain this lower estimate of low MC. Further support for this is shown in studies assessing FMS. When FMS are used to assess MC a much higher prevalence of low MC is reported in children and adolescents, with reports of 40% of young people performing one FMS adequately [19, 20]. As FMS assesses three main areas of movement quality e.g. object control, locomotor skill and balance [8], with many different sub-skills used to assess these three domains it highlights the wide-ranging prevalence of low MC.

Prevalence between genders also showed large variations, but research consistently indicates boys are more likely to be affected than girls [11, 14, 22]. Studies have reported that boys can be twice as likely to present with low MC, with the highest difference reported at 7:1 (boys:girls) [14, 22]. These differences may be as a result of the heterogeneous nature of low MC across multiple age groups and the variety of movement batteries used to assess MC, with many studies using either objective or subjective methods. There is additional evidence that suggests genders perform better at different motor tasks [24-28], with girls performing better at manual dexterity and balance tasks whereas boys perform better at aiming and catching tasks at pre-school ages [26, 29, 30]. This would further impact gender differences when movement battery tests apply the same normalised reference tables to assess MC in boys and girls as some movement tests weight subsections differently [27]. Bias may also increase when assessing the prevalence of low MC between genders. Evidence indicates that these sex differences track into adolescence [24], and more importantly low levels of MC in childhood are likely to track into adolescent without intervention, independent of gender which may further increase the variability of low MC prevalence in adolescents [11, 14, 31-33].

In addition, there is a high reported incidence of low MC in children who were born preterm and born with low birth weights [11, 14, 34-38]. A systematic review from Edwards *et al.,* [35] indicated that low birth weight and preterm populations showed a higher risk of low MC compared to prevalence described by the DSM-5 [14] of 5-6%. Further evidence from a large cohort study investigated early life factors which may increase the chance of developing low MC, such as smoking and alcohol consumption during pregnancy, maternal age of conception and severity of preterm birth [36]. They concluded that as gestational age decreased, thus, increased prematurity brought about increased risk of low MC. However, due to the large sample size (n=32,097), there are limitations in their measurement of low MC. A parental questionnaire, the DCDQ-07, was used to assess low MC, and recent evidence indicates this is inadequate when identifying low MC alone [34]. Even though these limitations require caution, supporting evidence indicates that there is a higher incidence of low MC in children born preterm and with low birth weights which are also associated with other comorbidities [34].

1.1.3 Comorbidities

The concurrence of other developmental disorders has been strongly identified in children with low MC. However, it has only been recently acknowledged in the latest definition from the DSM-5 [14] that other pervasive conditions can coexist with low MC [37]. Conditions such as Attention Deficit Hyperactivity Disorder (ADHD), Specific Language Impairment (SLI), learning difficulties, Autism Spectrum Disorder (ASD) and several other emotional and behavioural conditions have all shown a high level of prevalence in children with low MC [11, 14, 22, 37, 39]. ADHD has shown one of the highest rates of co-occurrence with low MC, with studies suggesting around 50% of children with low MC have symptoms associated with ADHD [11, 22, 37, 40, 41]. This high level of coexistence between low MC and ADHD has led to some researchers to define the condition as deficits in attention, motor control and perception (DAMP), [42] and hypothesised a shared aetiology, but this terminology is not universally accepted and has not been defined by the DSM-5 [14] manual. Even though these developmental disorders show high associations with low MC, the overall consensus is to define these terms separately and describe them as singular conditions with high comorbidity rates [1]. This is important as not all patients with low MC present with other developmental disorders and vice versa. Assessment of specific symptoms for individual conditions should thus be undertaken as set out by the DSM-5 [14], but understanding the frequency at which other developmental disorders coexist is important for clinicians and treatment plans [11, 43].

1.1.4 Guidelines

The European guidelines for children with DCD have been created by the European Academy for Childhood Disability (EACD) [11]. They set out to clarify the most recent clinical evidence in the definition, diagnosis, assessment and interventions for developmental coordination disorder (DCD). These guidelines were approved by the German Association of Scientific Medical Societies (AWMF)[12] and have been recommended for use in other countries [11]. As these guidelines were established through a European health care system, it was deemed appropriate to adapt them to the UK. This was important as there was a lack of guidance in the educational environment, which has been an important aspect for children with low MC in the UK [12].

Guidelines state that DCD should only be used as a clinical definition in countries which have adopted the classification according to the DSM-5 [14] and countries which have adopted the International Classification of Disease version 11 [ICD-11] are recommended to use the term Specific Developmental Disorder of Motor Function (SDDMF) [1, 11]. As the UK has adopted the DSM-5 [14] classification, the diagnosis of the term DCD should only be made by professionals who are qualified to examine the four criteria as set out by the DSM-5 [14]. It is recommended that the assessment of criteria A be carried out by the Movement Assessment Battery for Children 2nd edition (MABC2), using the lowest 15th percentile as a cut-off point to determine motor skills which are significantly below that of their expected age. All children with DCD should receive some form of intervention, as evidence indicates MC can be improved by a range of different treatment methods. It is recommended that task-oriented approaches, which focus on the motor learning of a specific task, have the strongest efficacy when trying to improve MC and should be adopted when treating children with DCD [11, 43, 44]. A recent systematic review and meta-analysis have since indicated a combination of task and process-oriented approaches are beneficial with greater importance placed on task duration, repetition and intensity when developing MC [45].

As the majority of improving MC in children and adolescents takes part in the school and specifically physical education lessons with a view to increase physical activity, it is important to understand the MC requirements each student must be taught at each key stage of the curriculum, as described by the UK Department for Education. The UK National Curriculum is divided into 4 key stages, which cover primary school children, Key Stage 1 (5-7year olds) Key Stage 2 (8-11 year olds) and secondary school children, Key Stage 3 (12-14 years old) and Key Stage 4 (15-16year olds)[46]. In Key Stage 1, children are required to master fundamental movements such as running, jumping, throwing and catching and start to use these in a range of physical activities. As they progress into Key Stage 2 they are then required to be taught to use these fundamental movement skills in isolation and in combination with each other [46]. In Key Stage 3 and 4, an emphasis is placed on developing the fundamental movement skills learned in Key Stage 1 and 2, which should improve competence and confidence in these movements and apply them to sports and PA [46]. However, it is unclear what standard these age groups need to accomplish, to indicate they have reached age-related MC, with no assessment or plan if these children show inadequate MC. Unfortunately, there is varying theories of MC development and how it interacts with PA therefore, it is difficult to provide adequate interventions to improve MC and PA. The next section will discuss the dominant theories of MC development.

1.2 Motor Development Theories

Motor development is viewed as the process of change in motor behaviours, involving interactions with task demands, the environment and biology of the individual [47]. Understanding motor development is important, as it improves educational techniques and interventions not only in typically developing population but in populations with slower or altered development [47]. Motor development can directly affect health in children, where delays can cause health problems as children age into adolescence and adulthood [3, 19, 48, 49]. Stodden *et al.,* [49] and Robinson *et al.,* [3] have shown that the development of MC positively affects PA levels, health-related fitness measures and weight status throughout the life span.

As motor development is an important area of research due to its association with PA and subsequent health benefits [3], it has become increasingly important to improve the validity and reliability of its measurement. Understanding motor development must have a strong underpinning theory and data to support it. However, there are many different motor development theories, with no overall consensus [50]. This section will describe the most common theories used to underpin assessments of MC and their association with PA and health-related fitness.

1.2.1 General Motor Abilities (GMA) Model

General motor ability (GMA) is a concept that a single trait or capacity of an individual underlies the performance of all movement skills [51, 52]. The first hierarchical ordering of this concept had GMA as the base level, then motor abilities on the second level, which consisted of multi-limb coordination, reaction time, explosive strength, and were thought of as biologically determined, which developed through maturation with little progression from practice. The third level was movement skill and consisted of movements such as running, throwing, writing and speaking. These movements were thought to be modifiable with practice and they were grouped into similar movement patterns. Movement skills differed from motor abilities because movement skills were considered external and observable, unlike motor abilities which are defined as internal processes [51, 52]. This concept was later developed by Burton and Rodgerson [51] into four levels of hierarchical motor development. Their concept built on the previous version, with GMA still at its base, with the addition of movement skill foundations at the second level, then followed by movement skill set and movement skills.

Movement skill foundations are defined as physical, mental and emotional constraints on the performance of movement skills (e.g. balance/postural control, body composition, flexibility, cognition, muscular strength, muscular endurance, sensory function). It is stated that genetics have the greatest influence on movement skill foundations, not directly on the movement skills themselves. It is also important to understand that movement skill foundations will affect movement skills in different ways. For example, increased body fat composition can be detrimental to endurance-based activities but may be beneficial when striking an object [51]. Movement skill sets are the grouping of similar movement skills into subsets, these include locomotor, object control and stability [50, 51]. Movement skills share a similar function and can be modified by practice. These include but are not limited to, running, walking, writing, jumping, speaking, catching, striking, and kicking.

Table 1 shows the difference between the old GMA concept and the new concept. Both define general motor ability the same and have it at the base of their concept. Motor abilities were separated into two levels, movement skill foundation and movement skill set. Movement skill foundations describe the facilitators and limiters to movement skills and the influence of genetics but are not classed as actual movement skills. Movement skill sets are groups of similar movements, which are influenced by age and practise. This was lacking in the previous version of the GMA where motor abilities were generalised across skills. Movement skills were defined as the same for both concepts.

Table 1: Summary of differences between Old and New GMA concepts

<table>
<tr><th>Old GMA Concept</th><th>New GMA Concept</th></tr>
<tr><td>Movement Skill - (walking, running, throwing, catching, striking, kicking, jumping etc.) (external process)</td><td>Movement Skill - (walking, running, throwing, catching, striking, kicking, jumping etc.)</td></tr>
<tr><td rowspan="2">Motor Abilities - Generalised across skills, and not thought to change with age or practice. (internal process)</td><td>Movement skillset – Groups of similar movement skills, will change with age and practice (locomotion, object control)</td></tr>
<tr><td>Movement skill foundations - Limiters and facilitators for movement skills, genetics has the biggest influence (muscle strength, muscle endurance, power, flexibility, body composition)</td></tr>
<tr><td>General Motor Ability – a single underlying trait of an individual’s movement performance.</td><td>General Motor Ability – a single underlying trait of an individual’s movement performance</td></tr>
</table>

Over recent years, evidence has supported [10, 50, 51, 53] and rejected [54, 55] the concept of general motor ability in motor development. After the introduction of a theoretical single trait underlying all movement skill, a new statistical analysis was used to assess MC. Factor analysis was introduced and applied to MC measures, which indicated low intercorrelations between multiple test items and composite scores with test batteries. This led to the conclusion that MC was derived from multiple latent factors rather than a single factor [10, 50, 51].

However, conclusions made from these statistical methods may be limited. Marteniuk [56] suggested that if a general motor ability was supported then correlations should account for 50% of the variance and therefore, correlations below 0.7 disprove GMA [10, 50, 51]. These cut-off values have no statistical or theoretical base and have been developed through expert opinion. It is argued that these cut-off values are too high to disprove GMA and there are many factors which have not been taken into consideration which might explain the low correlations but still support GMA [10, 50]. Factors such as task learning, task characteristics (dexterity vs strength), stability or dynamic tasks and biological development can reduce intercorrelations between skills and between movement batteries used to assess MC without concluding that there is an absence of a single trait for MC [50, 53].

Recent research has supported the presence of a single trait which underlies MC development as described by Burton and Rodgerson [51]. Ibrahim *et al.,* [53] performed a higher-order factor analysis on 330 adolescent's MC skills. The first order analysis identified that the individual test items used in the movement battery assessment loaded into four component groups consisting of movement coordination, kinaesthetic integration, postural control and explosive power for boys. The girl's group indicated a different first-order grouping of test items into movement coordination, postural control, and static balance. The second-order analysis conducted on the gender-specific first-order factor showed evidence of loading onto a single trait for MC. The second-order factor analysis indicated 45.5% and 59.5% of the variance for boys and girls respectively was attributed to one factor. This study not only suggests the presence of a single motor trait but also highlights the need to separate genders when assessing for MC. Therefore, the previous studies with low intercorrelations between test items, composite score and test batteries may have been exacerbated by the analysis of combined genders [50]. This study was unable to control for maturation, which can vary quite widely at this age (boys 13.1yrs ± 1, girls 13.4yrs ± 1) and can affect height, weight, and strength, which might impact these results when comparing to other age groups. The higher-order factor analysis also exhibits some limitations, and other methods have been proposed to clarify the presence of a single trait underlying motor performance [10].

Utesch *et al.,* [10] assessed the theory of a unidimensional concept of motor development using Item Response Theory (IRT). Their study assessed this concept in 1467 children aged 3-6yrs and measured MC using the MOT 4-6. Their results suggest a unidimensional concept of MC for young children, which is in agreement with Hands and Larkin [57]. However, this method also indicates that this model is adequate when assessing both genders together unlike the higher-order factor analysis of Hands and Larkin [57]. This may be because of the differences in ages of the participants between these two studies. Younger children are more likely to have similar MC levels compared to gender differences in adolescents, where biological and psychosocial influences may cause increased differentiation of movement skills. In addition, this study has assessed the unidimensional concept to one specific movement battery test (MOT 4-6). Therefore, other movement battery assessments may not fit this one-dimensional concept.

To date it is not possible to confirm or disprove a unidimensional concept for MC and further research is required to understand how age, gender, maturation and environmental factors may modify this concept. However, the majority of assessments used to measure MC (MABC 2, BOT 2, MAND, TGMD 2) produce a total test score of MC, which may suggest these tests assume a unidimensional concept [53].

1.2.2 Hourglass Model and Mountain of Motor Development

Clark and Metcalfe [58] mountain of motor development metaphor and Gallahue and Ozmun [47] motor development model both describe the development of motor skill progression across the life span and progress the work completed by Seefeldt [59]. These theories are both set in the dynamical systems perspective and explain and describe the product and process of motor development simultaneously [60]. Both theories organise the development of motor skills in a phase or stage-like process where more advance motor skills are produced through the cumulative and sequential progression of simpler more fundamental skills. However, it is important to state that these motor skill developments are not produced solely from maturation. These motor skill progressions require constraints from the environment to continually develop and adapt. Therefore, Gallahue and Ozmun [47] and Clark and Metcalfe [58] theories are thought of as a dynamic, non-linear process which can progress and decline at different time points across the life span [47, 58, 60, 61].

1.2.3 Hourglass Model

The Gallahue and Ozmun [47] model of motor development consist of four stages, reflexive movement stage, rudimentary movement phase, fundamental movement phase, and specialised movement phase. Each of these phases has sub-stages, which overlap with each other along with the four main phases. Information is also provided on the age at which these developmental periods should roughly coincide. This is a rough estimate and can vary significantly and should not be used for clinical judgement [60].

Reflexive movement phase

This phase is characterised by involuntary movements produced by stimuli and is controlled by the brain stem and spinal cord. This phase is sub-divided into two sections as stated by Gallahue and Ozmun [47] the encoding stage and the decoding stage. The encoding stage is where the infant gathers information from its external environment from different stimuli with varying intensity and duration. It is typically thought this stage lasts from foetus to four months of age [60]. The decoding phase involves the gradual decrease in reflexive movements to a more voluntary process, where the infant gathers and voluntary reacts to sensory information. This period ranges from four months to one year of age [47, 60].

Rudimentary movement phase

This phase focuses on the beginning of voluntary movements from the infant and ranges from birth to the second year of life. This phase is influenced by maturation and the sequence of movement progression can be predicted with some variation depending on the constraints applied by genetic and environmental factors. This phase is further sub-divided into two sub-sections, reflex inhibition and precontrol. The reflex inhibition stage overlaps with the previous decoding stage. This stage increases inhibition in the reflexive movement patterns and progresses to more global voluntary movements like grasping for an object. The precontrol stage is prevalent between the ages of one to two years and greater precision and control of movements is achieved. This increase in movement control has been explained through increased development of higher brain functions such as the integration of sensory and motor systems [47, 60].

Fundamental movement phase

This third phase describes movements, which are fundamental to activities of daily living and are required in the majority of physical activities. They include movements such as locomotor, object control and postural stability. This phase is sub-divided into three stages which describe the level of control associated with fundamental movement skills. These consist of the initial stage where goal-directed movement is produced in an uncoordinated unrefined manner typically in infants aged 2-3 years. The elementary stage, where movement refinement is improved with better spatial and temporal control in addition to benefits in movement products through maturation, but mastery of these skills are still lacking (ages 4-5 years). The last stage is the proficient stage whereby movement is efficient and controlled, which is typically determined at ages 6-7 years old [47, 60].

Specialised movement phase

The final stage of the Hourglass model describes the mastery of the fundamental movements and their adaption into more complex and demanding situations like competitive games and sports. This phase of motor development is divided into three subsections, the transitional stage, application stage and the life utilization phase. The transitional stage describes the further progression and development of the fundamental movement phase and their application into game-based activities, which typically occurs at 7-8 years. The application stage identifies the increased capacity of cognition to these fundamental movement skills with an emphasis on the measurement of the product of the movement becoming more widespread. This stage has typically been described in children and adolescents ranging from 10-13 years of age. It has been noted as a time period in which PA has started to decline at a quicker rate, with a reduction in sports and competitive games cited as a reason for this decline [62, 63]. The final stage of this phase is the lifelong utilisation phase. This phase identifies the mastery of fundamental movement skills and the process of using these skills to benefit PA participation across the life span [47, 60].

1.2.4 Mountain of Motor Development Metaphor

This metaphor describes motor development as a mountain which has to be climbed in order to achieve skilled movement. It is similar to the Gallahue and Ozmun [47] hourglass model where basic movements are built upon to produce more complex movements. This idea of motor development is categorised as a metaphor, which is different to a model, a metaphor is a first initial idea designed to help understand a complex process, whereas, a model has been supported through empirical evidence. As such, this metaphor should be considered a tool to help understand the complex process of motor development rather than a definitive theory of motor development, until further research has been concluded. There are six phases of Clark and Metcalfe [58] mountain of movement development metaphor, consisting of reflexive, preadapted, fundamental patterns, context-specific, skilful and compensation [58].

Reflexive period

The first stage of the mountain of motor development is similar to that of Gallahue and Ozmun [47]. The reflexive period is the initial stage of motor development where the infant reacts to stimulus in an automated manner and is seen as a protective mechanism necessary for survival [58, 61]. This period is subdivided into two subsections, primitive control and postural control. Primitive control can be described as reflexes necessary for feeding, and protection from harmful stimuli. Postural control is associated with reflexes triggered by changes in body position, as related to the environment such as head control. These reflexes are an important start to the progression of motor development but extended time in the reflexive period has indicated delayed motor progression in subsequent motor development periods [60].

Preadapted period

The preadapted period can be related to Gallahue and Ozmun [47] rudimentary phase in their hourglass model. The preadapted period also indicates the increase of voluntary movement and the inhibition of reflexive movement as the main part of their second level. However, Clark and Metcalfe [58] state that this period concludes with the ability of the individual’s attempt to feed themselves and initiate walking patterns. Therefore, the age ranges for this developmental stage differ between this metaphor and the previous model of motor development [58, 60, 61].

Fundamental patterns

This period describes the acquisition of fundamental movement skills, such as locomotor and object control. Clark and Metcalfe [58] state that this period is important for the development of complex movements required for games and sporting activities and can be negatively affected by a delay in the progression from the previous motor development period. This period is similar to that of the fundamental movement phase in the hourglass model and is important for future PA and health [47, 58, 61].

Context-specific

This period is defined as the stage at which the fundamental movement patterns are combined, practised and developed into more complex movements, which focus on specific environmental context [58, 61]. This period can be considered similar to that of Gallahue and Ozmun [47] specialised movement phase, where the three sub-sections track the progression of specialised movement skills from 7-13 years old.

Skilful period

The skilful period defines reaching the top of the mountain of motor development and is a consequence of years of practice in a particular movement skill or set of similar movement skills [58, 60, 61]. These are refined and adapt to changing environmental constraints. This period can be compared to Gallahue and Ozmun [47] lifelong utilisation phase, because to achieve such high levels of movement skill competence there needs to be a continued period of practice and development from adolescence into adulthood.

Compensation

The last stage in the mountain of motor development is the compensation period. This period describes the adaptations to movement skill in relation to the effects of injury or old age, whereby movement skills may reduce or become less refined due to different constraints applied from the environment and biology of the individual. However, this period is not about reduced movement competence but the ability to adapt to changing constraints in ways that are different to the initial ascent of the mountain, such as old age and injury [58, 60, 61].

1.2.5 Reciprocal relationship between motor competence and physical activity model

This recent model of motor development hypothesises a reciprocal relationship between MC and PA (see 1.3 Physical Activity (PA)) from early childhood into adulthood [3, 49]. Its development has been attributed to the Seefeldt [59] motor proficiency barrier and the Clark and Metcalfe [58] mountain of motor development metaphor. The model describes PA as the main driver in promoting MC in early childhood and due to the varying levels of PA and environmental constraints at this age, it is predicted that the relationship between PA and MC will be low [49]. As these children engage in greater levels of PA there is a higher probability for further development of fundamental movement skills. With the development of these more complex movements the opportunity to participate in sports and game-based activities increases. As these children age into adolescence, the relationship between PA and MC becomes reciprocal, thus, adolescents with adequate levels of MC engage in more PA, which develops more sophisticated movement skills whereas, adolescents with low MC reduce their levels of PA and have limited opportunity to develop their movement skills [49].

This reciprocal model is not a simple two-way process between PA and MC development. There are other factors which positively or negatively mediate this relationship [3, 49]. Robinson *et al.,* [3] state that health-related fitness (HRF), and self-perceptions of MC can affect this relationship which can change over developmental time. It is suggested that MC will promote HRF in early childhood, and then develops into HRF, mediating the relationship between MC and PA as children age into adolescence. The reasoning behind this concept is children with higher levels of fitness would be able to participate in PA for longer and therefore, give more opportunity for motor skill development. The influence of self-perceived MC in the reciprocal relationship between PA and MC is greater in late childhood and early adolescence, where increased cognition can better identify their own motor abilities. As these children age into adolescence, they are more aware of their limitations compared to their younger selves and this may modify their desire to participate in PA. In addition, bodyweight status such as healthy or unhealthy weight has been described as a factor which can influence this model. It is not stated as a mediator for the relationship between PA and MC but has an inverse relationship with MC. This relationship is suggested to become stronger from pre-school age to early childhood but evidence into adolescents is inconclusive [3]. The reciprocal relationship between PA and MC can have a positive and negative effect on body weight status, where a positive relationship promotes a healthy weight status and a negative relationship increases the probability of an unhealthy body weight status. Bodyweight status can then produce a negative or positive feedback loop into the PA MC reciprocal relationship causing increased or decreased engagement in MC and PA [49].

Evidence for the relationship between MC and PA has increased over recent years. Multiple cross-sectional studies have suggested a positive relationship between MC and PA [64-66] and a greater likelihood of children participating in high sedentary behaviour possessing low levels of MC [67]. Multiple systematic reviews concluded that there is sufficient evidence to support this relationship between MC and PA levels [7, 19, 68] with Lubans *et al.,* [19] directly supporting the Stodden *et al.,* [49] model. However, there have been inconsistencies in results from other studies that have analysed this relationship. Research from Hands *et al.,* [69] suggests there is no relationship between MC and PA in adolescents aged 14 years, and Khodaverdi *et al.,* [65] reported a significant relationship between locomotor skill and PA in girls aged 8-9 years but reported no relationship between object control and PA. The differences reported in these studies may be explained by the methodologies used and the theory of motor development from Stodden *et al.,* [49] model.

Across the literature, many methods have been used to measure MC and PA. Hands *et al.,* [69] measured PA through waist-worn pedometers, which are appropriate in population-based studies but are unable to measure the intensity of PA, unlike accelerometry measures. The McCarron Assessment of Neuromuscular Development (MAND)[70] was used to evaluate MC. This test has good reliability and validity but assesses five different gross motor tasks and five different fine motor tasks. This equal weighting of measures between fine and gross motor movements may confuse results when comparing to other studies which only assess fundamental movement skills (gross motor) with PA. It is also important to highlight the change in the relationship between MC and PA over developmental time as stated by Stodden *et al.,* [49] and Clark and Metcalfe [58]. When assessing locomotor and object control separately to PA then age must be considered, as locomotor skills are developed at an earlier age compared to object control which will affect the relationship with PA when measured cross-sectionally, with younger children showing a weaker relationship between object control and PA and older adolescents showing a strong relationship between object control and PA [65].

Further evidence from longitudinal studies supports the relationship between MC and PA [71-73] and Stodden *et al.,* [49] model. These three longitudinal studies all conclude that MC is associated with future PA levels, stating higher levels of MC resulted in higher levels of PA when compared to moderate or low levels of MC [73]. This relationship was similar to Green *et al.,* [71] who suggested low MC especially object control was predictive of low PA levels in boys but not girls. Larsen *et al.,* [72] evaluated the relationship between MC and PA in children aged 6-12 years and then followed up three years later. Their results indicate a significant positive association between MC measures and PA.

However, these studies have limitations in their respective study designs. Green *et al.,* [71] used one measure from each sub-section of the Movement Assessment Battery for Children 2 (MABC2), which consists of one fine dexterity test, one precision throwing test, and one dynamic balance test. This may explain the non-significant association between MC and PA for girls, as the validity of the MABC2 requires all test items to be completed [74]. The limitations presented in Lopes *et al.,* [73] methodology consist of the tests used to assess MC and PA. The Körperkoordinationstest für Kinder (KTK) was used to assess MC, which consists of four test items measuring locomotion and balance. There is no measure assessing object control which is a major component of other MC assessment tools. In addition, the measure of PA was a self-reported PA questionnaire for the previous 7 days. This type of PA measure is appropriate in large epidemiological studies but is less valid compared to more objective measures of PA. Larsen *et al.,* [72] showed similar limitations to their methodologies when measuring MC. Their study used two measures of MC one from the KTK (backward balance) and one from Der Allgemeiner Sportmotorischer Test fur Kinder von 6–11 Jahren (precision throw). These measures were analysed separately, transferred into z-scores and combined with other health-related fitness measures such as handgrip strength, shuttle run, vertical jump and the Andersen test. These measures, when used individually or as a composite score with these previously mentioned tests, have little or no validity when used in this way. Finally, these studies evaluated the effect of MC on PA but did not analyse the relationship of PA on MC and so the reciprocal relationship cannot be determined.

A recent study by Lima *et al.,* [75] analysed the reciprocal relationship between MC and PA in children and adolescents and how physical fitness mediates this relationship longitudinally. Their results indicated, from structural equation modelling (SEM), that physical activity (VPA) was directly associated with MC. MVPA presented an association with MC when cardiorespiratory fitness was introduced as a mediator. When this relationship was reversed MC was directly associated with VPA, but not MVPA, but fitness mediated the relationship between MC and MVPA. Overall they concluded that a reciprocal longitudinal relationship between PA and MC occurred, and this supported Stodden *et al.,* [49] model. To date, this is the strongest support for the Stodden *et al.,* [49] model of motor development, but limitations need to be considered when interpreting results. These include the measure of MC; the KTK only measures limited aspects of MC (locomotion and balance) and does not assess object control. This is important when considering the age of the participants as locomotor skills are developed before more complex object control skills, which may explain the subtle differences in the direct association between MVPA and MC.

1.2.6 Development of Foundational Movement Skills: A Conceptual Model for Physical Activity Across the Lifespan

This conceptual model of movement skill development [76] links and expands the work conducted by Robinson *et al.,* [3], Gallahue and Ozmun [47], Stodden *et al.,* [49], Burton and Rodgerson [51], Clark and Metcalfe [58]. The main phases of movement skill development are similar to that of Clark and Metcalfe [58] and Gallahue and Ozmun [47], where reflexive movements are followed by rudimentary movements, foundational movements and then specialised movement skills.

This model develops the idea of changing the categorisation of fundamental movement skills and expanding it into foundational movement skills. This change highlights the importance of including movement skills, which are beneficial in promoting PA, which has not been fully captured in the previous fundamental movement skills definition. It introduces movements such as swimming, cycling and resistance training into the new movement category along with locomotion, object control and stability. It is argued that these movement skills also provide a foundation which increases the opportunity to be physically active which was not covered by the previous models. Additionally, this new model introduces the concept of cultural and geographic constraints on foundational movement skill development. For example, developing swimming skills in a location which readily offers the opportunity (e.g. ocean, lake) may increase the participation in PA. Even though this model has expanded previous models of motor development which has a varied quality of empirical evidence, this specific model has yet to be supported by other research.

1.3 Physical Activity (PA)

1.3.1 Definitions and Terminology

PA is defined as any bodily movement produced by skeletal muscle that requires energy expenditure above resting basal metabolic rate [7, 77, 78]. This is different from exercise or physical fitness, whereby exercise is defined as a type of PA undertaken to improve a subsection of physical fitness in a planned and structured program. Physical fitness is comprised of skill-related components (e.g. agility, speed, power, balance etc.), and health-related components (e.g. cardiovascular fitness, muscular strength, body composition etc.) [78]. Moderate to vigorous physical activity (MVPA) is universally used to record PA levels with many international guidelines adopting this approach [77, 79-84]. Moderate physical activity (MPA) has been categorised as activities between 3-6 metabolic equivalents (METs), with vigorous physical activity (VPA) defined as activities >6METs [79, 82, 84] see section 2.2 Measuring Physical Activity (PA).

1.3.2 General Health Benefits of PA

Performing the recommended levels of MVPA bring about health benefits and promote normal growth and development across the life span [85]. MVPA has shown to reduce the risk of acquiring health conditions such as cancer, diabetes, cardiovascular disease, bone health, psychological/emotional health and unhealthy body composition [4, 77, 79, 85-88]. These extensive benefits of PA on health throughout all ages, has led to the development and research of the minimum requirements needed to promote these benefits.

1.3.3 PA Recommended Guidelines

The World Health Organisation and recent UK governmental health policies [89] recommend that children and adolescents should be completing 60 minutes of MVPA per day and participating in activities beneficial for musculoskeletal health three times per week [77, 79, 82, 83, 90]. Unfortunately, a large amount of data has reported that relatively few young people are meeting these recommendations [2, 91-95]. Data from the WHO in 2018 [77] indicate that the percentage of adolescents (11-17years) not meeting the recommended MVPA guidelines is 81%. This is supported by Hallal *et al.,* [96] where they report 80.3% of adolescents aged 13-15 years do not meet the MVPA guidelines, and Cooper *et al.,* [91] reporting only 9% of boys and 1.9% of girls aged between 5-17 years met these guidelines. This international data on PA levels in adolescents is also reflected in the UK population. Evidence from Wilkie *et al.,* [2] indicate 22.1% of boys and 15% of girls aged 11-15 years are meeting the recommended daily levels of MVPA, with supporting evidence indicating that boys are more active than girls across adolescents but the majority are not completing 60 minutes of MVPA per day [86, 97].

Further evidence reports a reduction in PA levels as children age into adolescence and adulthood [63, 98, 99]. Evidence from Corder *et al.,* [92] analysed these changes and reports a reduction in 5.2mins/day in MVPA from adolescence to adulthood. When MVPA was measured exclusively by accelerometers this reduction increased to 7.4mins/day. A gender difference was reported, suggesting a greater reduction in boys MVPA compared to girls, however, boys were more active than girls in early adolescence, which may explain this greater reduction over time. This reduction in PA levels from adolescence to adulthood is further supported by Dumith *et al.,* [63]. Their systematic review suggests a reduction in PA across adolescence of 7% per year. This would equate to an overall decline in PA across adolescences of 60-70%. These high levels of PA decline along with low levels of initial MVPA cause concern for current and future health status across the population. This effect has already been reported in the literature with a major increase in levels of overweight/obesity in children, adolescences and adulthood [99]. Evidence has suggested the prevalence of overweight/obesity has increased internationally in adults and children by 27.5% and 47.1% respectively, between 1980 and 2013 [99]. The reasons for the increase in overweight and obesity levels may be as a result of increased high calorie intake, changes in diet composition, increased sedentary time and reduced PA levels [87, 99].

This has led to the discussion that 30mins of MVPA may produce health benefits to body weight status and cardiovascular system which, are related to 60mins of MVPA and should be a target in the population of children and adolescents who are performing very little MVPA. This may also be used as a means to encourage more MVPA over time [79, 82, 100]. However, PA has a dose-response and greater PA durations and intensities increase further health benefits [101]. As so many children and adolescents are not meeting the PA guidelines, research has tried to identify areas which can be targeted to increase and maintain higher levels of PA. Increasing MC levels in children and adolescents has been hypothesised as way to increase current and future PA levels. [3, 7, 19, 68, 85]. However, there is inconsistent evidence regarding the relationship between MC and PA in adolescents [68]. Further information is required to understand the impact MC may have on PA duration and intensities especially in adolescents, as PA undertaken in adolescence is reflective in adulthood. And higher PA intensities have also been suggested to provide superior benefits and increase efficiency in improving overall health when compared to moderate PA intensities [102]. Furthermore, it is vital to provide information on the amount of MC required in order to gain improvements in PA duration and higher intensities. This will enable physical education teachers and health care professionals to test MC in adolescents and determine if it meets the requirements for PA durations and increasing higher intensities (discussed in section 1.1.4 Guidelines). Therefore, further research is required to explore MC and PA in adolescents (see section 1.5.3 study 1).

1.4 Walking Analysis

1.4.1 Definitions and Terminology

Normal human walking can be described as bipedal locomotion that provides support and propulsion which is energy efficient [103]. Walking is reliant on many different physiological processes working in combination with each other to function correctly. Neurological and musculoskeletal systems must produce a controlled and well-timed sequence of events for safe and efficient walking [103]. The inverted pendulum model describes the energy conservation (Figure 1) through the reciprocal transfer of potential and kinetic energies acting on the centre of mass throughout the gait cycle. This has evolved in humans to provide an efficient method of locomotion. However, reductions in motor control can cause inefficient walking patterns with reduced energy conservation between potential and kinetic transfer, which increases metabolic demand [104, 105]. This has resulted in research identifying and analysing the sequential events of the walking gait cycle. Initially, the walking gait cycle can be subdivided into two sections, the stance phase and the swing phase, which can then be categorised into the support phase and loading response (Figure 2).

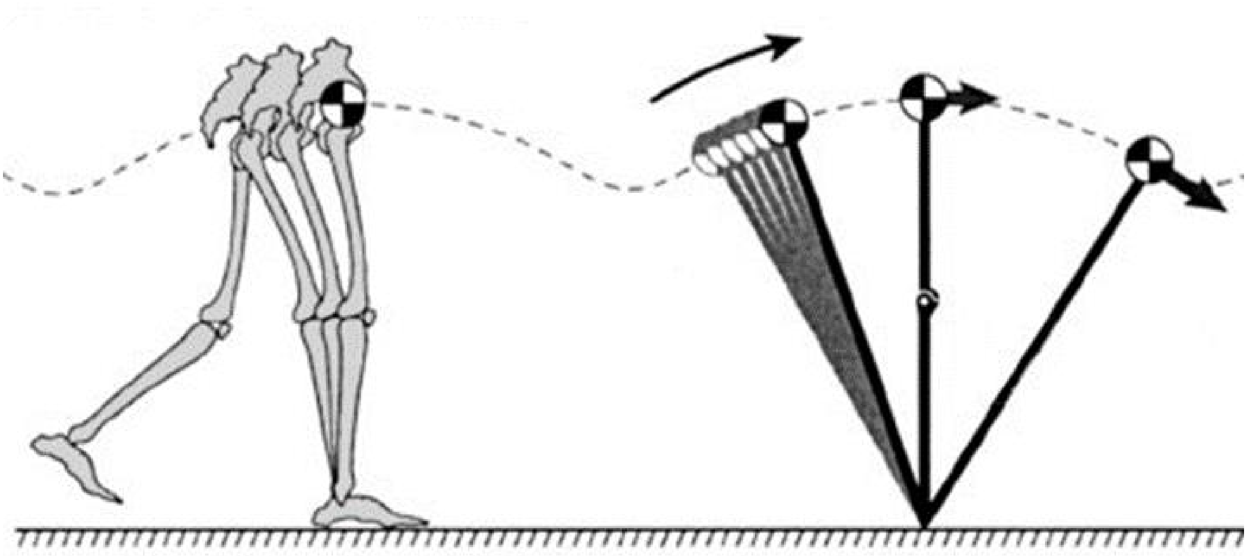

Figure 1: Inverted pendulum model [106]

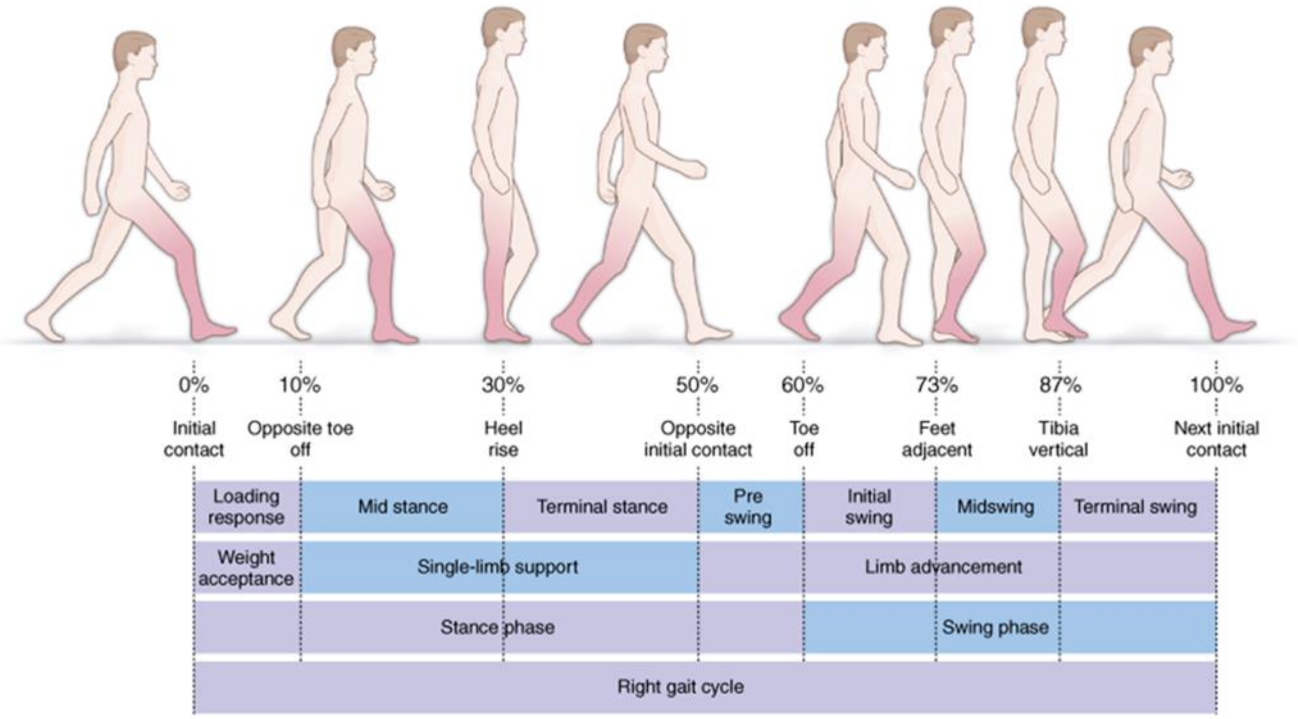

Figure 2: Gait Cycle of human walking [107]

1.4.2 Spatial-Temporal parameters

The events in the gait cycle allow for spatial (i.e. stride length) and temporal (i.e. stride time) measures (

Figure **3**) to be calculated and their variability [108]. Differences in spatial-temporal gait parameters compared to the typically developed population can indicate deficits in motor control [108, 109]. This can present as reduced walking speed through a reduction in cadence or stride length, and increased variability of spatial-temporal gait parameters have also been indicative of altered motor control [109]. Altered motor control can also cause reductions in postural control in children which can be detected through spatial-temporal gait parameters [110, 111]. Identifying these deficits in spatial-temporal walking parameters may highlight children and adolescents who may be at risk of altered motor control, which could be attributed to slower motor development. This will have a large impact on their overall health and will require some form of intervention in order to minimise the risk to current and future health. To date there is no consistent evidence reporting differences in adolescents with low and typical levels of MC [111]. Therefore, exploring the differences in spatial-temporal walking parameters amongst adolescents with varying MC under real world conditions may provide an adequate screening tool to assess functional MC [112] (Section 1.5.2 study 2). Previously, this has been difficult to assess as variability in walking development is high [111].

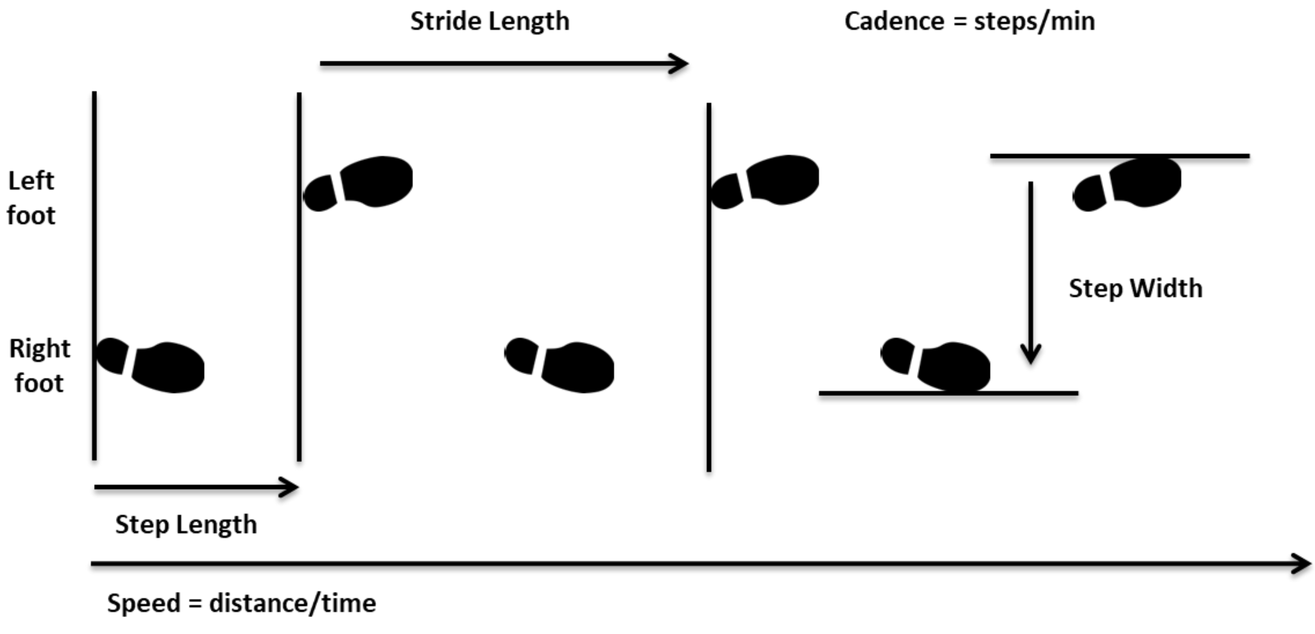

Figure 3: Spatial gait parameters

1.4.3 Development of Walking

Sutherland *et al.,* [113], have highlighted five key spatial-temporal (ST) measures which determine mature gait. These consist of cadence, walking speed, duration of double support, step length and pelvic span/ankle spread ratio. Independent walking is shown to occur around one year of age [109], with new walkers adopting a high cadence, small step length, slow walking speed and a wide base of support [113, 114]. As maturation takes place cadence decreases while step length and walking speed increase. The rate of change in these ST parameters is high up to around 4 years of age, after which the rate of change is much slower. Duration of double support and pelvic span/ankle spread ratio measures limb stability and dynamic base of support respectively. These measures are shown to improve as children age, with older children adopting a narrower base of support and longer duration in single limb support [113, 114]. Evidence indicates gait matures around 6-7 years old, with many of the ST parameters close to those measured in adults [108, 115]. As stature and lower limb length have not reached maturity at this age, the conclusion that this age group have similar ST parameters to adults are from the normalisation of ST measures. Any changes in ST parameters as children age beyond 6-7 years or differences compared to adult-like gait can be explained by growth [108]. However, other evidence has indicated only gait speed is similar from the ages of 8 years to 30 years, with normalised cadence, double support, single support, base of support and step length all continue to develop into the mid to late teens [116].

Variability of ST gait parameters has also shown to continue to develop into the mid to late teenage years [117-119]. This variability of ST parameters indicates how well gait is controlled, which may take longer to refine than functional measures of ST parameters such as overall group mean comparisons of ST measures [117]. Muller *et al.,* [119] reports variability in walking speed is inversely proportional to age, with Hausdorff *et al.,* [118] reporting variability in stride to stride parameters up to 14 years of age and Gouelle *et al.,* [117] concluded that gait variability decreases in children as they age but is still significantly different from adults at ages 14-17years. This slower maturation of gait variability may be explained by structural, biomechanical and neural control factors [118-121]. Studies have indicated that mature gait with adult-like variability scores may only be present when all these components have had time to fully develop, suggested to be around 14-17 years of age [116, 118]. Therefore, differences in gait variability in adolescents compared to peer-related norms may indicate some differences in the optimization of walking [119]. Muller *et al.,* [119] have indicated that fully developed walking variability is a result of optimal cadence, symmetry, stability of movement pattern and balance control. This has been supported by work from Assaiante *et al.,* [120] who has indicated that young children aged 7-8 years can improve walking variability as improvements in balance and posture increase. So adolescents with differences in walking variability compared to age matched peers may have reduced postural and balance control which could be caused by a deficit in MC. This has therefore, resulted in a large increase in research assessing levels of MC and walking control in children and adolescents [111, 122-124].

As previously discussed, insufficient information is available to determine the extent MC has on adolescent's PA durations and intensities. It is unknown if a certain level of MC is required to increase PA duration and intensities. Screening adolescents for movements that reflect MC that is performed in everyday physical activities may improve our understanding. Walking analysis could provide this as it has been used to measure MC and has been targeted to increase overall PA durations [125]. This could then lead to the use of walking analysis and MC measures providing a tailored objective method to screen adolescents at risk of low PA due to reduced functional MC (Section 1.5.3 study 3).

1.5 Overall Aims and Objectives

1.5.1 Study 1 - Determine the differences in Physical Activity Levels in Adolescents with Low and Typical levels of Motor Competence

Aims: To assess the number of adolescents meeting the recommended guidelines of MVPA and if there are differences in the duration of MVPA and VPA between adolescents with low and typical levels of motor competence. Furthermore, to evaluate the required level of motor competence which is required to discriminate higher levels of MVPA and VPA.

1.5.2 Study 2 – Determine the extent of the Interaction of Motor Competence and Cognitive Motor Interference on Walking Performance in Adolescents

Aims: To examine the interaction between motor competence and walking control under single task and cognitive-motor interference conditions in adolescents.

1.5.3 Study 3 – Determine the extent of the relationship between Physical Activity Levels with Spatial-Temporal Gait Parameters and Motor Competence levels in Adolescents

Aims: To investigate the relationship of spatial-temporal gait parameters and motor competence as measured by the MABC2 and the balance subsection on MVPA and VPA in adolescents.

Chapter 2 Measures of Motor Competence and Physical Activity

2.1 Measuring Motor Competence (MC)

Severe developmental delays in MC are most commonly diagnosed in preschool children [126] when mild MC deficiencies become more apparent as children start primary school. This new environment exposes children to more complex and diverse movements which can be more clearly compared to peers of the same age. A large number of MC assessments stem from a variety of different requirements from clinicians and researchers when assessing different age groups [127]. Measuring MC delay, changes due to interventions and population trends all require different considerations to most appropriately measure MC. Therefore, individual assessments have been created to answer these questions [126, 128]. This can be further complicated when taking into consideration the practical requirements of the assessment, such as the time taken to administer the test, user-friendliness, cost, equipment and assessment location may limit the choice of MC assessment [128, 129]. This section will describe the most common and most recent MC assessments in children and adolescents and discuss their purpose.

The two broad methods under which MC assessments can be categorised are objective and subjective measures [128]. Objective measures quantify MC and are independent of the observer assessing the task. Subjective measures infer more qualitative information of the movement and are dependent on the observer assessing the movement task. These methods have shown good validity and reliability, but assess different aspects of movement and therefore, cannot capture the complete assessment of the movement task separately [128].

2.1.1 Subjective MC Measures

Subjective measures of MC have been widely used in the literature across all ages from preschool children to adolescents [128]. These mainly consist of self-perception of MC, where information on how an individual rates their own MC is assessed [130], and proxy reports from either a parent or teacher [128, 131]. The construct of self-perception in relation to MC is thought to be multidimensional and changes with age [132, 133]. The use of self-perception and proxy report questionnaires have mainly involved large sample sizes as they provide a cheap and user-friendly option, which takes a relatively short time to complete [128].

In early childhood (< 8yrs) it has been hypothesized that the association between self-perceived MC and actual MC is low and does not reflect true MC abilities in this population [128, 130]. It is stated that younger children do not have the cognitive capacity to accurately assess their own MC abilities compared to older children and adolescents, with parents and PE teachers better at assessing children's MC levels than the children themselves [131]. Evidence indicates that younger children are unable to differentiate between the effort and the desire to produce a movement skill with the actual quality of the produced movement [130, 132]. This causes children with low MC to score themselves highly when assessing their own MC level as they perceive high amounts of effort as good MC ability [49, 134]. Therefore, the most appropriate method in assessing children's (<8yrs) MC subjectively is through a parental or teacher assessment [131].

However, evidence from Duncan *et al.,* [135], assessed self-perceived and actual MC in British children aged 4-7yrs and indicated that children who had low MC perceived their actual MC as low compared to children who had average or high levels of self-perceived MC. The differences in the reported association between perceived and actual MC may be explained by the differences in measures used to assess perceived MC. Understanding the concept which each measurement tool is designed to assess is important, as differences in self-perception and self-efficacy have been used to determine their relationship with actual MC. Self-efficacy is valid in understanding what the individual believes they can achieve whereas self-perception is more closely related to what the individual can perform [132]. More recently, simple pictorial methods have been used to assess perceived MC in young children with good levels of validity and reliability [135-138]. Their conclusions indicated that Pictorial scale for Perceived Movement Skill Competence for young children (PMSC) was valid when assessing children's perceptions of their own MC levels. However, further investigation revealed that if the movement task had been attempted before, then the children were more likely to rate their perceived MC score higher than those who had not completed the task [136]. This confounder may bias results as children may be assessing their familiarity with the movement task rather than their perceived competence.

The relationship between perceived MC and actual MC in adolescents is believed to be stronger when compared to younger children (<7yrs) [3, 49], but the evidence is inconsistent and still relatively low quality [128, 133]. Timler *et al.,* [139] assessed adolescent perceived MC compared to parental perceptions of their children's MC. They concluded that adolescent self-perceived MC is more accurate than their parent's perception. Assessment of adolescent self-perceived MC was measured using the Adolescent MC Questionnaire (AMCQ) and parental perception using the Developmental Coordination Disorder Questionnaire 2007 (DCDQ-07). Even though evidence has indicated the AMCQ was validated against the McCarron Assessment of Neuromuscular Development (MAND) no assessment of actual MC was performed in this study. Therefore, understanding the differences in adolescent or parental perceptions of MC to actual MC is limited, which could be exacerbated when comparing two completely different methods of perceived MC.

When actual MC was compared to perceived MC in a recent study, their results indicated no associations between FMS and perceived MC. McGrane *et al.,* [133] measured actual MC through 15 fundamental movement skills (FMS) and self-perception using the physical self-confidence scale in 584 adolescents, aged between 12-15yrs. They reasoned that self-perception could have been influenced by peer MC ability. If an individual was in a group of peers with low MC they may perceive themselves as having high MC abilities whereas being in a group with good MC abilities may cause a lower score of MC self-perception and therefore, introduce a bias into how they perceive their own MC levels. This indicates understanding MC through subjective measures such as self or proxy report may introduce increased measurement error when compared to objective measures [128].

2.1.2 Objective MC Measures

As MC has become widely studied in recent years, it has led to an increase in methodologies used to identify reductions or delays in children and adolescents, with a focus on as little measurement error as possible [140]. Therefore, introducing objective assessments will give a direct measure of MC and give a more valid comparison to other health measures over developmental time [128, 129]. These methodologies have ranged from lab-based assessments which have used advanced motion capture technology to assess fundamental movement skills [141, 142], to field-based assessments where direct observations have been undertaken to screen large sample sizes [24, 143, 144]. Quantifying MC is complicated as there are multiple approaches to understanding how proficiently someone can move. These approaches can be product-oriented where the end product of the movement is analysed to determine the quality of movement and processed oriented approach where the quality of the movement is assessed [129]. Understanding the differences between methodologies and approaches to assessing MC is important as there is no one method which captures a complete overview of MC [129]. This in addition to MC being a complex definition of gross, fine, upper and lower-limb movements or interactions. Objective measures, therefore, will only be able to assess one specific goal-driven movement, or provide a gross overview of MC during, for example, walking, stepping or jumping.

2.1.3 Observational MC Assessments

Direct observational measures have been used to assess MC in children and adolescents for many years [126, 128, 145, 146]. Generally, movements such as object control, locomotion, balance and fine motor control have been used to assess MC with variations on these movements between tests. These assessments are measured by a researcher or trained assessor against a set of performance criteria. This can be norm-referenced or criterion-referenced depending on the validation of the MC assessment. Similar to previous objective measures these assessments can be product or process-oriented in their approach [147] as seen in Table 2. They can be used to assess participants in a one to one setting or as a large screening session where multiple children are assessed simultaneously [128]. This large range of MC assessments is additionally influenced by the construct being assessed [148], the age group under investigation [145], and the focus on specific sub-sections of MC [149], while others report an overall score [74]. The validity and reliability differ for each of these assessments and therefore, using the most appropriate assessment for the cohort under investigation is difficult, with no agreed gold standard [127, 148].

This is highlighted by work completed by McIntyre *et al.,* [148], who compared two MC assessments, the Bruininks Oseretsky Test of Motor Proficiency-2 (BOT-2)[150] and the McCarron Assessment of Neuromuscular Development (MAND) [70]. Their results suggested that the differences in test procedure were due to the differences in individual tests used to assess MC even though they were similar in design and overall construct. The data indicates that these two assessments are identifying different populations of low MC, with the BOT-2 classifying twice as many participants with low MC compared to the MAND. The discriminatory analysis showed sensitivity of 13.2% for the BOT-2 and 6.6% for the MAND when classifying low MC, with only 4.4% of the participants classified as low MC by both MC assessments. The specificity for the whole sample was 89% which is attributed to a large number of participants with normal MC identified in both assessments. This was supported when the BOT-2 was assumed to be the gold standard measure and then compared to the MAND. Results indicated only 33% of participants were classified with low MC by both assessments.

These differences reported by McIntyre *et al.,* [148] may be attributed to variations in the way individual test items are performed and scored. Even though both assessments measure MC across all abilities there is a clear difference in the fine and gross motor skills used between the two methods. This may cause some children to perform better at one assessment compared to the other, even though they are similar in design, such as one leg balance in the MAND assessment compared to standing on one leg on a balance beam in the BOT2 assessment. In addition, variation in the transformation of raw scores to overall scores amongst MC assessment is vastly different and referenced against varying samples of children and adolescents. This may have an undesirable effect of masking some movement tasks as different subsections are loaded differently onto the overall MC score. Therefore, these variations in MC assessment can explain the different scores when using different MC assessments in the same sample. It is then important to understand which MC assessment is most appropriate for the given research question and population [148].

Once the most valid and appropriate assessment of MC has been chosen, identifying MC ability using direct observation has many advantages. This method allows for large screening sessions where multiple participants can be assessed in relativity quick and easy way [126, 147]. However, assessing large numbers in one go may be more beneficial than one researcher measuring individual participants over a longer time period, especially when interventions are applied. Equipment is cheaper than many other methods of MC assessment and teaching researchers to score individual tasks is relatively simple especially when using product-oriented approaches. Post-processing of data are simple and can give information on individual sub-sections of MC and overall scores depending on the MC assessment. Additionally, evidence has indicated that children find this type of MC assessment enjoyable when undertaken in their physical education lessons [151] which may improve engagement and therefore, the accuracy of the assessment when compared to lab-based assessments.

2.1.4 Motion Capture and Walking Analysis

Currently, there are many different movement analysis techniques which can quantify MC and walking control. These consist of kinematic and kinetic methodologies. Kinematic methods allow for continuous movement analysis and can assess MC in all fundamental movement skills (throwing, catching, locomotor, and balance), which includes walking. These range from basic video analysis of specific movements, to more advanced three-dimensional motion capture which can assess multiple kinematics in greater detail [128]. Kinetic assessment, derived from force production can also measure differences in locomotor skills, such as hopping jumping, walking and running as well as balance control [128]. These methods provide different assessments of movement and walking control with varying advantages and disadvantages.

Motion capture has been used to assess MC in children and adolescents in such movements as object control, balancing, walking and running [152, 153]. This kinematics analysis can measure acceleration, velocity, position and joint angles and had been reported to be accurate to levels of less than 1mm, depending on the measurement volume, but is regarded as the gold standard in kinematic analysis [103, 154]. However, there are some limitations to this method. As this is exclusively a lab-based method, measuring real-world movements may be less achievable. Space for more dynamic movements such as throwing, striking and game-based locomotion is impractical. In addition, cost, equipment set-up and post-assessment analysis will provide further barriers. More recent assessment methods have been designed to capture real-world movements with less obstruction on the mover, with lower costs and reduced set-up time for the researcher [155-158].

This relatively new method involves attaching a small lightweight inertial measurement unit (IMU) to the participant's body. IMUs contain multiple sensors, such as accelerometers, gyroscopes, temperature and magnetometers, which can either collect data locally or transmit data via wireless transfer protocols (Bluetooth). This allows movement to be captured in the real-world environment with little to no impact from the measurement device. This method for assessing MC can potentially assess more accurately, delays in MC and development in movements that are required in many activities of daily living in the free-living environment [157]. Activities such as hopping, running and throwing have been assessed in children and adolescents using IMU's attached to the dorsal trunk when assessing locomotor movements [155, 157] and the xiphoid process and wrists when assessing throwing MC [156].

Grimpampi *et al.,* [156] assessed overarm throwing action in 58 children aged between 5-10 years, using IMUs. Their study compared the IMU's ability to identify biomechanical markers to qualitative categorisation as set out by the developmental sequence of trunk component for overarm throwing [159]. The study concluded trunk and pelvis angular velocities and duration of time before the ball was released could identify differences in throwing development. This is supported by Masci *et al.,* [157] and Masci *et al.,* [155] who indicated IMU's are feasible for field-based assessments of locomotor skills in children.

However, the quantitative analyses were assessed against developmental sequences and further investigation should be completed with the process and product-oriented movement batteries to further validate their use in MC assessments [156].

Work completed by Bisi *et al.,* [160] has partially answered this question as their study compared the locomotor subsection of the Test of Gross Motor Development 2nd edition (TGMD2) with data produced from IMUs placed on the wrists, ankles and lower back. Children aged 6-10 years performed six locomotor skills consisting of a run, gallop, hop, leap, horizontal jump, and slide. The agreement between the TGMD-2 and the IMUs ranged from 82%-100% across the six locomotor movements and age groups. It was concluded that IMUs are valid for MC assessment of process-oriented measures of locomotor skills which are feasible to use in large sample sizes. However, for a full understanding of the validity of IMU's assessing overall MC then all movements within a test battery should be explored.

Jarchi *et al.,* [107] have recently reviewed the clinical application of trunk worn accelerometry in clinical gait analysis. They have reported that accelerometry has been widely used and validated as a clinical tool in gait analysis for multiple neurological and musculoskeletal conditions, in addition to assessments in children. A wide range of ST parameters was captured ranging from cadence, step, stride, asymmetry, and variability. This is further supported by Mannini *et al.,* [122]. They were able to classify children with developmental coordination disorder and early-onset ataxia using trunk and sternum mounted accelerometers while walking 15m in a straight line. Their accuracy rate for correct classification was 78.4% and it was concluded that gait parameters are a useful tool in diagnostic criteria for movement disorders in children. However, there are some limitations to this method. Integration from acceleration to speed then position can cause increased drift error in the signal, therefore, the accuracy of the ST parameters may be affected. This may also vary when fixing the accelerometers to different body locations. This will require different data processing applications, by skilled researchers trained in gait analysis [161].

The utilisation of Force platforms have generally measured kinetic properties of locomotor movements and more specifically walking. This method assesses the vectors applied to the ground in three axes, vertical, medial-lateral and anterior-posterior. These forces applied to the force plate are then exerted back on the body in the opposite direction as stated by Newton's third law. This is known as the ground reaction force (GRF) [162]. Differences in measures of GRF, when compared to healthy populations, can diagnose pathological gait in combination with other measures [163] and record events of the gait cycle [161]. Force platforms are well adapted to measure the initial foot strike, flat foot and toe-off gait phases of a single step. However, due to their cost and size, it is only practical to measure one or two consecutive steps as the standard size of a commercial force plate is 400mm x 600mm [162]. This reduces its capacity to measure complete gait cycles and variability between steps and strides [161].

One method has been designed to address this problem of capturing only a limited amount of steps from a participant. Instrumented walkways are a series of connected mats, which are positioned on the floor which allows the subject to walk across as they would do in the real-world environment. This measurement system can record ST parameters along with variability and symmetry [162]. The modern system requires no cables or sensors to be attached to the subject and allows them to walk freely in a straight line. The walkway contains switch contacts, which can detect initial foot strike, and toe-off gait cycle phases as well as, the forces which different parts of the foot generate on the mat [103]. The instrumented walkways are relatively portable which gives them an advantage over other systems, however, this method is limited to straight-line walking, requires time to set up and a large indoor space [103, 162].

Further advances in technology have been to insert instrumented walkway analysis into the soles of the participant's shoes. These consist of switches, which detect heel strike and toe-off gait phases when force is applied between the foot and the ground [161, 162]. This enables adequate detection of temporal gait parameters at a relatively low cost. It has been stated that footswitch technology is the gold standard in gait phase detection in the field environment. However, sub-phases of the gait cycle, such as initial, mid, and terminal swing phases do not apply a force to the switches and are therefore not detectable. Taborri *et al.,* [161] indicates that the increased granularity of gait phase detection becomes less accurate in footswitch measurements. There are also inaccuracies in stance phase detection, as inadequate positioning of the switch in patients with altered initial contact, such as Parkinson's shuffle gait, may cause reduced signal detection [161]. Therefore, basic foot contact and toe-off gait phase detection are achievable in non-lab based environments, but further detailed gait analysis becomes less reliable.

Table 2: Motor Competence Assessments

Name	Abbreviation	Year	Country	Fine/Gross movements	Age range	Norm / Criterion Referenced	Product / Process Oriented	Administration Time	Number of total test items	Cut points
Movement Assessment Battery for Children -2	MABC-2	2007	UK	fine and gross	3-16yrs	norm-referenced	product	20-40mins	8	Likelihood of motor difficulty = <5%, at risk = <15%, TD = >16th
Bruininks-Oseretsky Test of Motor Proficiency -2	BOTMP-2	2005	USA	fine and gross	4:0-21:11yrs	norm-referenced	product	15-20mins (short form) 40-60mins (long form)	14 short form (53 long form)	Well above average = ≥70, above average = 60-69, average = 41-59, below average = 31-40, = well below average = ≤ 30
McCarron Assessment Of Neuromuscular Development	MAND	1970	USA	fine and gross	3-35yrs (but only norms to 16yrs)	norm-referenced	product	20mins	10 (5 fine, 5 gross)	70-85 = standard score
Test of Gross Motor Development-3	TGMD-3	2013	USA	gross (locomotor + ball skills)	3-10yrs	norm / criterion referenced	process / some product oriented tests	15-20mins	13 FMS (locomotor, ball skills)	Gross motor Quotient >130 very superior, 121-130 superior, 111-120 above average, 90-110 average, 80-89 below average, 70-79 poor, <70 very poor
Peabody Developmental Motor Scales -2	PDMS -2	2000	USA + Canada	2 fine tests and 4 gross tests	birth - 6:11yrs	norm-referenced	product / process	45-60mins	249 (reflexes 8 items, stationary balance 30 items, locomotion 89 items, object manipulation 24	1 SD (16th percentile) or more below the mean = moderate deficits

								items, grasping 24 items, visual motor integration 72)	
Körperkoordinations Test für Kinder - 2	KTK-2	2007	Germany	gross (body control, coordination and dynamic balance)	5-14yrs	norm-referenced for genders	product	20mins	4 locomotor skills	Less than 15th percentile
Test of Motor Competence	TMC	2016	Norway	fine and gross	5-83yrs	criterion-referenced	product	10mins	4 (2 fine, 2 gross)	N/A - sum of 4 test items transferred into z-scores
Maastrichtse Motoriek Test	MMT	2004	Netherlands	fine and gross	5-6yrs	norm-referenced	product / process	long version 30mins, short version 7mins	Long version (70 items) short version (20 items)	Ranges fom 0 = extremely poor, to 140 = excellent
Tuft's Assessment of Motor Performance	TAMP	1988	USA	fine and gross	6yrs - adult	criterion-referenced	process	45-60mins	32	Doesn't classify motor impairment
Zurich Neuromotor Assessment	ZNA	2006	Switzerland	fine and gross	5-18yrs	norm-referenced	product	20mins	11	Below the 3rd percentile for age
Motoriktest für vier- bis sechsjährige kinder (Motor proficiency Test)	MOT 4-6	1987	Germany	fine and gross	4:0-6:11	norm-referenced	product	15-20mins	18	≤ percentile 2 impaired, <16 poor, between 16 and 84 normal, >84 good and >98 high

2.2 Measuring Physical Activity (PA)

There is growing importance and demand in measuring PA levels in children and adolescents. As high levels of inactivity are becoming more prevalent, these have a greater impact on health in children, adolescents and adults [164]. Measuring PA can be achieved through different processes when analysing data such as type, frequency, duration and intensity. Most guidelines and recommendations focus on duration and the intensity of daily PA levels [164-166] as seen in section 1.3.3 PA Recommended Guidelines. Intensity levels are usually related to energy expenditure above basal metabolic rate (BMR) and resting metabolic rate (RMR). BMR is defined as the energy required in order maintaining functions which are important for life such as respiration, circulation, renal and gastrointestinal function as well as other metabolic activities within other tissues and cells. RMR is 10-20% higher than BMR due to increases in energy requirements such as sitting quietly, which is classed as 1 metabolic equivalent (MET) or 3.5 $mL.kg^{-1}.min^{-1}$ of oxygen [164, 167]. Any energy expenditure which is above 1.5METs is classes as PA which then corresponds to light, moderate, and vigorous forms of energy expenditure in adults [168]. Child METs are less well developed and studied, compared to adults METs, and recent research has indicated that higher METs are required in children when classifying moderate and vigorous levels of PA particularly, in young children [169, 170]. However, there are still limitations in this approach as age-specific measures of resting metabolic rate were not calculated [169, 171] and data have suggested resting metabolic rate in children and adolescents can range from 1.2-1.7 METs which would require different METs to categorise MVPA in these age groups [170].

These intensities and durations have been measured in multiple ways each with their advantages and disadvantages. Ainsworth *et al.,* [172] have highlighted four domains which should be considered when applying a method to capture PA. These include the characteristics of the study (e.g. cross-sectional or interventional), population characteristics (e.g. age, gender, and socioeconomic status), instrument characteristics (e.g. cost and application) and activity characteristics (e.g. PE lesson, overall PA). Furthermore, ten questions have been developed which aim to reduce the measurement error when deciding which PA assessment to choose [172]. These questions include: what PA domains need to be measured, who is the target population, what is the study design and what logistical constraints are imposed. These questions may be able to indicate which method of PA assessment (such as subjective or objective) is most valid for the desired research question [172]. Therefore, this section will look to describe the most common and most recent PA assessments in children and adolescents and discuss their purpose.

2.2.1 Subjective PA Measures

Subjective measures of PA have predominantly consisted of questionnaires, PA diaries and logs [166, 172, 173]. PA diaries and logs require participants to record activities which have been completed for the previous day and can involve entering physical activities up to every 15mins of waking time [172]. Longer and more detailed versions can involve collection over multiple days with additional information which can assess the intensity (e.g. rate of perceived exertion), duration and type of activity performed [173]. These can then be further analysed to estimate the amount of time spent in certain METs and therefore describe the time spent in MVPA. The advantages of this method is that it is easy, cheap and data are reported within close proximity to when it was performed, reducing any bias in the recall of activities. Additionally, it can record information on the type of PA performed which can be beneficial in behavioural change studies and understanding sedentary time [172]. However, both of these methods can impose a large burden on the participants and is very time consuming, which may lead to missing data and reduced engagement. These methods may additionally be less sensitive when comparing different populations such as obesity level, MC level, and age, as self-evaluation of energy expenditure may differ between these groups and healthy individuals.

Questionnaires range from global PA questionnaires which have 2-4 questions assessing if a participant has met the recommended levels of PA and generally focus on domains of PA such as transportation, leisure time or occupation [172]. Short recall PA questionnaires range from around 7-12 questions are additionally used on large samples such as epidemiological studies to calculate the proportion of participants meeting the recommended PA guidelines, this requires information on intensity, frequency and duration [172]. History of PA questionnaire has a larger number of questions ranging from 20-60 and is usually interviewer led whereas the previous two questionnaires can be self-administered. These larger questionnaires can be used to understand morbidities and health behaviours and are much more comprehensive than many other questionnaires as they report PA over 1 year [166, 172].

The main disadvantages to questionnaire led PA assessments are comparing the result with the recommended guidelines of PA. Interpretation of light, moderate and vigorous PA will vary for different populations, ages and genders, and could, therefore, increase measurement error. For questionnaires, which require recall even over a short period of time may cause less accuracy in reporting the correct duration and intensity [172]. This may be further exacerbated when biases are introduced by participants reporting what they think is healthy rather than what they are actually performing, especially when parents are filling out the questionnaire for their child [174]. Further information reported by Hidding *et al.,* [173] systematically reviews childhood PA questionnaires. They reviewed 89 different questionnaires and assessed methodological quality, validly and reliability. Their results concluded that the majority of all the questionnaires had a low methodological quality and had a lack of construct validity and reliability. From this they were unable to recommend any questionnaires to be used in the measurement of childhood PA and caution should be exercised when using the questionnaires reviewed in their study, and future research should look to address this problem immediately. Therefore, this has led to the increased development and use of objective measures of PA.

2.2.2 Objective PA Measures

Objective measures of PA can be categorised into direct and indirect methods. These have been used to establish energy expenditure across different ages and populations, with different levels of accuracy, precision and reliability [175]. Direct methods involve the measurement of heat loss from a participant using a calorimeter. Even though this method is the gold standard in measuring energy expenditure, it does place a large burden on finances, highly qualified researcher's time and generally requires the participant to be confined to a chamber for 24hrs. Indirect calorimetry measures the gas exchange volumes of O_2 and CO_2 and has been used regularly to assess the criterion validity of other objective PA measures [166, 175]. It provides an indirect measure of energy expenditure and can identify which substrate is being utilised for fuel. This method allows more opportunity for ambulatory assessment of energy expenditure but, is generally restricted to lab-based protocols. Both direct and indirect calorimetry provide highly reliable and valid methods of human energy expenditure but ultimately their methods are impractical when free-living PA measurements are desired [175].

These restrictions to lab-based assessments have led to the development of technology which has allowed the assessment of PA and the estimation of energy expenditure in free-living conditions. Doubly labelled water (DLW) is a method of indirect calorimetry which measures total energy expenditure in free-living conditions [176]. Stable isotopes of oxygen ^{18}O and hydrogen ^{2}H are consumed by the participant and their elimination from the body through water (H^2O) and carbon dioxide (CO^2) are measured. As ^{2}H is eliminated through H_2O only and ^{18}O is eliminated through H_2O and CO_2, then the difference between these two elimination rates can indicate CO_2 production [164, 172, 176]. This method has shown to be the gold standard in energy expenditure in the free-living environment [176]. However, it shares some limitations to that of direct calorimetry. The production of DLW is expensive and requires qualified researchers and specialist equipment to produce and analyse its elimination. In addition, DLW can only report total energy expenditure and cannot give any information on PA intensity, duration or frequency [175].

Wearable devices have addressed these limitations through the measurement of physiological responses to PA or bodily movements, either from limb or CoM [165-167, 172]. Heart rate (HR) monitors measure the physiological response to exercise and PA. The relationship between HR and energy expenditure is linear and proportional for activities of moderate and vigorous intensities [165-167, 172, 175]. Studies have indicated that the overall error rate for HR monitoring can be as low as 3% for steady-state exercise, but this may vary amongst different populations and when exercise intensity is not consistent [172]. Furthermore, benefits from HR monitoring involve capturing activities additional to ambulation such as swimming, cycling and lifting weights [165], which provides advantages over other devices such as accelerometry. This method is still used in scientific research as it is cheap [165] and places a relatively low burden on the participant.

There are some limitations which are associated with this method such as inaccuracies in the relationship between light and sedentary activities. This has been explained by the effects of other physiological systems on HR. Emotional stress, fitness levels, muscle mass percentage as well as gender and age can all affect HR when performing PA [165, 175]. Further limitations are associated with the timing of the HR response when starting and finishing exercise. The monitoring of HR can lag behind the onset of exercise and continue to be elevated once exercise has finished and this may be further compounded in children as exercise is more spontaneous and therefore HR could be over-predicting PA [165]. This can also be exacerbated when performing exercise or PA with upper-body limbs as HR is significantly elevated when compared to lower limbs, but produces lower levels of energy expenditure [166].

Pedometers can assess movements related to ambulatory PA, which can make up a large majority of overall PA [4]. These devices can count the number of steps performed by a participant by detecting the heel strike within the gait cycle [166, 172]. They can be worn on the wrist or at the hip (CoM) during waking hours which reduces the burden placed on the participant and are relatively cheap and easy to process the data [167]. Studies have reported a step count measurement error of 3-37% [167] with the greatest reliability and accuracy produced from the latest microelectromechanical systems (MEMS) [172]. A review from Ainsworth *et al.,* [172] reports that 8 out of 10 pedometers reported excellent retest reliability and validity in detecting step counts which improved as walking speed increased. Recent studies still use this method to quantify PA levels in children. McIntyre *et al.,* [134], recently assessed PA, MC and perceived MC in children aged 6-9 years. They concluded that measuring PA through step counts requires caution and is restricted by some major limitations.

These limitations are mainly due to the devices inability to measure non-ambulatory PA and its difficulty in measuring PA intensity [134, 165, 172]. Some devices do try to address this limitation by calculating steps.min^{-1}, but it cannot determine accurate differences in energy expenditure between walking, running and jumping movements [165]. Furthermore, inaccuracies have been indicated with slow walking speeds (54m.min^{-1}), and therefore may not be appropriate in certain populations such as young children, older adults or people with disabilities [166].

Accelerometers have been developed to provide more information on PA levels than is possible from simple pedometer step counts. These devices are small and lightweight, which can be attached to the body's CoM, wrist or placed on multiple limb positions to measure acceleration from body movements. These accelerations can be measured in three axes, vertical, medial-lateral and anterior-posterior [165-167, 172, 175, 177]. If three axes of acceleration are measured then these can be transformed into a single vector magnitude (SVM) which can give an overall measure of movement and intensity. This is completed by reducing the resolution into epochs. Once this has been completed thresholds are applied to the chosen epoch which categorises the intensity level into sedentary, light, moderate or vigorous. This can then indicate the different types of PA intensities the participant has completed and the duration they have spent in these intensities. This method has been calibrated against gold-standard measures like indirect and direct calorimetry to validate energy expenditure indirectly from free-living conditions [172].

Unfortunately, accelerometry data have been analysed in many different ways with large varieties in thresholds, epochs, non-wear time and valid wear time (as seen in Table 3) [167, 174]. This makes it very difficult to compare studies with different inclusion/exclusion criteria, as lower thresholds may overestimate time spent in MVPA [165]. Further limitations exist with accelerometers as they are unable to accurately assess the energy expenditure on non-ambulatory PA, which could underestimate actual PA levels. However, the use of accelerometers has become more prevalent with larger studies opting to use this objective method in their sample population [178]. It also has proven to be a reliable method for measuring PA in children as it can reliably capture sporadic PA in children which is much less regimented than adults. Therefore, accelerometers have proven to be cheap, user-friendly, and place a low amount of burden on the participant and researcher, while providing valid and reliable information on children's and adolescent's PA duration and intensity [165-167, 172, 175, 177].

Table 3: Accelerometry data analysis method

Reference	Non-wear time	wear time / days	Week days/Weekend days	Hours.day^{-1}	Epoch durations	Age group	PA monitor type	PA monitor placement	Counts per minute /thresholds
Banda *et al.,* [179]	multiple	7 days (minimum 3 week days, 1 weekend day)	both	6hrs	1-, 5-, 10-, 15-, 30-, and 60s	7-11 yrs	ActiGraph GT3X+	right hip	multiple
Boddy *et al.,* [180]	>20mins of consecutive 0 counts	7 days (minimum wear time any 3 days)	any 3 days	9hrs	5 s	10-12 yrs	ActiGraph GT1M	right hip	SED ≤100 counts/min
Cain *et al.,* [181]	20mins consecutive 0 count	3 days	3-4 days including a weekend	10hrs	60s	multiple (review paper)	multiple (review paper)	multiple (review paper)	multiple (review paper)
Chaput *et al.,* [182]	>20mins of consecutive 0 counts	7 days (minimum wear time 4 days)	at least one weekend day	10hrs	1 s	9-11 yrs	ActiGraph GT3X+	waist-worn accelerometry	≥574/15s MVPA, ≤25 counts/15s SED
Chinapaw *et al.,* [183]	60 mins of consecutive 0 counts	at least 6 days	including at least 1 weekend day	10 hrs	15 s	9-13 yrs	ActiGraph GT3X and GT1M	waist	<100cpm SED , 3000cmp MVPA
Cohen *et al.,* [184]	20mins of consecutive 0 counts	7 days (minimum 3 weekdays and 1 weekend day)	both	8 hrs	10 s	7-10 yrs	ActiGraph GT3X+	waist	SED ≤25 counts/min, LPS = 26-573, mod = 573-1002, VPA = ≥1003
De Meester *et al.,* [185]	not stated	minimum of 5 days (3 weekdays and 2 weekend days)	both	9 hrs	15 s	6.92-11.83 yrs	ActiGraph GT3X+	right hip	mod 2292-4011 counts VPA >4012
Doherty *et al.,* [178]	60 mins of consecutive 0 counts	7 days (minimum of 3 days wear time)	both	worn continuously	5 s	45-79yrs	Axivity AX3	wrist	100 mg - da Silva *et al.,* [186]

DuBose *et al.,* [187]	not stated	7 days (minimum wear time 4 days)	both (at least one weekend day)	8 hrs	15 s	3-10 yrs	ActiGraph	waist	3-5yrs 240-2110 LPA, >2120 MVPA, 4450 VPA. 6-20yrs >101-2295 LPA, >2996 MVPA, >4012
Edwardson and Gorely [188]	20mins of consecutive 0 counts	7 days (minimum wear time 3 weekdays , 1 weekend)	both	9hrs	5 ,15, 30 ,60s	7-11yrs, 12-16yrs	ActiGraph GT1M	waist	Rest 0-8, LPA 9-74, MPA 75-288, VPA >289 for children. Rest 0-8, LPA 9-134, MPA 135-397, VAP >398 for adolescents
Fröberg *et al.,* [189]	60 consecutive mins of 0 counts	7 day (minimum of 3 days)	both	8 hrs	1, 5, 10, 15, 30, and 60 s	12.8±0.5 yrs	GT3X	hip mounted	5 different sets of cut points were assessed
Hall *et al.,* [190]	20mins of consecutive 0 counts	4 days (minimum 4 days)	Not Stated	10 hrs	1 s	4.28±0.74 yrs	GENEActiv	dominant hand	Roscoe *et al.,* [191]
Keane *et al.,* [86]	30 mins consecutive 0 counts	7 days	both	10hrs	60 s	8-11 yrs	GENEActiv	wrist nondominant hand	Phillips *et al.,* [168]
Kwon *et al.,* [192]	60 mins consecutive 0 counts	minimum 3 days	Not Stated	10hrs	60 s	3-18 yrs	ActiGraph	waist	2,296 - 4011 counts/min = mod ≥ 4012 counts/min
Larsen *et al.,* [72]	30 mins of consecutive 0 counts	7 days (minimum 4 days)	both	10hrs	not stated	6-12 yrs	ActiGraph GT3X	hip mounted	Evenson *et al.,* [193]
Logan *et al.,* [194]	60 min of consecutive 0 counts	8 days (<4days were excluded)	both	8 hrs	1, 5, 15, 30 and 60 s	12-18 yrs	ActiGraph GT3X+	right hip	4 different sets of cut points assessed
Lopes *et al.,* [195]	60mins of consecutive 0 counts	5 days (minimum 2 weekdays 1 weekend day)	both	8 hrs	2 s	12-14 yrs	ActiGraph GT1M	right hip	Evenson *et al.,* [193]
Riddoch *et al.,* [196]	10mins of consecutive 0 counts	4 days (minimum 3 day with 1 weekend day)	both	10 hrs	60 s	9-15 yrs	MTI 7164	hip mounted	1000 and 1500 counts·min^{-1}as cut-points for 9- and 15-yr-old

Rowlands *et al.,* [197]	imputed (GGIR signal processing)	7 days (minimum 3 days)	Not Stated	16 hrs	5 s	11-14 yrs	GENEActiv	non dominant wrist	200 mg
Süda *et al.,* [198]	20mins of consecutive 0 counts	7 days	both	10hrs	15 s	7-9 yrs	GT3X accelerometer ActiGraph	hip	0-100 counts = SED, 101-2295 counts = LPA, >2296 = MVPA
Toftager *et al.,* [199]	Assessed	Assessed	Assessed	Assessed	2 s	11-14 yrs	Actigraph GT3X	waist	<100cpm as sedentary time
Trost *et al.,* [200]	Assumed that the PA monitor was worn	7 days	both	waking hours	60 s	American school grades 1-12	uniaxial vertical	hip	Freedson *et al.,* [201]
Van *et al.,* [202]	180mins consecutive 0 counts	7 days	both	13 hrs weekdays, 9 hrs weekends	60 s	American school grades 6-8	Actigraph 7164	waist	not stated

Chapter 3 General Methods

3.1 Summary

This chapter will introduce the general methods from which data were collected for the studies of this thesis. It will highlight the participant characteristics and the exclusion and inclusion criteria long with recruitment methods and gaining informed consent. Studies in this thesis followed a cross-sectional design and was reported according to the STROBE guidelines [203]. Oxford Brookes University Research Ethics committee (UREC) approved all procedures (No: 161033) which were completed in accordance with the declaration of Helsinki (2013). See Appendix A for the ethical approval letter. Data were obtained as part of the screening process for the 'Rhythmic Motor Learning in Children with Developmental Coordination Disorders (EPIC2) trial (ClinicalTrials.gov Identifier: NCT03150784). Within this clinical trial the author was responsible for all stages of the trial, which included recruitment, obtaining consent, school screening, intervention training and assessments at three time points. As this thesis only reports data from the screening phase, specific responsibilities will only be discussed for this part of the trial. The author was responsible for all organisational requirements between the three schools and the research department. All aspects of data collection with in the screening phase. This involved organising and gathering data on all motor competence, walking analysis, physical activity, anthropometrics and health-related fitness measures. All post-processing, signal analysis and statistical analysis was completed by the author with support from supervisors. The overall design and selection of validated screening measures which would address the aims of the thesis were also the responsibility of the author.

3.2 Participants

Three mainstream secondary schools in Oxfordshire were invited to take part in this research. Across the three schools, a ranging demographic was captured [204]. These schools were chosen as they have taken part in previous research studies undertaken by Oxford Brookes University and their local proximity to Oxford Brooke's campus. All students enrolled in Year 9 at the start of the academic year of 2017-2018 were potentially eligible for this study. Exclusion criteria were any known medical conditions, which could explain deficits in walking, MC or movement. This included pathology in cognitive, neurological, musculoskeletal, behavioural or visual function, as described by the DSM-5 [14]. This was screened through a parental health questionnaire (PAR-Q), and each school had information regarding each student's medical needs, allowing PE staff to exclude students who met the exclusion criteria.

3.3 Recruitment and Consent

Contact was initially made to each school's respective Head where information was sent outlining the details and aims of the prospective study. Consent was granted from each school's Head which outlined the acceptance for the study to take place within school grounds and during school time. Information was then distributed to the Head of the Physical Education (PE) departments and disseminated to all PE staff.

Meetings between the lead researcher, project manager and PE staff were conducted in order to answer any questions and explain the study in more detail.

Further consent was required from each student taking part in the study and from their parents or legal guardians. To gain informed consent, information of all assessment procedures were explained to the students in a whole year group assembly with each student receiving a participant information sheet and a separate information sheet for their parents or legal guardians. Opt-Out consent forms and health questionnaires were distributed to each parent or legal guardian. If the parent or legal guardian did not want their child to take part in the study then the opt-out consent form was filled out and returned to the Head of PE at their child’s respective school, only 11 potential participants opted-out. This was completed at least one week in advance of all testing sessions to allow for enough time for forms to be returned and questions to be answered from the parents. Opt-out consent was used for the school screening sessions as the assessments taking place were similar to that of a normal PE lesson and deemed low risk by the University Ethics Committee [205]. It was appropriate to use this method of consent as it allowed the maximal number of students to take part in the assessment sessions as it replaced a timetabled PE lesson.

3.4 Research Setting

Data collection took place at each school's respective sports hall, with Oxford Brookes University research assistants, lead researcher and PE staff in attendance. The assessment sessions took place in a PE lesson as timetabled by the school, which lasted one hour. Assessment time was designed to last 45-50 minutes and 5-10 minutes were given before and after the lesson for the participants to change into sportswear and be on time for their next lesson. Approximately, 50 students could be screened in one session. As these screening sessions took the place of a normal PE lesson, the classes were generally separated by gender and ability. This was then repeated to capture the whole year group. However, this varied depending on the size of the school and number of students enrolled.

3.5 Study Sample Sizes and Data Flow

The overall sample for this thesis consisted of 606 participants screened from the three schools. Measures of PA levels were only conducted in one school year as there were limitations on the equipment required to carry this out in all schools. The sample sizes for Chapter 4, Chapter 5 and Chapter 6 are present in Figure 4.

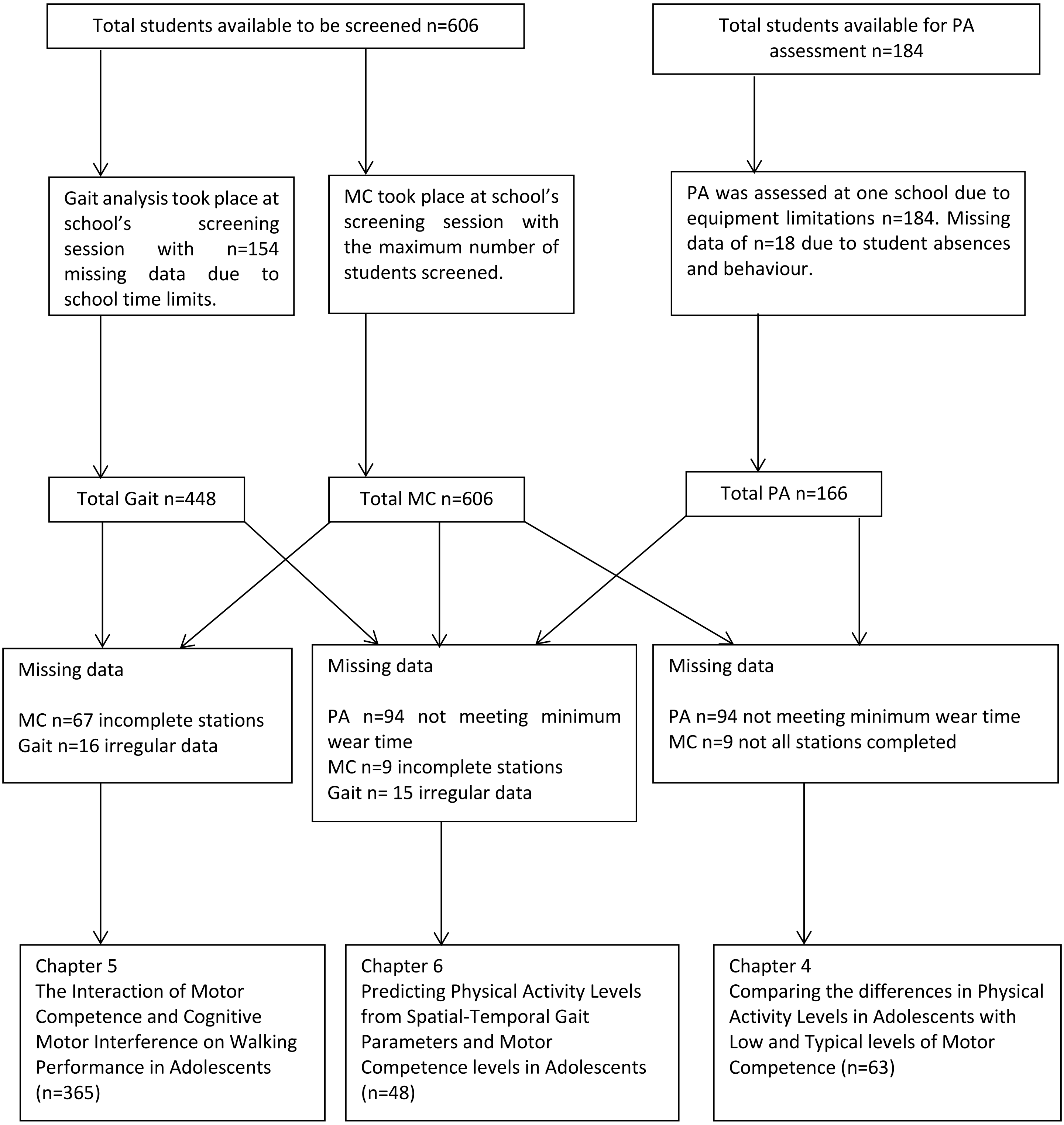

Figure 4: Sample sizes of thesis chapters from the original screening numbers

3.6 Procedure

At the start of each assessment, a brief introduction was given by one of the researchers to underline what was expected from the participants overall, with instructions provided according to set standard operating procedures (SOP) before the test was administered. The tests were set up in a circuit style programme (see Figure 5), where each test had its own designated station. Each station occupied 2-3 participants (apart from 20 m shuttle run, n=15) and once they had all completed the test they moved onto the next station until all tests had been completed. Each station was manned by a qualified researcher who had been trained by the lead researcher in how to explain, demonstrate, score and give feedback to participants completing the test, as set out in the relevant SOP.

3.7 Researchers

On average each testing session required 20 researchers to collect the data, who were trained by the author. Where possible, researchers would be assigned to administer the same test across all schools to achieve consistency in scoring and avoid bias. This enabled continuity across all tests while reducing the workload on each researcher. All researchers were current members of the Centre for Movement, Occupational and Rehabilitation Sciences (MOReS) group. This mainly consisted of postdoctoral fellows, PhD students, and research assistants engaged in clinical rehabilitation studies in physiotherapy, occupational therapy, nursing and clinical conditions. All researchers attending the school assessment sessions were required to have a Disclosure and Barring Service (DBS) check, and read and signed the child safeguarding policy. Experience in school-based testing was high with the majority of researchers having previous experience in school population studies since 2014 (ClinicalTrials.gov Identifier: NCT02517333).

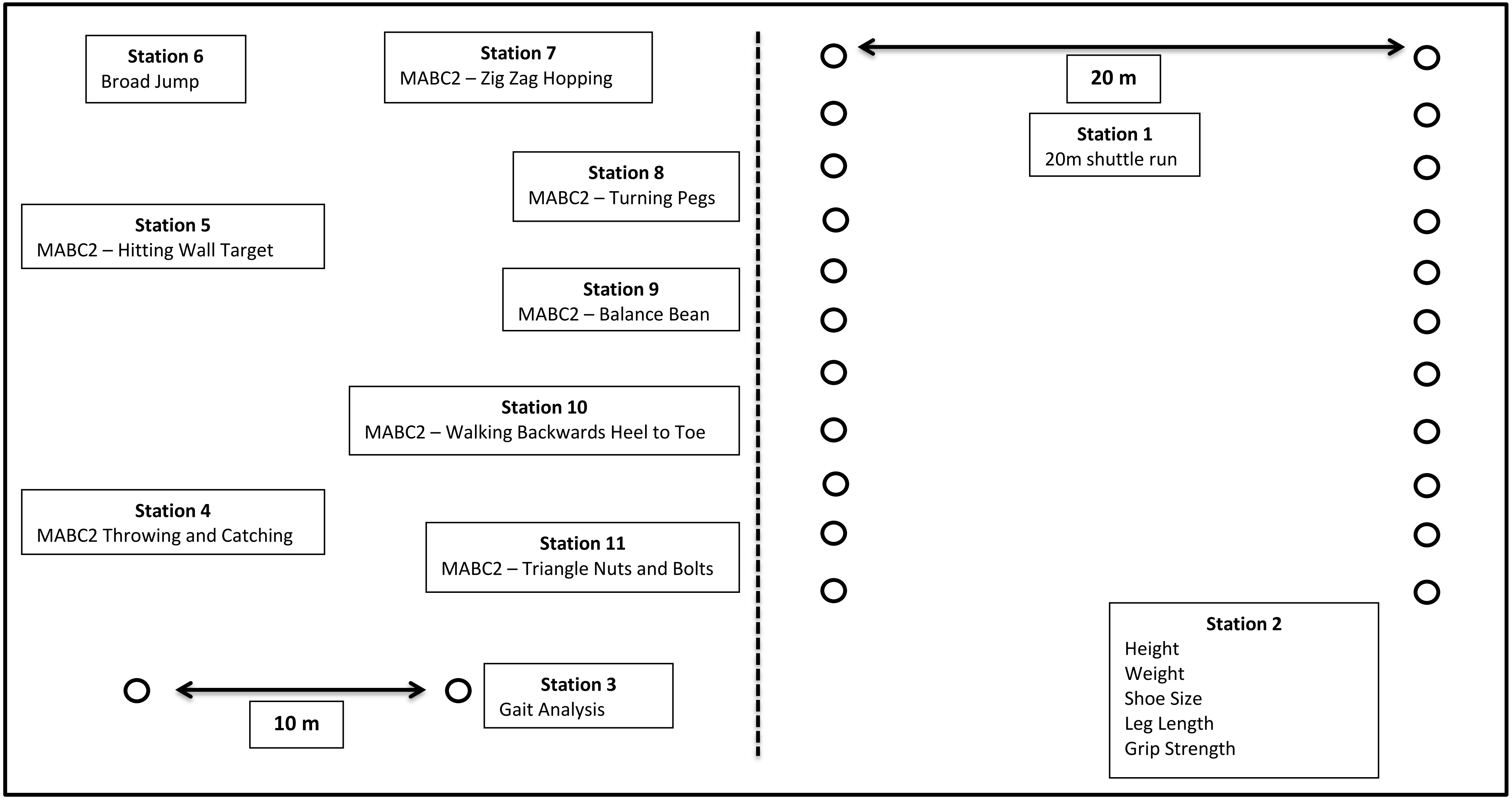

Figure 5: A typical assessment set up at each school's sports hall. Black circles represent cones as distance markers, the dotted line represents a curtain separating sports hall into two sections (The drawing trail from the MABC2 was completed in tutor lessons)

3.8 Measures

3.8.1 Motor Competence (MC)

Introduction

The assessments which took place at each school's screening session were made up of test items from the Movement Assessment Battery for Children 2nd Edition (MABC2). Only one test item, the drawing trail was completed separately in class registration time within 5 days of the PE screening session. The completed MABC2 assessment was used to assess overall MC in adolescents (see Table 4). The test is split into three age groups 3-6 years, 7-10 years and 11-16 years. Each age group is subdivided into three sub-groups of MC, manual dexterity, aiming and catching, and balance. Each age range has the same number of total test items (8 items) which are subdivided into the same three areas of MC, however, each test item is age-appropriate and increases in difficulty as age increases [74].

MABC2 is the most widely used test to assess MC deficiency and is used in many different countries as part of diagnostic criteria to identify Developmental Coordination Disorder [11, 206]. The most recent guidelines [1] recommend the MABC2 is used as an objective assessment of criteria A (as seen in Chapter 1), as stated by the DSM-5 [14]. This test has been used as a reference marker when evaluating other movement battery tests [206] and has shown good validity and reliability [55, 74, 207, 208]. Additionally, the MABC2 has shown good convergent validity when assessed against another widely used motor competency test, the Bruininks-Oseretsky Test of Motor Proficiency 2nd edition (BOT2) [209]. As the MABC2 has been developed in the UK it is culturally appropriate for this study sample [23, 210, 211]. It also has norm reference values for adolescent age range which are not present in other movement tests such as the Test of Gross Motor Development 3rd edition (TGMD3) or the Peabody Developmental Motor Scales 2nd edition (PDMS-2). The MABC2 covers a wide range of movement skills for upper and lower body assessment [74]. This is not assessed as fully in other movement tests such as the Körperkoordinations Test für Kinder 2nd edition and the TGMD3, which only assess MC in areas of locomotor control and ball skills, as seen in Table 2. Whereas, the BOT2 was referenced in children and adolescents in America which causes concern as cultural differences effect MC ability for specific tasks such hand-eye coordination sports, which are more predominant in America than European countries [211]. Furthermore, the BOT2 requires more time to administer all of the tests accurately as the short-form test involves 14 separate measures (Table 2). This makes it impractical for large screening assessments within a PE lesson and is why the MABC2 is as an appropriate test for MC in this thesis.

Data Collection

Each test item from the MABC2 was recorded by hand onto a unique case report form which was tailored to the number of participants at each school. All participants were assessed on one to one bases with one qualified researcher present at each station. At the end of each screening session, all researchers checked for missing data by cross-referencing their scoring sheets. This enabled any participants that had missing data to be tested on the test items they had missed before the PE session ended. Once each screening session had finished all data forms were collected by the lead researcher and input into an excel spreadsheet.

Data Analysis

All raw scores were transferred into overall MC percentile scores using reference tables provided by the MABC2 examiner's manual [74]. First, all test item scores were converted to an item standard score from a reference table. These standard scores were then summed for each of the three sub-groups of MC (manual dexterity, aiming and catching and balance), producing a component score. These component scores were then transferred into standard scores and percentile scores using a reference table for the subgroups of MC. Once the component scores for the individual sub-groups were summed and transferred using a total test score reference table, then a total standard score and total percentile score for MC were produced. Converting raw scores to percentiles score was completed using a custom programme in MatLab (MathWorks®, R2018a, USA). According to Henderson *et al.,* [74] a score above the 15th percentile is described as having no movement difficulties, a score between the 5-15th percentile is deemed to suggest the participant is at risk of having movement difficulties, and below the 5th percentile is described as having severe movement difficulties [74]. For this thesis, any participant scoring at or below the 15th percentile was deemed to have low MC (As described in 1.1.1 Definitions and Terminology).

Analysis within this thesis will assess MC as measured by the MABC2 overall test score percentile and the balance subsection of the MABC2. This will look to explore the effects of overall MC on movement quality and quantity as well as assessing the MC as measured by balance. This should give further understanding to the effects of low static and dynamic balance competence on movement quality and quantity [74, 212].

Table 4: Movement Assessment Battery for Children 2nd Edition (ages 11-16 years)

Test Name	Test number	Test Item	Description of Test	Scoring of Test	Total Time to Complete Test†
Manual Dexterity	1	Turning Pegs*	12 pegs are situated in a pegboard, the participant must individually remove and invert the peg back into the board as quickly as possible.	Complete the test as quickly as possible	31s
	2	Triangle Nuts and Bolts	Participants must assemble the nuts and bolts into a triangle as quickly as possible.	Complete the test as quickly as possible	65s
	3	Drawing Trail 3	Participants must draw a single continuous line within the two boundary lines.	To produce fewer errors as possible	N/A
Aiming and Catching	4	Catching with one Hand*	Participants must throw a tennis ball against the wall from a 2m distance and catch it with one hand. A total of 10 attempts.	Most successful catches	N/A
	5	Hitting Wall Target	Participants must throw a tennis ball and hit a target on the wall from a 2.5m distance. A total of 10 attempts.	Most successful times the target was hit	N/A
Balance	6	Two Board Balance	Participants must balance on a balance beam for as long as possible or 30s with feet in a heel to toe position.	Longest time spent balanced	30s
	7	Walking Toe to Heel Backwards	Participants must walk backwards with feet in a heel to toe position. A maximum of 15 steps attempted.	Most successful consecutive steps	N/A
	8	Zig-Zag Hopping*	Participants must hop on one leg diagonally, staying on the mats and holding the single-leg position on the last mat. A total of 5 hops attempted.	Most successful consecutive hops	N/A

* Measured bilaterally, † Maximum time scored for ages 13:0 to 13:11 and 14:0 to 14:11, N/A No Associated time limit

3.8.2 *Physical Activity (PA)*

Introduction

This method of PA assessment has been recently adopted in large population studies in adults, [178] where 96,600 participants had their PA levels measured over seven days using the wrist-worn AX3 accelerometer. Seven days of PA monitoring has been reported as an adequate number of days to record objective measures in all ages of adolescents [181, 213]. This method has shown good compliance with wear time when compared to the hip or waist-worn accelerometry especially in children [214, 215]. Previous research has validated this method against heart rate and trunk accelerometry measures in the free-living environment [216] and it has been used in other population-based PA studies in children and adolescents [86, 184, 217]. Further studies have measured the criterion validity of wrist and hip accelerometry against lab-based and free-living energy expenditure through indirect calorimetry [168, 169, 171, 218]. Even though there was greater variance reported for hip accelerometry compared to wrist accelerometry [218] and increased validity from hip-mounted accelerometers compared to the wrist [168], it may be more feasible and increase wear time when the accelerometer is placed on the wrist [168, 218]. Overall, wrist placed accelerometry has indicated good acceptability for group-level estimation of PA [169]. PA was measured over 7-days using a triaxial accelerometer measuring in three axes of motion, vertical, anterior-posterior and medial-lateral (Axivity AX3, Axivity Ltd, UK). For this thesis an AX3 (Dimensions - 23 x 32.5 x 7.6mm, Weight 11g) was worn on the right wrist by all participants as indicated by Phillips *et al.,* [168].

Data Collection

Each device was set to record continuously for seven consecutive days at a sampling frequency of 100Hz. All participants were asked to wear the AX3 from the moment they woke to the moment they went to bed, apart from any water-based activities such as swimming or showering. The devices were distributed by each form tutor at the beginning of the school week at registration on a Monday morning. Each AX3 had a unique serial number which was to identify which watch had been given to each participant. After seven days the AX3 watches were collected by the form tutor and returned to the lead researcher.

Data Analysis

Once returned, the data were downloaded using the manufacturer's software (OmGui, version V43, Newcastle University, UK). This allowed the raw acceleration signal to be analysed using a customised programme in LabVIEW 2015 (National Instruments Austin, USA). Individual [x, y, z] axes were read from the main file in 100-samples per cycle and transformed into a single vector magnitude (SVM).

$$\mathrm{SVM} = \sum\left(\sqrt{x^2+y^2+z^2}\right)$$

SVM was filtered using a zero-phase Butterworth bandpass filter (0.016-12Hz) to remove the gravity component and de-noise the signal. Following this, 100 samples were compressed to a 1-second epoch by taking the average of data points [188, 219]. Epochs were compared with adjusted cut-off points by Phillips *et al.,* [168] by using the adjustment as per Esliger *et al.,* [220], whereby the original cut-off points were divided by the original sampling rate, and multiplied by the sampling rate used within this study methodology. This was to overcome the epoch size multiplier going from 80Hz to this study's 100Hz, resulting in larger epochs (80 samples per epoch to 100 samples per epoch). From this, cut points were applied to categorise time spent in sedentary (Sed < 6 g s), low (LPA 6-21 g s), moderate (MPA 22-56 g s), and vigorous PA (VPA >56 g s) as stated by Phillips *et al.,* [168]. PA was analysed over 14 hours, from 08:00 in the morning to 22:00. A minimum of 8 hours of wear time was used to represent a valid day. Non-wear time was calculated as consecutive time spent in the sedentary category for ≥60 minutes. For a valid assessment of PA, it was required that each participant had at least 3 weekdays and 1 weekend day measured as the minimum time required to capture overall PA levels [68, 181-184].

3.8.3 Gait Analysis

Introduction

Walking was analysed using an inertial measurement unit (IMU) (LP-RESEARCH Inc. Tokyo, Japan, LPMS-B), consisting of a triaxial accelerometer, gyroscope and magnetometer (dimensions 45 x 37 x 20 mm, and weight 34g). This method of walking analysis has been developed as a cost-effective, valid and reliable method in field-based assessments in clinical and healthy populations (see section 2.1.4 Motion Capture and Walking Analysis). It can assess acceleration in three axes, vertical, anterior-posterior, and medial-lateral, which has been used to measure participant's spatial-temporal parameters [221, 222], dynamic balance [107, 223] and motor control [224].

IMUs have been used extensively to measure spatial-temporal walking parameters when fixed to the Centre of Mass (CoM) in adults [225, 226] and adolescents [223, 224, 227]. This method has also been validated against the gold standard in human movement analysis Optical Motion Capture Systems (OMCS) [228] and has shown good reliability [228-230]. IMU gait analysis has shown some advantages over the OMCS method. IMU gait analysis enables assessments to take place outside the laboratory which, allows for real-world walking analysis, which has shown significant differences when compared to lab-based assessments [231]. Furthermore, gait analysis using single CoM IMUs provides the opportunity for a greater number of participants to be assessed in a shorter time, making it easier and cheaper to assess large cohorts, as well as lowering the demand on the participant [232]. This reduces the demand placed on the researcher or clinician analysing the data and drastically lowers post-processing time [233].

Data Collection

Data were collected from the IMU to a laptop in real-time via Bluetooth connection, at a sampling rate of 100Hz. LP-RESEARCH software (OpenMAT Version 1.3.5, Tokyo, Japan) was used to collect the gait data in the screening sessions. A description of both walking tasks was given to each participant, with a description of what was being measured and where the IMU was going to be placed before starting the test. Leg length and shoe size were measured at station 2 in order to analyse the gait data [226]. Any further questions were answered at this time by the lead researcher. The IMU was placed on the participant's lower back, over lumbar vertebra L4 (estimated CoM), using double-sided hypoallergenic sticky tape [233].

The first walking test was designed to measure normal, steady-state walking and required each participant to walk 10m in a straight line. The walking distance was marked by two cones, and each participant was asked to walk at their normal walking speed. Once they reached the end of the 10m walking distance, the researcher asked them to stand still and keep facing forwards for 3 seconds. Then they were asked to turn around and face the start position for 3 seconds then walk back to the start line while reciting out loud alternate letters of the alphabet (see Figure 6). This second walking test was designed to measure the effects of cognitive-motor interference (CMI) on walking parameters [234, 235]. A small feasibility study was conducted in a group of age matched adolescents to determine the most appropriate field-based CMI assessment (n=33). Time limitations imposed on explaining the task to each participant and engagement with the CMI task indicated that the n-back [236], and serial subtractions [237] were not appropriate, with many adolescents refusing to engage with the task. However, reciting out loud alternate letters of the alphabet produced engagement from all participants and required less time to explain the task. Data from Chapter 5 indicated that the alternate alphabet CMI task provided significant interference to walking parameters when compared to the signal task walk.

Data Analysis

Raw acceleration files were analysed using a custom programme in LabVIEW 2015 (National Instruments Austin, USA). Vertical acceleration was transformed from the object to global frame using quaternions [228], filtered with a zero-phase, Butterworth bandpass filter (0.5-25Hz) between each step of Simpson's rule of integration resulting in vertical CoM excursion. Peak-to-peak intervals were checked and if needed corrected by peak FFT frequencies to obtain step time, stride time and cadence throughout the walk cycle. CoM excursion peak-to-trough difference was used to drive an inverted pendulum [226, 233, 238] and corrected for 86% of the participant's foot length [239] to obtain spatial (step & stride length) parameters. Walking speed was derived as stride length/stride time and expressed as ms^{-1}. Outcome parameters displayed were taken as averaged single-step temporal-spatial parameters with their relevant standard deviation. This sinusoidal model of walking allows estimation of gait phase detection, which has previously been established in children [227].

Walking parameters were normalised to control for variation in leg length [240]. Spatial-temporal parameters were normalised into dimensionless units according to calculations by Hof [241]. These included speed (walking speed), frequency (cadence) and distance (stride length).

Walking speed

$$\text{Normalised Walking Speed}=\frac{\text{Walking Speed}}{\sqrt{\text{LL} \times \text{g}}}$$

Cadence

$$\text{Normalised Cadence}=\text{Cadence} \times \sqrt{\text{LL} \div \text{g}}$$

Stride length

$$\text{Normalised Stride Length}=\frac{\text{Stride Length}}{\text{LL}}$$

Where LL is leg length [m] and g is the acceleration due to gravity [9.81 m s^{-2}]. Walk ratio [mm/steps min^{-1}] was calculated as follows.

$$\text{Walk ratio}=\frac{\text{Step length}}{\text{Cadence}}$$

Variability of each normalised spatial-temporal gait parameter was assessed using the coefficient of variation (CV).

$$\text{Coefficient of Variation}= \frac{s}{x} \times 100$$

Where s is the standard deviation and x is the sample mean.

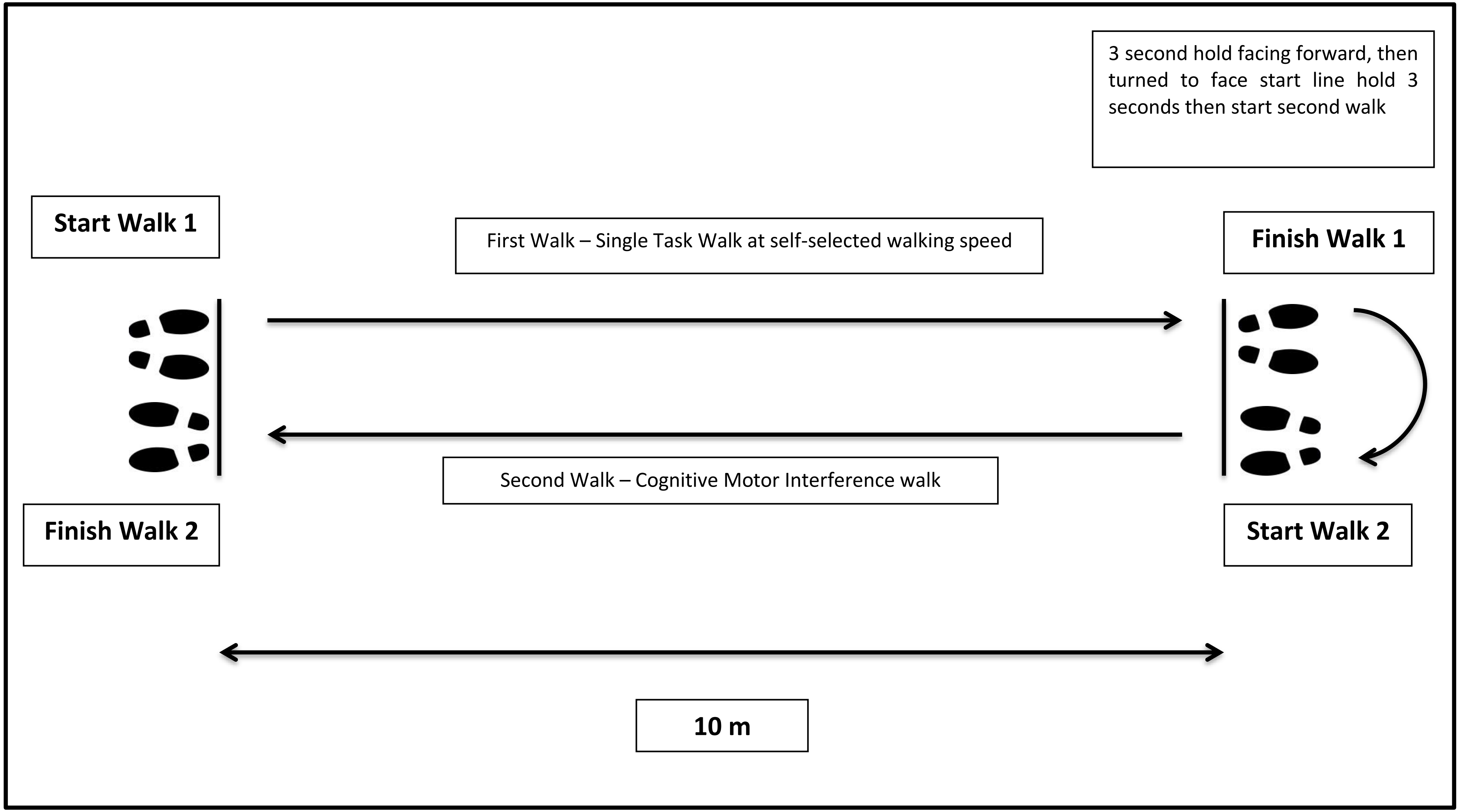

Figure 6: Gait Analysis protocol for single and cognitive-motor interference walking task

3.8.4 Health-Related Fitness Measures

Aerobic Capacity

Introduction

Aerobic capacity is the ability of the cardiorespiratory system to uptake, transport and utilizes oxygen when performing maximal exercise [242, 243]. It can be measured through lab-based analysis of expired air. Indirect estimates of aerobic capacity can be obtained through field-based assessments [243]. The 20 m shuttle run test (20mSRT) is a widely established field-based measure in estimating aerobic capacity in children and adolescents in large screening sessions [243-247]. The test was initially developed by Leger and Lambert [248] in adults and then validated in 188 children and adolescents aged 8-19 years [249].

The 20mSRT has shown good validity and reliability when estimating aerobic capacity in field-based assessments [250, 251]. Mayorga-Vega *et al.,* [251] found moderate to high criterion-related validity when assessing aerobic capacity in healthy participants, from a meta-analysis of the 20mSRT to estimate aerobic capacity. This method for estimating aerobic capacity requires prediction equations to transfer the number of shuttles completed into the predicted VO_2max. Silva *et al.,* [252] assessed the accuracy of two predictive VO_2max equations in children and adolescents. The multiple linear regression (MLR) equation and the artificial neural network (ANN) equation were analysed. The MLR equation reported reduced systematic error and reduced dispersion of random error as measured by Bland-Altman plot and limits of agreement.

Furthermore, the criterion-validity was increased in children when other moderating variables were introduced such as sex, age [years], body mass [kg], and body mass index [kg.m^{-2}]. This field-based assessment has been used to estimate aerobic capacity in children and adolescents with low MC, [144, 244, 253-256] which allows for multiple participants with varying levels of MC to be assessed simultaneously providing a quick and easy measure of each participant's aerobic capacity [251].

Data Collection

The test requires each participant to run to maximal volition and therefore, requires cardiovascular stability to complete the test safely. At the start of each test, the lead researcher would explain the test procedure, and highlight any symptoms which may be caused by an adverse event. It was then explained that this is a very rare occurrence but should be disclosed to the PE staff or researcher leading the test if any of these symptoms were experienced. The dynamics of the test involved 15 participants being tested at once. Each participant was required to run back and forth between two lines of cones, separated by 20m (as seen in Figure 5). Participants were instructed to reach the opposite side of the 20m distance in time with the beep which, was played by an audio device. The test speed started at 8.5km/h and increased by 0.5km/h each minute. When the participants were unable to reach the end of the 20m distance in time with the frequency of the beeps then their last stage and level were recorded as their final score [248, 249].

Data Analysis

All final scores were then converted into predicted VO_2max using a customised programme in LabVIEW 2015 (National Instruments Austin, USA). A multiple linear regression equation designed for ages 10-18 years was used to predict their maximal aerobic capacity [252].

$VO_2maxMLR = 43.313 + 4.567*sex - 0.560*BMI + 2.785*stage$

Strength

Introduction

Strength is an important measure for determining general health in children and adolescents and has shown an inverse relationship with adiposity, cardiovascular disease, and metabolic risk factors, in addition to, associations with bone health and physical self-perception [250, 255, 257]. Muscle strength has been defined as the ability to produce muscular force [257], which is a foundation movement skill required for activities of daily living and sports participation [51].

Grip strength assessment is used to predict overall muscle strength in children and adolescents [258], with good validity and reliability [250, 259] when screening large numbers of participants in a field-based setting [260]. This measure is quick and easy to complete with low demand on the participant and researcher. Therefore, grip strength has been identified as an appropriate measure of strength levels in adolescents when screening large samples.

Data collection

Strength was measured using a hand-held dynamometer (Takei model TKK 5401 Grip D, Takei Scientific Instruments Co. Ltd, Tokyo, Japan). The test was completed in a standing position with the TTK 5401 in their dominant hand. The starting position required the elbow to be fully extended [261] with the shoulder in 180^o of flexion so that their arm is positioned vertically into the air. From this position, the shoulder was extended, with the elbow maintaining full extension, so that the arm came to rest at the participant's side. While the arm was in motion the participant was encouraged to squeeze as hard as possible until their arm reached their side. A maximum of two attempts was assessed with the best score recorded as their maximal grip strength.

Lower limb Power

Introduction

Field-based testing has used many different types of jumps to assess lower limb power such as vertical jump, squat jump, countermovement jump and standing long jump [203]. These require the participant to move their whole body weight against gravity in a vertical or horizontal distance. These methods have been designed to allow for large population-based studies to assess lower limb power with a relativity low amount of equipment in a short period of time.

The standing long jump (SLJ) is a practical field-based fitness assessment when measuring large numbers of children and adolescents in screening sessions [246, 250, 262]. Many studies have indicated good reliability and validity when compared to the gold standard measure of a one-repetition max of a leg press exercise [250, 263, 264]. In addition, comparison to peak and mean anaerobic power measures such as 10 and 30 second Wingate test indicated moderate correlations with the SLJ in children with typical and low MC levels [265]. Therefore, in conjunction with the two previously mentioned health-related fitness measures, we can gain an indication of each participant's aerobic capacity, strength, and power which are associated with overall health and PA [6, 261, 266].

Data Collection

This test involved each participant standing with feet shoulder-width apart behind a line marking the beginning of the test. They were then instructed to jump as far as possible in a straight line, without stepping forwards or backwards, while landing on both feet. The distance from the start line to the nearest point of initial ground contact (heels of the feet) was measured as their maximal jump distance. Each participant had two attempts and the longest jump was recorded as their final score.

Chapter 4 Comparing the differences in Physical Activity Levels in Adolescents with Low and Typical levels of Motor Competence

4.1 Summary

Chapter 1 discussed the evidence that children and adolescents do not complete the required guidelines for PA. This chapter investigates the effects of MC on PA levels in adolescents to determine if low levels of MC discriminate PA levels and intensities.

4.2 Introduction

MC has been theoretically discussed as an important factor for improving, maintaining and engaging children and adolescents in PA. Two models have been developed to explain the relationship between PA and MC in children and adolescents. Stodden *et al.,* [49], postulates a reciprocal relationship between PA and MC in adolescents, with the association increasing in strength as children age into adolescence. It also describes the effects of perceived MC, health-related fitness measures and obesity on this relationship (as seen in 1.2.5 Reciprocal relationship between motor competence and physical activity model). The proficiency barrier also indicates that children must have a certain level of MC to engage in PA [59]. If this hypothetical barrier is not reached then it is less likely that adequate levels of PA will be performed. Reaching this proficiency barrier coincides with the developmental stage when children are mastering fundamental movement skills such as locomotor (running, jumping, and hopping) and object control (throwing, catching, and striking) [185]. These movements have been described as the building blocks for more complicated movements which are necessary for sport and game-based activities [8]. If these building blocks are not adequately mastered or there is a delay in their procurement then this can lead to disengagement with PA compared to their typically developed peers.

Previous studies have indicated limited evidence assessing the effects of low MC on PA levels in adolescents [267]. A systematic review from Lubans *et al.,* [19] was focussed on FMS and PA, were only able to assess two longitudinal studies, which had conflicting conclusions as to the significance of the relationship between PA and MC. The first study indicated a longitudinal relationship, but actually assessed physical fitness [268] with MC, while the second study measured PA in children aged 4-6 years, using qualitative methods [269]. These limitations in study methodology make it difficult to clearly understand the effect of MC on PA.

Recent research has identified improving MC as a way to increase PA levels amongst children and adolescents [83, 93-95]. A study carried out by De Meester *et al.,* [185] measured MC using the Test of Gross Motor Development second edition (TGMD-2) and measured PA using accelerometers. Their results indicated that if a certain level of MC was not achieved then it was more likely that these children would not meet the recommended requirements for MVPA. This is further supported by DuBose et al., 2018 [94] who measured MC using the MABC2 and PA through accelerometry in children aged 3-10 years. Their data suggested that PA is positively related to MC, but only 46% of the total participants met the MVPA daily guidelines. Therefore, this may indicate that further improvements in MC levels may further increase PA participation and engage more children in being physically active for longer. Unfortunately, these studies were carried out in young children and pre-adolescence, which makes it difficult to infer these results for adolescent populations, especially when different theoretical models explain the relationship between MC and PA in adolescence [3, 49].

Furthermore, combinations of individual, subset grouping and total measures of MC with different test items have raised concern when evaluating its effect on PA in young people [75]. Multiple measures of fundamental movement skills, fine motor skills and fitness measures have been used to assess MC [70, 74, 126, 145, 150]. Global measures of MC generally cover fundamental movement skills and fine dexterity with some incorporating fitness component measures [267]. This vast array of movement skill tests assessing MC with some incorporated tests having little impact on PA such as fine dexterity may be causing a masking effect for the true interaction between MC and PA and could be the cause of inconsistent and conflicting results. A recent study conducted by Lima *et al.,* [75] has indicated that the relationship between PA and MC in adolescence is more complicated and less understood compared to younger children and further evidence is required.

This highlights the need to further understand the effects of MC on PA through measures which are required when performing PA [73]. As this mainly consists of locomotor activities in adolescents [4] then measuring the MC level of locomotor skills such as dynamic and static balance and centre of mass control, may give a clearer indication of the reduced effect of MC level on PA, and indicate more effective evidence to increase PA in adolescents [66]. Furthermore, information is required on the discriminatory effect of MC level through global MC and balance MC measures in adolescents and if specific balance measures can better discriminate high or low levels of PA duration and intensity. This would then provide information on the cut-off levels required to most likely produce higher levels of PA for higher intensities and could provide more targeted interventions for those with low MC and provide physical education teachers a means to test low MC in school aged population, as information for teachers in the UK is limited [46].

Therefore, this study aims to determine the differences in PA Levels in adolescents with low and typical levels of MC. Firstly, to determine the relative number of adolescents meeting the recommended levels of PA and compare differences between total MC and balance MC groups. Secondly, to determine the discriminatory ability of low total MC and low balance MC on low or higher levels of PA across different intensities and finally, what is the minimum cut-off required for higher levels of PA. The hypothesis is that adolescents with low total MC and balance MC will perform lower amounts of PA compared to TD peers. However, we suspect a low percentage of low total MC, balance and TD adolescents will be meeting the recommended guidelines. In addition, we predict low total MC and balance MC will have good discriminatory power for adolescents performing low levels of MVPA and VPA.

4.3 Methods

4.3.1 Participants

This cross-sectional study assessed 13-14 year-old adolescents, from a single mainstream secondary school in Oxfordshire between September 2017 and July 2018. Inclusion and exclusion criteria are presented in General Methods, Section 3.2 Participants.

4.3.2 Anthropometrics

Each participant was measured for height [cm] and weight [kg], as part of this study. A portable stadiometer was used to measure height to the nearest 0.1 cm, with shoes removed and a SECA medical 770 digital floor scale measured body mass to the nearest 0.1 kg. Height and weight were used to assess Body Mass Index (BMI) to the nearest 0.1 $kg.m^{-2}$.

4.3.3 Procedures

The assessment procedures took place over two conditions. MC, health-related fitness measures and all anthropometrics were assessed within the school PE lesson. As seen in section 3.6 Procedure. PA assessment was collected over seven days, as seen in section 3.8.2 Physical Activity (PA).

4.3.4 Motor Competence

MC was measured using the MABC2 and the balance subsection of the MABC2 [74]. As seen in General Methods Section 3.8.1 Motor Competence (MC). Low MC and low balance MC were classified at or below the 15^{th} percentile and TD MC was classified as a score greater than the 15^{th} percentile for the total MABC2 and the balance subsection.

4.3.5 Physical Activity

PA was assessed in free-living conditions over the course of a school week and weekend. This required the whole year 9 cohort to wear PA monitors throughout the day. As seen in General methods section 3.8.2 Physical Activity (PA). The PA data were categorised into two groups, those who performed low PA and those who performed higher levels of PA. Low MVPA was categorised into <30 mins and higher PA was categorised into ≥30 mins of MVPA per day [79, 100]. Low VPA was categorised into <5 mins and higher VPA were categorised into ≥5 mins per day. There is limited evidence for minimum levels of VPA which is beneficial to health in adolescence [101], as moderate and vigorous are normally combined to set guideline requirements. Therefore, setting a minimum VPA requirement for adolescents is unclear. However, a previous study has shown adolescents (12.9 ± 0.9 years) averaged around 10 mins of VPA per day, with none accumulating this in a 10 min bout [270]. This combined with data from the present study indicated that 5mins would be an adequate cut-off to determine low and higher levels of VPA.

4.3.6 Health-Related Fitness

Aerobic capacity was measured using the 20m Shuttle Run [249] As seen in General Methods Section 3.8.4 Health-Related Fitness Measures.

Grip Strength was measured using a handheld dynamometer [271] As seen in General Methods Section 3.8.4 Health-Related Fitness Measures.

Lower limb explosive strength was measured using the broad Jump [272] As seen in General Methods Section 3.8.4 Health-Related Fitness Measures.

4.3.7 Statistical Analysis

PA and MC measures were assessed for normal distribution using Q-Q plots. All were deemed to be normally distributed (Appendix F). For descriptive characteristics a one-way analysis of variance (ANOVA) assessed the differences in MC level MVPA and VPA across genders, a LSD post-hoc test assessed individual group differences. An independent t-test was used to assess the mean differences between PA levels in the Low MC and Low Bal groups vs the TD groups at a significant level $p<0.05$ and effect size according to Cohen's d, small 0.2 – 0.5, medium >0.5 – 0.8, large > 0.8 [273]. Homogeneity of variance was assessed using the Levene's test which indicated homogeneity between groups. A chi-square test assessed MC and PA association at a significant level <0.05 with relative risk used to assess effect size. The receiver operation characteristic (ROC) curve was used to explore the discriminatory power of MC level to differentiate grouping into low PA or higher levels of PA. The area under the curve (AUC) with a p-value <0.05 was used to assess the significance of this test with a score between 0.7-0.79 defined as acceptable discrimination, 0.8-0.89 as excellent discrimination, and ≥0.9 as outstanding discrimination. This method provides information on sensitivity and 1-specificity which can estimate the optimal cut-off points for MC and balance MC level when differentiating low or higher levels of PA. All data analysis was performed using IBM SPSS v.25.

4.4 Results

4.4.1 Descriptive Characteristics

A total of 166 adolescents took part in this study (as seen in Figure 4), The catchment area for this school ranges from the 1^{st} to the 3^{rd} quintile on the Index of Multiple Deprivation (IMD) score [204] and the socioeconomic status as measured by free school meals was 7.7% [274]. Missing data from the MC battery test (n=9) and the minimum required days of wear time for the PA assessment (n=94), resulted in a total of 63 adolescents. Descriptive characteristics for gender and MC level for total MABC2 and balance subsection are presented in Table 5 and Table 6 respectively, with time spent in MVPA and VPA. There was no significant difference in PA levels, total MABC2 score and balance score, for low MC females compared to low MC males and TD females compared to TD males. Therefore, further analysis was performed with genders combined.

4.4.2 Differences in PA between MC groups

Only one individual met this recommendation, with a total MABC2 score in the 75^{th} percentile. This was similar when assessing the number of adolescents reaching more than 45 mins of MVPA. Slightly more TD adolescents (n=5) reached 45 mins of MVPA than the Low MC group (n=3), which was similar when MC was measured using the balance subsection of the MABC2 (TD n=6, Low Bal =2). Overall, this indicates that adolescents are not performing adequate levels of MVPA (Appendix I).

There was no significant difference ($t_{(61)}$=1.814, *p*= 0.075, 95%CI -13.5-0.65) between the low MC group as measured by the total MABC2, (25.3±13.4 mins) compared to the TD group's (31.7±14.3 mins) MVPA. There was also no significant difference between low MC (3.8±3.8 mins) and TD (5.3±4.3 mins) adolescents VPA ($t_{(61)}$=1.477, *p*= 0.145, 95%CI -3.4-0.54) see Figure 7a. However, there was a significant difference in MVPA between the TD balance group compared to the low balance MC group. The low balance group performed less MVPA (23.1±14.0 mins) compared to the TD group (31.8±13.5 mins) ($t_{(61)}$=2.365, *p*=0.02, 95%CI -16.0 -1.34, Cohen's d = 0.63, 95%CI 0.094 – 1.17). This was similar when comparing VPA. The low Bal MC group performed less VPA (3.0±2.7 mins) on average over 7 days compared to the TD Bal group 5.5±4.5 mins ($t_{(61)}$=2.343, *p*=0.02, 95%CI -4.62 -0.37, Cohen's d = 0.63, 95%CI 0.088 – 1.16) (see Figure 7b).

4.4.3 Group Allocations

Figure 8 shows the proportion of MC level as measured by the total MABC2 and the balance subsection of the MABC2 in MVPA as categorical date (4.3.4 Motor Competence, 4.3.5 Physical Activity). A greater proportion of adolescents with lower levels of MC were reported in the lower PA group and a greater proportion of TD adolescents were reported in the higher PA group (χ^2_1 = 6.563, *p* = 0.01). The relative risk indicated it was 1.75 times more likely that low MC would be in the low PA group and a relative risk of 0.438 that the low MC would be in the high PA group. The balance subsection of the MABC2 also indicated a higher proportion of low balance MC in the low PA group ($\chi^2_1 = 7.292$, $p = 0.007$). The relative risk indicated that it was 3.19 times more likely that low balance performance would be in the low PA group and a relative risk of 0.62 that the low balance performance would be in the high PA group.

4.4.4 ROC Curve analysis

The ROC curve analysis suggested that the optimal cut-off points to discriminate either low or higher levels of MVPA and VPA was the 15th percentile of the total MABC2 when all possible scores were assessed. This is used as a classification cut-off between low MC and TD. This suggests adolescents with low MC are more likely to be in the low MVPA and VPA group. When assessing MC using the balance subsection of the MABC2, greater discriminatory power was reported. However, the optimal cut-off point was at the 31st percentile (Table 7).

Table 5: Descriptive Characteristics of participants MC, PA, HRF measures and Anthropometrics for total MABC2

	Female Low MC n=13		Female TD n=18		Male Low MC n=15		Male TD n=17	
	mean±SD	95%CI	mean±SD	95%CI	mean±SD	95%CI	mean±SD	95%CI
Height [cm]	160.0±18.7	148.7-171.3	166.0±6.6	162.7-169.3	171.9±6.9	168.0-175.7	167.7±10	162.6-172.9
Weight [kg]	64.1±14.9	55.1-73.2	57.1±11.6	51.4-62.9	59.9±13.8	52.3-67.5	52.7±14.6	45.2-60.2
BMI [$kg.m^{-2}$]	26.6±13.1	18.7-34.5	20.8±4.1	18.8-22.8	20.2±4.0	18.0-22.4	18.5±3.3	16.8-20.2
Broad Jump [cm]	128.5±48	99.4-157.5	156.1±28.7	141.9-170.4	157.7±29.2	141.5-173.8	175±27.1	161.1-188.9
Grip Strength [kg]	22.3±6.0	18.7-25.9	25.9±6.7	22.5-29.2	25.3±5.9	22.1-28.6	26.9±8.7	22.4-31.3
VO_2max [$mL.kg^{-1}.min^{-1}$]	39.8±10.3	33.6-46.0	47.6±10.4	42.4-52.8	51.5±6.7	47.7-55.2	54.9±7.6	51.0-58.9
MABC2 Total [Percentile rank]	5.2±3.1†	3.3-7.0	34.7±17.7†	25.9-43.5	5.4±3.3	3.6-7.3	41.6±18.3	32.3-51.0
Average 7day MVPA [min]	24.4±15.0†	15.3-33.5	30.7±16.5†	22.5-38.9	26.1±12.2	19.4-32.9	32.9±12.0	26.7-39
Average 7day VPA [min]	3.0±2.8†	1.3-4.7	4.4±4.7†	2.1-6.8	4.5±4.5	2.0-7.0	6.3±3.7	4.4-8.2

MC = Motor Competence, TD = Typically Developed, SD = standard deviation, 95%CI = 95% Confidence Intervals, BMI = Body Mass Index, MVPA = Moderate to Vigorous Physical Activity, HRF = Health Related Fitness. † = no significance difference between genders for Low MC and TD groups.

Table 6: Descriptive Characteristics of participants MC, PA, HRF measures and anthropometrics for balance subsection of MABC2

	Female Low Bal n=10		Female TD n=21		Male Low Bal n=11		Male TD n=21	
	mean±SD	95%CI	mean±SD	95%CI	mean±SD	95%CI	mean±SD	95%CI
Height [cm]	159.3±21.5	144.0-174.7	165.4±6.4	162.5-168.4	171.2±9.3	164.9-177.4	168.9±8.7	165-172.8
Weight [kg]	69.0±16.0	57.5-80.4	55.8±9.6	51.4-60.2	60.6±12.0	52.6-68.7	53.7±15.3	46.7-60.6
BMI [kg m^{-2}]	29.1±14.3	18.8-39.3	20.5±3.5	18.8-22.1	20.6±2.9	18.6-22.5	18.6±4	16.8-20.4
Broad Jump [cm]	117.0±47.4	83.1-150.9	157.6±28.3	144.7-170.5	159.5±24.7	142.9-176.2	170.7±30.9	156.7-184.8
Grip Strength [kg]	21.4±6.0	17.1-25.7	25.8±6.4	22.9-28.7	27.3±8.9	21.4-33.3	25.5±6.7	22.5-28.6
VO_2max [mL.kg^{-1}.min^{-1}]	35.6±9.8	28.6 42.6	48.5±8.9	44.5-52.6	50.9±7.2	46.0-55.8	54.6±7.2	51.3-57.9
MABC2 Balance Percentile rank	6.2±3.4†	3.7-8.6	44.3±28.8†	31.2-57.4	7.5±2.7	5.7-9.4	49.6±24	38.6-60.5
Average 7day MVPA [mins]	18.7±14.1†	8.6-28.8	32.5±15.1†	25.6-39.4	27.2±13.3	18.2-36.1	31±12	25.6-36.5
Average 7day VPA [mins]	2.6±3.1†	0.4-4.8	4.4±4.3†	2.4-6.4	3.3±2.4	1.7-4.9	6.5±4.5	4.5-8.6

Bal = balance subsection MABC2, TD = Typically Developed, SD = standard deviation, 95%CI = 95% Confidence Intervals, BMI = Body Mass Index, MVPA = Moderate to Vigorous Physical Activity, HRF = Health-Related Fitness. † = no significant difference between genders for Low MC and TD groups.

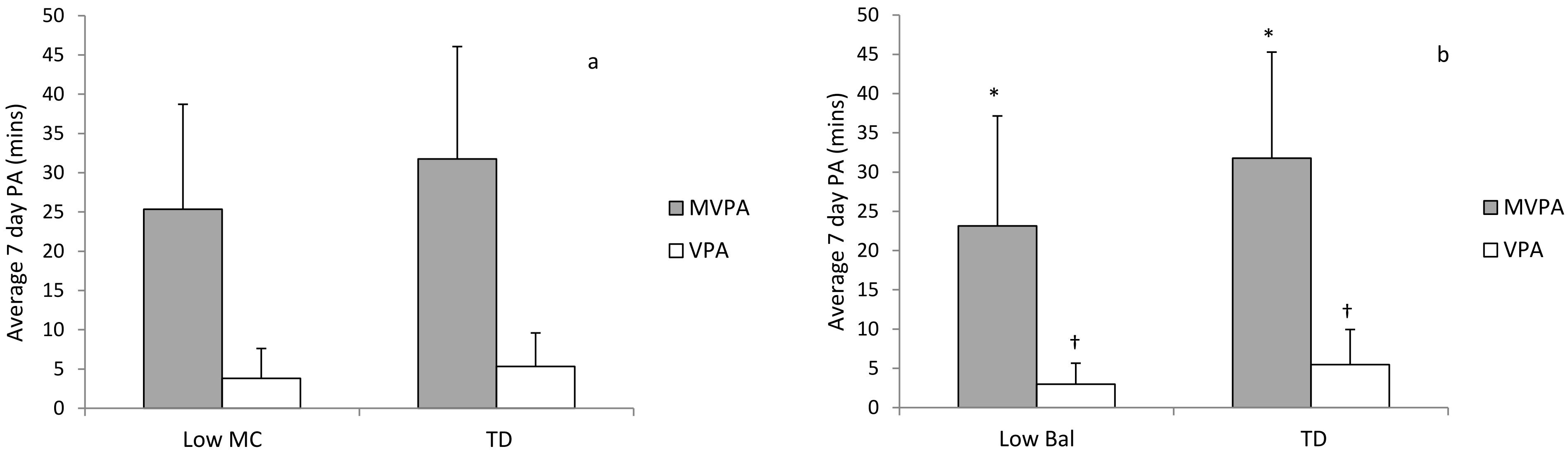

Figure 7: Average time adolescents spent in MVPA and VPA with low motor competence (Low MC) and typically developed motor competence (TD) as measured by the Movement Assessment Battery for children 2nd edition (MABC2) total test score (Fig a) and the total balance subsection score of the MABC2 (Fig b).
* = significant difference in MVPA time, between low balance group (Low Bal) and typically developed group (TD), $p < 0.05$
† = significant different between VPA time, between low balance group (Low Bal) and typically developed group (TD), $p < 0.05$

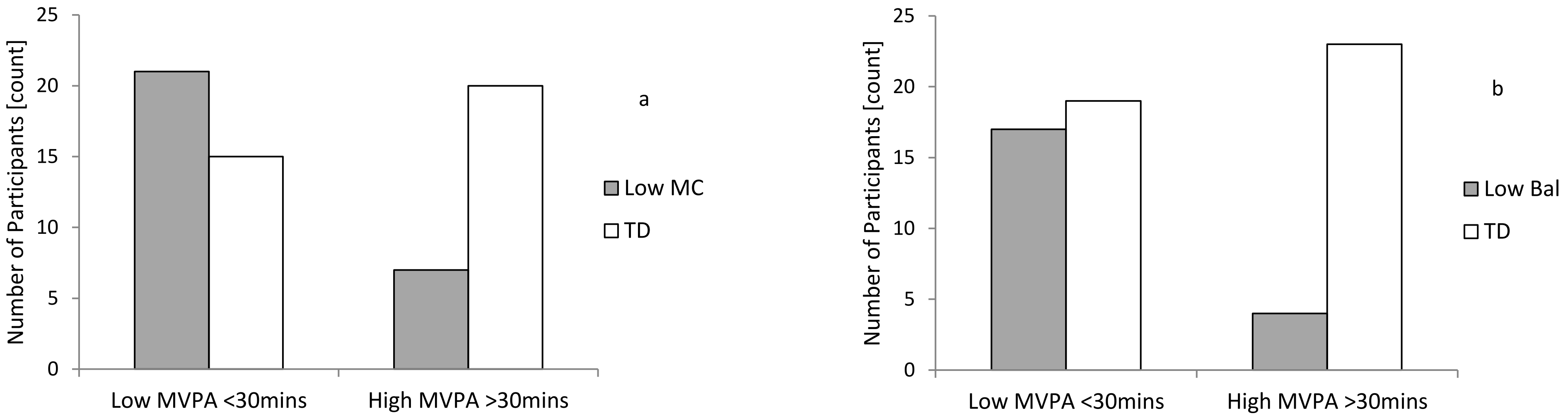

Figure 8: The number of adolescents with low and typical levels of MC as measured by (a) the total Movement Assessment Battery for Children 2nd edition (MABC2) and (b) the balance subsection of the MABC2 into groups of low or higher levels of PA.

Adolescents who were categorised with low MC were more likely to be in the low PA group compared to the typically developed group ($\chi^2_1 = 6.563$, $p = 0.01$). Adolescents who were categorised with low balance (low Bal) were also more likely to be in the low PA group ($\chi^2_1 = 7.292$, $p = 0.007$).

Table 7: ROC analysis of Motor Competence as measured by the Movement Assessment Battery for Children 2nd Edition (MABC2) and the Balance subsection score of the MABC2 discriminating PA levels in adolescents

	Total MABC2		Bal MABC2	
	MVPA	VPA	MVPA	VPA
AUC	0.70	0.66	0.75	0.77
p-value	0.008	0.033	0.001	0.0003
95% CI	0.56-0.83	0.52-0.81	0.62-0.88	0.64-0.90
Cut off	15	15	31	31
Sensitivity	0.61	0.58	0.78	0.77
1-Specificty	0.27	0.29	0.30	0.25

ROC = Receiver Operator Characteristic, AUC = Area Under the Curve, 95%CI = 95% Confidence Intervals, MVPA = moderate to vigorous physical activity, VPA = vigorous physical activity, MABC2 = Movement Assessment Battery for Children 2nd Edition, Bal = Balance subsection of the MABC2.

4.5 Discussion

This study found that low MC, low balance MC and typically developed adolescents were not meeting the recommended daily PA levels of 60 mins per day. Only one individual met this recommendation and the majority completed around 30 mins or less per day. For the first time, this study found that adolescents with low balance MC performed less MVPA and VPA compared to their TD peers. This was further supported by low MC and low balance MC adolescents being categorised into the low PA group. MC level was also able to discriminate between low and higher MVPA and VPA levels, with low balance MC providing better discriminatory power compared to total MC. This suggests that MC and PA are closely linked in adolescents and both require promotion especially in those with low balance MC when targeting an increasing VPA.

PA levels in children across Oxfordshire indicated that the present study's results are below average. Data from Sport England [275] surveyed PA and sports participation in children aged 5-16 years in Oxfordshire. Their results reported that children and adolescents [n=1408] are performing low amounts of PA with 21.2% [95%CI 18.4-24.45] performing 60 mins or more per day and only 23.2% [95%CI 20.2-26.6%] performing between 30-59 mins a day. The most common amount of time recorded for average PA participation was less than 30 mins a day, reported at 29.5% [95%CI 26.6-32.5%]. These differences may be explained by the differences in socioeconomic status between Oxfordshire and the present study's sample size, as the present study included a school in the three lowest quintile scores for deprived areas in Oxford [204]. Physical inactivity is associated with deprivation [276], however, data from Brodersen *et al.,* [62] indicates that PA differences are only reported in girls with low socioeconomic status but not in boys, which may further explain differences in the present study.

The low number of adolescents reaching 60 minutes or more of MVPA is widely reflected across the literature [2, 91-95] and is further supported in this study (Appendix I). Information from Tremblay *et al.,* [94], reported PA levels in children across 38 countries. Their results concluded that PA levels are low in young people and that the majority were not reaching the recommended levels of daily PA. This data are consistent in UK children and adolescent populations [2] and is further supported by the present study with 57.1% of 13-14 years olds completing on average less than 30 mins per day. Wilkie *et al.,* [2] reported data on PA for ages 11-15 years, were 35.8% or less meeting the MVPA guidelines for boys and 21.8% or less for girls. Further data from NatCen Social Research [93] provides information on young people's health and PA and indicates as little as 15% of boys and 9% of girls, aged 13-15 years were completing the MVPA guidelines. Similar results are reported in the present study with boys and girls reporting low levels of PA with the only reported differences between MC levels. Therefore, low PA was further exacerbated by MC level and not by gender.

This is cause for further concern as evidence has indicated that PA levels steadily decline throughout adolescents, and these low levels of PA track into adulthood [63, 92, 98]. A systematic review and meta-analysis from Corder *et al.,* [92] suggests a 7% reduction in PA levels in adolescents per year, with Metcalf *et al.,* [98] reporting a reduction in PA of 20% in boy and 30% in girls from the ages of 9-15 years. Evidence from the current study already indicates low levels of PA with, previous evidence indicating that this will decline further. This may have a highly detrimental effect on many health parameters and therefore, any further reduction in PA levels would exacerbate these health concerns. Even though the vast majority of adolescents were not meeting the recommended daily PA guidelines, data from Janssen and Leblanc [100] has indicated that averaging 30mins of MVPA may produce some of the health and fitness benefits associated with 60 mins of MVPA [82]. The UK guidelines reviewing PA have indicated that children who are engaged in high sedentary levels should aim for 30 mins as a progression to further increase levels of PA [79]. Unfortunately, the present study indicates that the majority of low MC (75.0%) and low balance (81.0%) adolescents are performing less than 30 mins of MVPA on average per day, while the majority of the TD group is slightly above this threshold. This may indicate that acquiring any health benefits from PA is not being achieved in adolescents with low MC or low balance MC, whereas children with TD MC may be able to acquire some health benefits and more importantly, be more likely to increase their levels of PA.

Previous research has shown children with low MC have further reductions in their PA compared to typically developed peers [3], but less evidence has been conducted in adolescents [3, 195]. Our data indicates (Figure 7) that adolescents with low MC and low balance MC were more likely to be in the low PA group (<30 mins), with the TD adolescents more likely to be in the higher PA group (≥30 mins). This is supported by previous research in TD [7, 19, 68, 85, 133] and clinical population [71, 277, 278]. Evidence focussing on TD children and adolescent's fundamental movement skills (FMS) and their relationship to PA has indicated clear associations [7, 19, 68]. However, these associations have limitations and require caution when deriving conclusions. Three systematic reviews assessing the relationship between FMS and PA all indicate medium to strong associations but were limited in their methodologies. These excluded any data which recorded children with any motor difficulties such DCD, and any movement battery test which incorporated fine motor skills e.g. MABC2 and BOT2 which are two of the most widely used motor assessments [1]. Even though the justification for removing these criteria is clear, as fine motor skills impact on PA is negligible [7, 19, 279], a significant amount of information has been lost, which might add further understanding to the relationship between MC and PA. Therefore, this study adds knowledge to the relationship between full valid measures of MC and PA and how this relationship is affected when a subsection of balance is used to measure MC, as this has a greater theoretical impact on PA compared to fine motor skills [7, 279].

Additional limitations in previous studies involve the methods used to assess FMS and PA. Many of these reviews limited their search strategies to process-oriented approaches to FMS assessment. This has limitations in assessing the end product of the movement and focusses on the quality of the movement which, can improve subjectively but may have no effect on the objective outcome of the movement, which may differ between raters and highlights the differences in information assessed between these two approaches [129]. The present study was able to assess a product-oriented approach to MC assessment with PA levels which may improve positive feedback on individuals MC level and encourage more PA compared to improvements in process-oriented approaches. Thus, improving MC which highlights better scoring in a sport maybe be more beneficial than improving the action of the movement.

PA can be measured in multiple ways (as seen in 2.2 Measuring Physical Activity (PA), with many studies adopting self-report questionnaires. These have limitations compared to objectively measuring PA such as accelerometry, with larger bias in overall PA recorded for self-reported methods [174, 280, 281]. These included over-reporting the amount of actual PA performed over a certain time period and less accurate ways of determining PA intensity compared to objective measures. However, recent studies measuring PA using accelerometry also have limitations. Data collected by McGrane *et al.,* [133] assessed 548 adolescents MC using the TGMD2 and PA using accelerometry. PA data were collected using vertical accelerations only, with 10s epochs and non-wear time indicated at ≥20 minutes of consecutive 0 counts. Only measuring vertical acceleration may under-estimate certain activities which involve more medial-lateral and anterior-posterior accelerations, which may compound the bias when using 10s epochs, as these have shown to be inappropriate when assessing vigorous types of activities in young people [282, 283]. Using a cut-off of ≥20 mins of consecutive zero counts may underestimate sedentary time as many children and adolescents are becoming more sedentary [183] and therefore this information would be classified as non-wear time instead of sedentary behaviour. Therefore, the methods used by the current study have been able to minimise these effects by using an objective method, lowering the epoch length to one second, increasing the sedentary cut-off to 60 mins and measuring acceleration in all three axes.

Further limitations have also been identified in previous studies reporting the association between MC and PA in clinical populations such as DCD [71, 277, 278]. Evidence from Green *et al.,* [71], who assessed 7-8 year olds longitudinally over 5 years with probable DCD, indicated that boys with probable DCD performed less MVPA than TD, but indicated no differences between girls. However, only three tests from the MABC2 were used to assess DCD and PA was only recorded using vertical acceleration. More recent work has assessed objective measures of PA using accelerometry and MC using the full MABC2 [278]. Their results indicated children with DCD perform less MVPA than TD children. However, this analysis was completed on children aged 6-12 years and does not capture the relationship in adolescents. Therefore, the present study has supported the evidence of MC and PA relationship in adolescents, with low MC adolescents more likely to perform <30 mins of PA compared to their TD peers and highlighted that balance MC plays a major role in this relationship at this age.

More recently data from De Meester *et al.,* [185] has provided evidence for the proficiency barrier model. Their study assessed MC and PA in 326 children aged 9.5±1.24 years. Their results support the proficiency barrier as more children (90%) with low MC did not meet the recommended guidelines of 60 mins PA per day. However, only a low percentage of children with average or high MC met the PA guidelines (25% average MC, 41% high MC) which, is supported by the present study. Therefore, our data may suggest that this proficiency barrier is also important in adolescence (Figure 8). Dynamic and static balance as measured by the balance subsection of the MABC2 may play an important role in this proficiency barrier threshold for higher levels of PA especially for more vigorous forms of PA [284].

Studies assessing the reciprocal relationship of PA MC have indicated inconclusive results. Both Barnett *et al.,* [64] and Lima *et al.,* [75] tested this reciprocal relationship through cross-sectional and longitudinal data respectively. Barnett *et al.,* [64] indicated that motor skill proficiency as measured by combining locomotor skill and object control was only significant for object control when separated into two subsections of motor proficiency. This may be explained through the assessment of MC and PA. As object control is perhaps associated with higher frequencies and intensities such as game-based activities when adolescents use self-recall to assess their PA levels. Lima *et al.,* [75] also assessed this reciprocal relationship and concluded that their evidence supported the Stodden *et al.,* [49] model. It was reported that an increase in MVPA and VPA resulted in an increase of MC, and the increase of MC resulted in an increase in MVPA and VPA, which is further supported by the present study. However, the reciprocal relationship between MVPA and MC was only significant when the relationship was mediated by fitness. There was no direct association between MVPA and MC or MC and MVPA. This may be explained again through the method used to assess MC. The Körperkoordinationstest für Kinder (KTK) was used to assess MC and assesses a total of four balance and locomotor skills, walking backwards on a balance beam, moving sideways on wooden boards, 1-legged hop over obstacles and 2-legged jumps from side to side [149]. These four tests were used to assess MC longitudinally across three age groups and even though they were norm-referenced, using the same MC tests for different ages may cause younger children to all perform badly independent of PA level and may cause all adolescents to perform well independent of PA level. Therefore, using MC tests which have been designed for specific ages and norm-referenced may indicate reciprocal relationships, which was conducted in the present study [3]. Unfortunately, the present study did not test the reciprocal relationship between PA and MC, but it did use age validated MC measures of locomotor MC assessments (Balance) and age validated measure of overall MC ability. This may provide a more appropriate method in assessing MC in relation to age specific PA and which specific measures are most effective when assessing the association to PA.

Further analysis from the present study indicated that the total MC and the balance subsection of the MABC2 were acceptable discriminators for those with low levels of MVPA and VPA (Table 7). The data suggests that the balance subsection was the best discriminator for VPA. This indicates that dynamic and

CoM control are better at discriminating between time spent in higher intensities of PA, as better movement control of whole-body position and individual limb position is required when moving more vigorously, which has not been assessed in previous literature [85]. This may be extenuated when manual dexterity and hand-eye coordination are taken into consideration as a total measure of MC. The discriminatory power of MC on PA is further supported by longitudinal data. Studies have reported MC levels in children can predict PA levels in adolescence and adulthood [75, 195, 279, 285, 286]. Lopes *et al.,* [195] reported higher MC ability is associated with higher amounts of MVPA, moderate PA and total amount PA performed when balance and locomotor movements were used as a measure of MC (KTK). This further supports the idea that MC measures should involve actions that are required when performing PA activities, especially when more vigorous PA is either tested or trying to be improved.

Data from the ROC curve analysis indicated that the 15th percentile threshold for low and TD total MC levels is also an acceptable threshold to discriminate high and low levels of MVPA. This suggests that the total MC method used to assess MC is an able discriminator for moderate and vigorous levels of PA. However, as a large majority of MVPA in this study is accumulated from moderate levels of PA, therefore, it can be hypothesised that overall MC measures can discriminate between low and high durations of moderate PA. This could be used as a screening tool which could highlight adolescents who may be at risk of low levels of moderate PA due to low total MC. This may be able to target specific interventions which can simultaneously improve MC and PA in this population. Furthermore, the optimal threshold for discriminating low and higher levels of MVPA and VPA for the balance subsection is the 31st percentile. This may indicate that higher levels of balance performance as measured by the MABC2 is required to achieve higher levels of PA [279]. So instead of performing the whole MABC2, it may be more efficient to perform the balance subsection of the MABC2 only, while setting a higher cut-off for low and TD balance, which provides a greater discriminatory capacity for MVPA and VPA. This may be more useful when screening large samples of adolescents who are not meeting adequate PA levels through reduced balance and locomotive control.

4.6 Limitations

These are the first results to explore the discriminatory power of MC level and balance performance on MVPA and VPA in adolescents. However, there are limitations to this study. The relatively small sample size may limit the overall conclusion to the wider population of adolescents as this study only sampled from one UK secondary school. This was also affected by the large exclusion of data which was due to a high number of participants not meeting the valid PA wear time over the 7 days. In addition, using these results to compare to other countries requires caution as many other studies use different validated MC tests which have been validated for different cultures [23, 210, 211]. Furthermore, a lack of covariates which may have been used to control for biases in the data was limited. Information on parental PA level, MC self-perception and maturation were not measured and have been associated with effects on MC level and PA participation [195].

4.7 Conclusion

Adolescents with low MC are more likely to spend less than 30 mins in MVPA compared to TD peers which may have very little health benefits compared to more than 30 mins of MVPA per day, which was reported in the TD MC group. In addition, this is the first study to highlight the discriminatory power of MC as measured by balance on MVPA and VPA while indicating a higher cut-off for this skill compared to a total measure of MC. This indicated that MC, as measured by balance, maybe a more valid measure of MC when assessing the effect on PA. This may be beneficial when screening school-aged populations and give physical education teachers a targeted way to improve MC and PA simultaneously. As these balance measures are representative of locomotor control, it may be possible to assess MC through walking control. However, previous research is limited and inconsistent results have been reported. As children and adolescents with low MC have reported low automatisation of movement introducing a dual-task while walking may highlight the differences between low and TD balance MC more clearly.

Chapter 5 The Interaction of Motor Competence and Cognitive Motor Interference on Walking Performance in Adolescents

5.1 Summary

Chapter 4 found that lower PA levels were performed in adolescents with low balance MC which was also an important factor when discriminating MVPA and VPA. As balance is vital in walking control, then differences in walking performance may be apparent in adolescents with low balance MC. Therefore, walking analysis might have utility in assessing balance related risk of low PA levels in adolescents. This chapter will therefore, evaluate the interaction between movement quality as measured by spatial-temporal parameters while walking in adolescents performing a cognitive-motor interference task. A greater reduction in movement quality may explain the reduction in movement quantity and would lead to further analysis of linear relationships.

5.2 Introduction

Spatial-temporal walking parameters [111] and variability in walking [287] have been utilised to understand deficits in motor control. Studies have used these assessment methods to analyse walking parameters in an adult population with neurological disorders [233, 288] and pathological gait patterns in elderly fallers [289, 290] as well as changes due to interventions [291]. More recently, work has been completed in children and adolescents with low MC, as growing evidence indicates differences in gait within this population [111, 122, 123, 292]. However, differences between children with and without low MC have shown inconsistent results which could be due to the differences in methodologies used to assess either MC level or walking control. It may also be an indication that low MC is a heterogeneous group with large variability across multiple gait parameters. It is unclear if there is a systematic pattern differentiating low MC gait patterns from those of controls [110, 122, 123, 287, 293, 294].

Cognitive motor interference is a method which may be used to highlight the differences in walking control between adolescents with low and typical levels of MC. There are many different neural mechanisms which have been hypothesized to why there is a reduction in motor performance when a second concurrent task is performed. However, there is no leading model which best explains this in adolescents with low MC [295]. Recent studies have indicated that children with low MC require more attentional and cognitive workload to control movement compared to typically developed peers [294]. This may explain why some studies report no differences in gait parameters, whiles others show inconsistent differences. Children with low MC may be using more attentional resources to produce typical walking patterns, which may have a masking effect [296]. When an additional load is placed on these attentional resources then children and adolescents with low MC may exhibit clearer differences in gait control compared to control groups. This has been described as a deficit in the automation of movement [22, 297, 298]. The automatisation deficit hypothesis is modelled on the reasoning that walking is a task that requires little attentional control in low demanding and steady-state situations [296]. However, when a second concurrent task is performed, then a relatively low change in gait control should be reported if walking is truly automated. Children with low MC who may need more attentional resources to control walking, and therefore have low walking control automaticity, may experience a greater reduction in walking performance compared to controls [295].

Further clarity is needed to understand the differences in walking control between adolescents with low and typical levels of MC and may be achievable when assessing MC through balance measures independently. As Chapter 4 has shown balance to be an important skill in discriminating PA levels in adolescents, it has also shown to be of importance in walking control in young children [299]. Guffey *et al.,* [299] have indicated that balance is correlated with spatial-temporal gait parameters in children aged 2-4 years, and concluded that functional balance can be assessed by spatial-temporal gait parameters. This is supported by Speedtsberg *et al.,* [123] who highlighted lower dynamic stability in children with low MC compared to typically developed peers when walking on a treadmill [123, 300-303]. Furthermore, evidence of standing postural control is reduced in children with low MC compared to TD children [123, 302]. These reductions in control of CoM in standing and walking have been related to the impairments in feedforward and feedback mechanisms [304]. This may be attributed to reduced balance control compared to their typically developed peers and could also result in increased variability of spatial-temporal gait parameters [123, 302].

However, there is limited evidence on the impact of a second concurrent task on this relationship in adolescents. The combination of assessing the differences in adolescents with low balance MC while performing a walking task and a concurrent cognitive task may report more systematic differences compared to previous studies. This study will, therefore, compare the interaction between MC level as measured by total MC and balance measures independently with walking performance while concurrently performing a cognitive-motor interference (CMI) task. We hypothesize, that adolescents with low MC and low balance MC will report differences in their walking control than their TD peers on all gait parameters and gait variability.

5.3 Methods

5.3.1 Participants

This cross-sectional study assessed 13-14 year-old adolescents from three mainstream secondary schools in Oxfordshire between September 2017 and July 2018. Inclusion and exclusion criteria are the same as Chapter 4.

5.3.2 Procedure

As Seen in 3.6 Procedure.

5.3.3 Anthropometrics

Each participant was measured for height [cm], weight [kg], leg length [cm] and shoe size (UK). A portable stadiometer was used to measure height, with shoes removed to the nearest 0.1 cm and a SECA medical 770 digital floor scale measures body mass to the nearest 0.1 kg. Height and weight were used to assess Body Mass Index (BMI) to the nearest 0.1 $kg.m^{-2}$. To analyse walking parameters further anthropometrics were recorded, these included leg length which was measured using a handheld 3 m tape measure, from the anterior superior iliac spine to the medial malleolus of the ipsilateral leg. In addition, shoe size was recorded from the participant's shoe.

5.3.4 Motor Competence

As seen in Chapter 4.

5.3.5 Gait Analysis

Gait analysis was assessed using an Inertial Measurement Unit (IMU) (General Methods section 3.8.2 Gait Analysis). As maturity in spatial-temporal gait parameters are significantly different between genders, [116] further analysis was conducted separately.

5.3.6 Statistical Analysis

Gait and MC measures were assessed for normal distribution through visual inspection of the Q-Q plots. All were deemed to be normally distributed (Appendix G). A one-way ANOVA assessed the differences in group characteristics between MC level for boys and girls. A least significant difference (LSD) post-hoc test assessed the individual differences between groups (significance set at <0.05). A two way mixed ANOVA was used to assess a 2 x 2 (MC x CMI) interaction between MC (between subjects Low MC, TD) and the effects of CMI on gait parameters (within-subjects STW, CMI) ($p < 0.05$). Partial eta squared (η_p^2) was used to measure effect size (0.01-0.06 small, 0.06-0.14 medium, >0.14 large). Homogeneity of variance was assessed by Levene's tests at $p < 0.05$, as there were only two within-subject factors, the Mauchly's test of sphericity was not performed. All data analysis was performed using IBM SPSS v.25.

5.4 Results

5.4.1 Total Motor Competence

A total of 365 participant's data were analysed in this study (Figure 4) with their characteristics presented in Table 8. The catchment area ranges from the 1st to the 4th quintile on the Index of Multiple Deprivation tool [204], with pupils claiming free schools meals shown in section 4.3 Methods [274]. The ANOVA reported a significant difference between groups for weight ($F_{(3,361)}$ = 3.993, p = 0.008, η_p^2 = 0.032, 95%CI 0.0024 - 0.07), height ($F_{(3,361)}$ = 12.139, p < 0.001, η_p^2 = 0.092, 95%CI 0.038 – 0.146), BMI ($F_{(3,361)}$ = 5.624, p = 0.01, η_p^2 = 0.045, 95%CI 0.008 – 0.087) and total MABC2 score ($F_{(3,361)}$ = 121.414, p < 0.001, η_p^2 = 0.502, 95%CI 0.431 – 0.557). The post hoc analysis reported differences in group comparisons between the girl's low MC group, weighing more than the girls TD group (SE 2.05, p = 0.036, 95%CI 0.28-8.35) and the boy's TD group weighed more than the girls TD group (SE 1.63, p = 0.045, 95%CI 6.48-0.075). The boy's low MC group was taller than the girls low MC group (SE 1.60, p < 0.001, 95%CI 5.0-11.3). This was similar for the TD groups, with the TD boy's group being taller than the TD girls group (SE 1.17, p = 0.001, 95%CI 1.44-6.03). The girl's low MC group also reported higher BMI scores compared to the girls TD group (SE 0.75, p < 0.001, 95%CI 1.33-4.28) and the boys low MC group (SE 0.72, p < 0.001, 95%CI 1.21-4.02) see Table 8.

5.4.2 Balance Motor Competence

The ANOVA reported significant differences between groups for weight ($F_{(3,361)}$ = 6.728, p < 0.001, η_p^2 = 0.053, 95%CI 0.013 – 0.098), height ($F_{(3,361)}$ = 11.130, p < 0.001, η_p^2 = 0.085, 95%CI 0.033 – 0.138), BMI ($F_{(3,361)}$ = 7.565, p < 0.001, η_p^2 = 0.059, 95%CI 0.017 – 0.11) and Balance score ($F_{(3,361)}$ = 62.856, p < 0.001, η_p^2 = 0.343, 95%CI 0.264 – 0.41). The post hoc analysis reported that girls with low balance weighed more than their TD peers (SE 2.73, p = 0.002, 95%CI 3.05-13.8), TD boys weighed more than TD girls (SE 1.42, p =0.03, 95%CI 0.30-5.9) and boys with low balance also weighed more than their TD peers (SE 2.32, p =0.014, 95%CI 1.16-10.29). The low balance girl's group was shorter than the low balance boy's group (SE 2.39, p = 0.001, 95%CI 3.45-12.86), which was similar for the girls TD group who were shorter than the boys TD group (SE 1.03, p < 0.001, 95%CI 2.90-6.75). On average girls with low balance had a higher BMI than their TD girl peers (SE 1.00, p < 0.001, 95%CI 2.3-6.25) and had a higher BMI than boys with low balance (SE 1.21, p < 0.017, 95%CI 0.53-5.3) see Table 9.

Table 8: Descriptive Characteristics of Participant's Anthropometrics and Motor Competence as measured by the total MABC2

	Girls				Boys			
	Low MC (n=58)	95%CI	TD (n=103)	95%CI	Low MC (n=67)	95%CI	TD (n=137)	95%CI
Weight [kg]	56.3±14.0	52.6-60.0	52.0±9.1*‡	50.2-53.8	58.5±12.8	55.4-61.6	55.3±13.8	52.9-57.6
Height [cm]	159.9±11.6†	156.9-163.0	162.8±6.5‡	161.5-164.0	168.1±9.1	165.9-170.3	166.5±9.2	164.9-168.0
BMI [kg m^{-2}]	22.4±7.7†	20.3-24.4	19.6±3.1*	19.0-20.2	20.6±3.9	19.7-21.6	19.8±4.0	19.1-20.5
Motor Competence Percentile [%]	5.6±2.9	4.8- 6.4	33.1±16.0*‡	29.9-36.3	6.3±2.9	5.6-7.0	39.7±19.0*	36.4-43.0

* = $p < 0.05$ Low Motor Competence [Low MC] compared to Typically Developed [TD]

† = $p < 0.05$ Low MC boys compared to Low MC girls

‡ = $p < 0.05$ TD boys compared to TD girls

Table 9: Descriptive Characteristics of Participant's Anthropometrics and Motor Competence as measured by the Balance subsection of the MABC2

	Girls				Boys			
	Low Bal MC (n= 24)	95%CI	TD (n= 137)	95%CI	Low Bal MC (n= 34)	95%CI	TD (n= 170)	95%CI
Weight [kg]	60.7±16.9*	53.6-67.8	52.3±9.5‡	50.7-53.9	61.1±12.9*	56.6-65.6	55.4±13.5	53.3-57.4
Height [cm]	160.9±13.5†	155.2-166.6	161.9±7.7‡	160.6-163.2	169.0±8.8	166.0-172.1	166.6±9.2	165.2-168.0
BMI [kg m^{-2}]	24.2±10.6*†	19.8-28.7	20.0±3.5	19.4-20.6	21.3±4.0	19.9-22.7	19.8±3.9	19.2-20.4
Balance Percentile [%]	6.9±3.0*	5.6-8.2	57.5±28.5	52.7-62.3	7.5±2.7*	6.6-8.4	54.1±25.4	50.3-58.0

* = $p < 0.05$ Low balance Motor Competence [Low MC] compared to Typically Developed [TD]

† = $p < 0.05$ Low balance MC boys compared to Low MC girls

‡ = $p < 0.05$ TD boys compared to TD girls

5.4.3 Spatial-Temporal Parameters

Walking Speed

Interactions and group differences between subjects and within subjects for spatial-temporal gait parameters for both walking tasks are presented in Table 10. There was no significant group (MC) by walking task (CMI) interaction for walking speed in boys or girls. A within-subjects main effect (SWT - CMI) was found for walking speed in boys ($F_{(1,195)}$ = 252.375, p <0.001, η_p^2= 0.564, 95%CI 0.475 – 0.632) and girls ($F_{(1,154)}$ = 155.801, p <0.001, η_p^2 = 0.503, 95%CI 0.394 – 0.586). Both low MC and TD groups reduced their walking speed when performing CMI walk compared to STW. There were no significant effects between subjects (MC groups) for walking speed in boys or girls.

Cadence

There was no significant group (MC) by walking task (CMI) interaction for cadence in boys or girls. A within-subjects main effect (SWT - CMI) was found for cadence in boys ($F_{(1,194)}$ = 109.983, p <0.001, η_p^2 =0.362, 95%CI 0.258 – 0.451) and girls ($F_{(1,151)}$ = 124.008, p <0.001, η_p^2 =0.451, 95%CI 0.336 – 0.542). Both low MC and TD groups reduced their cadence when performing CMI walk compared to STW. There were no main effects between subjects (MC groups) for cadence in boys or girls.

Stride Length

There was no significant group (MC) by walking task (CMI) interaction for stride length in boys or girls. A within subject main effect (SWT - CMI) was found for stride length in boys ($F_{(1,198)}$ = 131.467, p <0.001, η_p^2 =0.399, 95%CI 0.297 – 0.485) and girls ($F_{(1,158)}$ = 225.333, p <0.001, η_p^2 =0.588, 95%CI 0.491 – 0.658). Both low MC and TD groups reduced their stride length when performing CMI walk compared to STW. A between subjects (MC groups) main effects was found for stride length in girls ($F_{(1,158)}$ = 5.779, p = 0.017, η_p^2 0.035, 95%CI 0.0008 – 0.11). There was a greater stride length in the low MC group (1.66 ± 0.157) compared to TD group (TD 1.602 ± 0.1407) for the STW (t_{159} = 2.011, p = 0.046, ES 0.32). However, there was no significant difference in CMI walk, for the low MC group (1.49 ± 0.154) compared to the TD group (1.45 ± 0.121) in girls, (t_{158} = 1.963, p = 0.051, ES 0.29). There was no main effect between subjects for stride length in boys.

Walk Ratio

There was no significant group (MC) by walking task (CMI) interaction for walk ratio in boys or girls. A within-subject main effect (SWT - CMI) was found for walk ratio in boys ($F_{(1,200)}$ = 7.178, p = 0.008, η_p^2 =0.035, 95%CI 0.002 – 0.97) but not girls ($F_{(1,158)}$ = 0.596, p = 0.441, η_p^2 =0.004). Both low MC and TD groups increased their walk ratio when performing CMI compared to STW. There were no main effects between subjects (MC groups) for walk ratio for boys or girls.

5.4.4 Spatial-Temporal Parameters Coefficient of Variation (CV)

Walking Speed CV

Interactions and group differences between subjects and with subjects for spatial-temporal gait variability for both walking tasks are presented in Table 11. There was no significant group (MC) by walking task (CMI) interaction for walking speed CV in boys or girls. A within-subjects main effect (SWT - CMI) was found for walking speed CV in boys ($F_{(1,195)}$ = 15.959, p = <0.001, η_p^2 = 0.076, 95%CI 0.197 – 0.154) and girls ($F_{(1,154)}$ = 33.149, p = <0.001, η_p^2 = 0.177, 95%CI 0.8 – 0.28). Both low MC and TD groups increased their walking speed variability when performing the CMI walk compared to the STW. There were no main effects between subjects (MC groups) for walking speed CV for boys or girls.

Cadence CV

There was no significant group (MC) by walking task (CMI) interaction for cadence CV in boys or girls. A within-subjects main effect (SWT - CMI) was found for cadence CV in boys ($F_{(1,194)}$ = 35.728, p = <0.001, η_p^2 = 0.156, 95%CI 0.728 – 0.247) and girls ($F_{(1,151)}$ = 44.898, p = <0.001, η_p^2 = 0.229, 95%CI 0.121 – 0.336). Both low MC and TD groups increased their cadence variability when performing the CMI walk compared to the STW. There were no main effects between subjects (MC groups) for cadence CV for boys or girls.

Stride Length CV

There was no significant group (MC) by walking task (CMI) interaction for stride length CV in boys or girls. A within subjects main effect (SWT - CMI) was found for stride length CV in boys ($F_{(1,198)}$ = 17.494, p = <0.001, η_p^2 = 0.81, 95%CI 0.231 – 0.16) and girls ($F_{(1,158)}$ = 19.656, p = <0.001, η_p^2 = 0.111, 95%CI 0.35 – 0.21). Both low MC and TD groups increased their stride length variability when performing the CMI walk compared to the STW. A between subjects (MC groups) main effects was found for stride length CV in boys ($F_{(1,198)}$ = 4.046, p = 0.046, η_p^2 = 0.02, 95%CI 0.001 – 0.0734). There was a greater stride length variability in the low MC (6.9±3.8) group compared to the TD group (5.7±3.4) for the CMI walk (t_{198} = 2.134, p = 0.034, ES 0.33). However, there was no difference in variability between the low MC group (5.1±4.3) compared to TD group (4.6±3.0) for STW (t_{201} = 0.962, p = 0.337). There was no main effect between subjects for girls.

Walk Ratio CV

There was no significant group (MC) by walking task (CMI) interaction for walk ratio CV in boys or girls. A within-subjects main effect (SWT - CMI) was found for walk ratio CV in boys ($F_{(1,200)}$ = 5.825, p = 0.017, η_p^2 = 0.028, 95%CI 0.0007 – 0.869) and girls ($F_{(1,158)}$ = 35.569, p = < 0.001, η_p^2 = 0.184, 95%CI 0.0863 – 0.287). Both low MC and TD groups decreased their walk ratio variability when performing the CMI walk compared to the STW. There were no main effects between subjects (MC groups) for walk ratio CV for boys or girls.

Table 10: Spatial-Temporal gait parameters for single task walk and cognitive-motor interference walk in boys and girls with low and typical levels of motor competence as measured by the total MABC2

	Single Walk Task		CMI Walk Task	
Boys	Low MC	TD	Low MC	TD
ND Normalised Walking Speed	0.45±0.05 *	0.45±0.05	0.37±0.05	0.38±0.06
ND Normalised Cadence	33.39±2.73 *	33.62±2.11	30.06±3.40	30.65±4.24
ND Normalised Stride length	1.60±0.15 *	1.60±0.14	1.47±0.15	1.48±0.14
Walk Ratio mm/[steps min^{-1}]	6.54±1.20 *	6.46±0.75	6.8±1.20	6.67±1.32
Girls	Low MC	TD	Low MC	TD
ND Normalised Walking Speed	0.46±0.05 *	0.46±0.05	0.38±0.08	0.37±0.07
ND Normalised Cadence	33.86±2.92 *	34.05±3.02	30.36±4.66	30.10±4.03
ND Normalised Stride length	1.66±0.15 *†	1.6±0.14	1.49±0.15	1.45±0.12
Walk Ratio mm/[steps min^{-1}]	6.03±0.93	6.11±0.76	6.05±1.33	6.22±1.21

Within-subjects effect [single walk task to CMI walk task]: *= p <0.05

Between subjects effect [Low MC to TD]: † = p <0.05

ND = non-dimensional, Low MC = low motor competence, TD = typically developed motor competence, CMI = cognitive motor interference

Table 11: Variability (CV) for spatial-temporal gait parameters for single-task walking and cognitive-motor interference walking in boys and girls with low and typical levels of motor competence as measured by the total MABC2

	Single Walk Task		CMI Walk Task	
Boys	Low MC	TD	Low MC	TD
ND Normalised Walking Speed CV [%]	10.3±8.0 *	10.1±10.1	14.5±10.7	14.3±10.7
ND Normalised Cadence CV [%]	8.7±6.8 *	9.1±7.9	15.0±10.7	14.4±12.0
ND Normalised Stride length CV [%]	5.1±4.3 * †	4.6±3.0	6.9±3.8	5.7±3.4
Walk Ratio CV [%]	80.7±46.5 *	80.6±46.4	66.2±42.1	71.6±56.2
Girls	Low MC	TD	Low MC	TD
ND Normalised Walking Speed CV [%]	8.7±3.5 *	8.6±3.7	14.5±10.1	14.8±13.6
ND Normalised Cadence CV [%]	7.6±6.4 *	7.6±4.7	16.6±12.0	13.7±13.9
ND Normalised Stride length CV [%]	4.4±2.6 *	4.0±2.5	5.3±2.6	5.7±3.1
Walk Ratio CV [%]	92.4±54.6 *	83±43.2	55.2±35.6	64.0±37.4

Within-subjects effect [single walk task to CMI walk task]: * = p <0.05

Between subjects effect [Low MC to TD]: † = p <0.05

ND = non-dimensional, Low MC = low motor competence, TD = typically developed motor competence, CMI = cognitive motor interference, CV = Coefficient of Variation

5.4.5 Spatial-Temporal Parameters – Balance subsection of the MABC2

Walking Speed

Interactions and group differences between subjects and within subjects for spatial-temporal gait parameters for both walking tasks are presented in Table 12. A significant interaction was reported for both boys ($F_{(1,195)}$ = 5.233, p = 0.023, η_p^2 = 0.026, 95%CI 0.0001 – 0.084) and girls ($F_{(1,154)}$ = 4.048, p = 0.046, η_p^2 = 0.026, 95%CI 0.001 – 0.092). Both genders in the low Balance group had their walking speed reduced more so than the typically developed group. A significant within subjects effect was reported for boys ($F_{(1,195)}$ = 191.184, p = <0.001, η_p^2 = 0.495, 95%CI 0.399 – 0.571) and girls ($F_{(1,154)}$ = 117.329, p = <0.001, η_p^2 = 0.432, 95%CI 0.318 – 0.525). There was no significant difference between subjects effect (MC group).

Cadence

There was no significant interaction between MC level and CMI on cadence for boys or girls. There was a significant within-subjects effects for boys ($F_{(1,194)}$ = 89.501, p = <0.001, η_p^2 = 0.316, 95%CI 0.213 – 0.408) and girls ($F_{(1,151)}$ = 81.951, p = <0.001, η_p^2 = 0.352, 95%CI 0.234 – 0.453). Both genders reduced their cadence when preforming the CMI walking task. There was no significant difference between subject effects (MC groups) for cadence performance (see Table 12).

Stride Length

There was no significant interaction between MC level and CMI on stride length performance for boys or girls. There was a significant within-subjects effects for boy ($F_{(1,198)}$ = 92.187, p = <0.001, η_p^2 = 0.318, 95%CI 0.216 – 0.409) and girls ($F_{(1,158)}$ = 148.375, p = <0.001, η_p^2 = 0.484, 95%CI 0.375 – 0.569). Both genders reduced their stride length when performing the CMI walking task. There were no between-groups effects (MC groups) for boys or girls (see Table 12).

Walk Ratio

There was no significant interaction between MC level and CMI on walk ratio performance for boys or girls. There was a significant within subject effect for boy (Boys $F_{(1,200)}$ = 5.206, p = 0.024, η_p^2 = 0.025, 95%CI 0.001 – 0.082) but not girls ($F_{(1,158)}$ = 0.178, p = 0.674, η_p^2 = 0.001). There was no between subject effect (MC group) for boys or girls (see Table 12).

5.4.6 Spatial-Temporal Parameters Coefficient of Variation (CV) – Balance Subsection of the MABC2

Walking Speed

Interactions and group differences between subjects and within subjects for spatial-temporal gait variability for both walking tasks are presented in Table 13. There was no significant interaction for walking speed variability and MC level for boys or girls. There was a significant within-subject effect for boys ($F_{(1,195)}$ = 6.936, p = 0.009, η_p^2 = 0.034, 95%CI 0.0021 – 0.097) and girls ($F_{(1,154)}$ = 15.110, p = <0.001, η_p^2 = 0.089, 95%CI 0.022 – 0.182). Both genders increased their walking speed variability when performing the CMI task. There was no significant between-subject effect (MC group) for boys or girls.

Cadence

There was no significant interaction for cadence variability and MC level for boys or girls. There was a significant within subject effect for boys ($F_{(1,194)}$ = 17.77 8, p = <0.001, η_p^2 = 0.084, 95%CI 0.024 – 0.165) and girls ($F_{(1,151)}$ = 29.719, p = <0.001, η_p^2 = 0.164, 95%CI 0.07 – 0.269). Both genders increased their cadence variability when preforming the CMI walking task. There was no significant between subject effects (MC group) for boys or girls (see Table 13).

Stride Length

A significant interaction was reported for boys (Boys $F_{(1,198)}$ = 4.398, p = 0.037, η_p^2 = 0.022, 95%CI 0.001 – 0.076), but there was no significant interaction for stride length variability for girls. There was a significant difference between within-subject effects for girls ($F_{(1,158)}$ = 15.014, p = <0.001, η_p^2 = 0.087, 95%CI 0.022 – 0.178), but not boys. However, there was a significant difference between subject effects (MC group) for boys ($F_{(1,198)}$ = 5.678, p = 0.018, η_p^2 = 0.028), but not for girls. This indicates that there was a significant difference in stride length variability for low balance group when performing the STW, for boys. When the CMI walk task was performed there was no change from the low balance group, but a significant increase in stride length variability for the TD group (see Table 13).

Walk Ratio

There was no significant interaction for walk ratio variability and MC level for boys and girls. There was a significant within-subject effect for girls ($F_{(1,158)}$ = 18.958, p = 0.001, η_p^2 = 0.107, 95%CI 0.033 – 0.202), with a reduction in walk ratio variability when performing the CMI walk task. There were no significant within-subject effects for boys. There were no between-subject effects (MC groups) for boys or girls (see Table 13).

Table 12: Spatial-Temporal gait parameters for single task walk and cognitive-motor interference walk in boys and girls with low and typical levels of motor competence as measured by the balance subsection of the MABC2

	Single Walk Task		CMI Walk Task	
Boys	Low MC	TD	Low MC	TD
ND Normalised Walking Speed ‡	0.46±0.05 *	0.45±0.05	0.36±0.06	0.38±0.06
ND Normalised Cadence	33.80±2.51 *	33.49±2.29	29.62±3.22	30.63±4.11
ND Normalised Stride length	1.61±0.14 *	1.59±0.14	1.47±0.17	1.48±0.14
Walk Ratio mm/[steps min^{-1}]	6.71±0.77 *	6.45±0.94	7.00±1.17	6.65±1.30
Girls	Low MC	TD	Low MC	TD
ND Normalised Walking Speed ‡	0.48±0.04 *	0.46±0.05	0.36±0.06	0.37±0.07
ND Normalised Cadence	34.87±2.4 *	33.82±3.05	30.47±3.79	30.14±4.33
ND Normalised Stride length	1.67±0.16 *	1.61±0.14	1.47±0.13	1.46±0.14
Walk Ratio mm/[steps min^{-1}]	5.97±0.67	6.1±0.85	5.97±1.08	6.2±1.28

Interaction between MC and CMI ‡ = p <0.05

Within-subjects effect [single walk task to CMI walk task]: * = p <0.05

ND = non-dimensional, Low MC = low motor competence, TD = typically developed motor competence, CMI = cognitive motor interference, CV = Coefficient of Variation

Table 13: Variability (CV) for spatial-temporal gait parameters for single-task walking and cognitive-motor interference walking in boys and girls with low and typical levels of motor competence as measured by balance subsection of the MABC2

	Single Walk Task		CMI Walk Task	
Boys	Low MC	TD	Low MC	TD
ND Normalised Walking Speed CV [%]	9.9±3.4 *	10.2±10.3	12.3±8.3	14.8±11.1
ND Normalised Cadence CV [%]	8.5±5.5 *	9.1±7.9	12.8±9.7	15.0±11.9
ND Normalised Stride length CV [%] ‡	6.5±5.4 †	4.4±2.8	6.4±3.6	6.0±3.5
Walk Ratio CV [%]	83.8±32.9	80.0±48.5	75.3±46.9	68.8±53.0
Girls	Low MC	TD	Low MC	TD
ND Normalised Walking Speed CV [%]	9.1±4.4 *	8.6±3.4	13.7±6.4	14.9±13.2
ND Normalised Cadence CV [%]	9.1±9.1 *	7.3±4.3	18.9±12.8	14±13.3
ND Normalised Stride length CV [%]	4.3±2.7 *	4.1±2.5	6.0±2.7	5.5±3.0
Walk Ratio CV [%]	84.7±48.9 *	86.6±47.6	53.5±33.5	62.1±37.4

Interaction between MC and CMI ‡ = $p < 0.05$

Within-subjects effect [single walk task to CMI walk task]: * = $p < 0.05$

Between subjects effect [Low MC to TD]: †= $p < 0.05$

ND = non-dimensional, Low MC = low motor competence, TD = typically developed motor competence, CMI = cognitive motor interference, CV = Coefficient of Variation

5.5 Discussion

The main findings indicated that there was an interaction between low balance and walking control in boys and girls for walking speed. The low balance group reduced their walking speed more so than the typically developed group when under CMI conditions. In addition, there was an interaction between low balance MC and stride length variability in boys. With a lower variability in stride length for the typically developed group compared to the low balance group when performing a single task walk. When the CMI task was performed the typically developed group increased their variability to a level comparable to that of the low balance group. This indicates that the low balance group had similar stride length variability in single task walking conditions compared to the typically developed group under CMI conditions.

This greater reduction in walking speed in the low balance group may be caused by reduced postural control [123, 302]. Speedtsberg *et al.,* [123] assessed local dynamic stability in young children with and without DCD. Their results indicated that the Lyapunov exponent was an excellent discriminator between MC groups in the anterior-posterior (AP) direction. This suggests that children with low MC may find it more difficult to control their CoM in the AP direction which could explain the reduced walking speed in the low balance MC group compared to the TD MC group. Even though the previous study did not involve a concurrent CMI task when walking, these children did walk on a treadmill. A five-minute familiarisation to the treadmill was part of the procedure and therefore, this might have required increased attentional demand on the children to walk safely. This could have caused a more demanding condition on the DCD group's ability to control their CoM. In addition, the treadmill was used to control for walking speed. If the previous study performed the walking task on normal ground then the difference in local dynamic stability may have caused a reduction in walking speed similar to the present study.

The interaction for stride length variability in boys can be explained by the greater increase in variability in the TD group when performing the CMI task compared to the low balance group. As previously mentioned both TD balance and low balance MC groups reduced their walking speed when performing the CMI walking task. This reduction in speed may have affected the stride length variability more in the TD compared to the low balance group, as the low balance group already had high stride length variability in the STW. Speedtsberg *et al.,* [302] indicated that standing still requires complex integration between motor and sensory pathways to remain fully automated [301]. They found that children with DCD had impaired postural control compare to TD children. This increased postural sway when standing still could be exacerbated when natural walking speed is reduced through a CMI task and may manifest as inconsistent foot placement. This is supported by Rosengren *et al.,* [287] who assessed walking variability in children with and without DCD. They summarised through elliptical Fourier analysis that children with DCD have greater variability in their leg movements when walking compared to TD peers. This could explain the differences in the MC group stride length variability when performing the STW and why the TD increased their stride length variability to match the low balance MC group when performing the CMI walking task. However, these studies both have low sample sizes in children aged 9 and 7 years old. This makes it difficult to directly compare the results to the present study as further differences in maturation and lack of CMI task in the previous studies compound possible standardisation errors [305].

Even though there were significant interactions between low balance MC and TD groups when performing CMI walking task, there were no interactions between total MC score and the effects of CMI on walking parameters or walking variability. There was a significant reduction in walking speed, cadence and stride length for both MC groups and an increased walk ratio for boys when performing the CMI walk. This was mirrored when assessing the gait variability, with walking speed, cadence and stride length all increasing in variability and walk ratio decreasing in variability for both MC groups and sexes. This suggests that walking parameters and walking variability were affected equally in the total MC groups when performing the CMI walk task. The only significant differences between MC and TD groups were shown for stride length in girls. With an increased stride length in the low MC group compared to the TD group when performing the STW, and variability of stride length in boys. With increased stride length variability in the low MC group compared to the TD group when performing the CMI walk however, these group differences showed a small effect size.

The lack of interaction between total MC level and the effects of CMI on walking parameters and gait variability may be explained by the heterogeneity within the low MC group when measured by all the subsections of the MABC2 [292, 306]. As previous studies have indicated differences in walking parameters in children with low MC, these have not been consistent and have ranged across spatial-temporal measures. Schott *et al.,* [294] assessed walking speed and indicated differences in the single and dual-task condition in children with low and TD MC levels, however, no other gait measures were reported [294]. Wilmut *et al.,* [124] assessed step length and step time symmetry in children and adults across an age range of 7-34 years and indicated a difference between low MC and TD groups, but did not assess walking speed, cadence or walk ratio. Velocity and acceleration of CoM indicated more variability in double support, stride time, and mediolateral (ML) acceleration in children with low MC, in addition, wider step length and greater variability in stride and double support duration. However, there were no significant differences between MC groups for normalised step length, double support percentage, anterior-posterior (AP) and vertical (V) acceleration and velocity or variability in normalised step length, width, ML and AP velocity or acceleration and ML velocity [111]. This is supported by the present study, as significant interactions were only reported for walking speed and stride length variability when the balance subsection was used to measure MC. Therefore, this study highlights the need for future research to focus on MC skills which are required in order to control walking gait, to fully understand if there is a systematic deviation in the pattern of walking in adolescents with low MC.

Earlier research has reported similar differences in spatial-temporal parameters with reduced stride length and increased cadence in children with low MC, however, when these parameters were scaled to the overall gait cycle these differences became non-significant. Further data analysis from the previous study reported differences in joint angles across the gait cycle between MC groups. A more flexed position in the hips, knees and ankles were shown in the low MC group compared to the TD group, but inexperience in using treadmills may have caused low MC children to adopt a more cautious kinematic pattern compared to inexperienced TD children [110]. The present study would have reduced this bias through free-living straight-line walking in a familiar environment, which may have encouraged a more normal walking pattern. The variety of differences across these studies suggests there is no clear pattern affecting walking parameters in people with low total MC compared to TD peers [292]. Thus, differences in walking parameters as measures by spatial-temporal measures may not be subtle enough to detect these differences, when low MC may manifest in some with spatial deficits, temporal deficits or deficits in fine motor dexterity or upper limb coordination [307]. Therefore, measuring large samples sizes, in a free walking environment where age differences are more tightly controlled and the MC is assessed with measures that resemble walking such as dynamic balance and locomotor skills, could improve overall understanding of MC effects on gait and CMI walking conditions.

Even though some differences and interactions were reported between gait measures in adolescents with low and typical levels of balance and total MC, the majority of findings reported no significant differences. This may be explained through the difficulty and type of the CMI task in this population. A previous study assessed the effects of motor and cognitive concurrent tasks on walking in children with low MC and showed similar results to the present study. Cherng *et al.,* [112] assessed children with low and typical levels of MC while walking and performing easy and hard, motor and cognitive tasks. They reported no differences in single-task walking between low MC and TD groups and reduced walking speed, cadence, and stride length when performing a concurrent task except when performing an easy motor task. However, when a motor task (balancing marbles on a try) was incorporated, they found an interaction between MC levels, with a greater effect on low MC gait parameters compared to the TD group. The differences compared to the present studies cognitive task may be explained by the increased difficulty of the task and task prioritisation challenge motor processing capacity enough to overload the children with low MC more so than their TD peers [112].

In the present study, a cognitive task was performed simultaneously with walking, which produced interference in gait parameters for both MC groups. The influence of the second task (CMI) on the first task (walking) might not have provided enough competing capacity with the automatisation of walking to affect the low MC group more so than the TD group and therefore, control of walking in both MC groups would be similar [236, 308, 309]. It may have been more appropriate to use a motor task simultaneously with walking as this may have stressed the automaticity of gait more so than a cognitive task in some of the other gait parameters [112, 308]. As low movement quality and control is the main deficits present in adolescents with low MC, then testing this interaction with two concurrent motor tasks may have been more valid in understanding the effect of low MC on walking control as shown by Cherng *et al.,* [112].

This has further support, as children with low MC have shown differences in gait control when more complex walking strategies are required. Studies conducted on children, adolescents and adults with and without low MC when walking on irregular terrain [307] or when traversing an obstacle [293] have indicated differences in gait control. These studies have shown children with low MC walk with a larger step width, reduced step length and walking velocity on irregular terrain [307] and increased medial-lateral displacement of the CoM when crossing an obstacle [293]. Even though these studies do not have a concurrent task being performed while walking, it shows that the increased difficulty in the motor task may highlight the differences in low MC and TD groups more clearly. Interestingly, Gentle *et al.,* [307] reported the only interaction between MC level and age was for step width ratio, however, there was only group (MC level) differences reported in children (8-12 years) and adults (18-32 years). There was no significant difference between MC groups for adolescents (12-17 years). They concluded that growth spurts in adolescence could negatively affect the TD group's MC level more than the low MC group [310], which would cause these groups to report similar walking patterns that would not be a factor in children or adults. This is further supported by Wilmut *et al.,* [111] who indicated that differences in gait parameters may only become apparent when gait in the TD population has fully matured and the variability has reduced. However, the present study's results indicate that there are differences in gait performance between adolescents with low and TD MC levels. With these differences only becoming apparent when balance measures are used to assess MC level and a second concurrent task is performed while walking. This resembles conditions experienced in the free-living environment and may have more ecological validity compared to the previous studies.

The two main effects for MC level in the present study were shown for stride length in girls performing STW and stride length variability in boys performing CMI walk. It has been indicated that straight line, level ground walking produces either very small detectable reductions [110] in step/stride length or no differences when comparing low MC to TD groups [112, 293]. However, the present study indicates a greater stride length in the low MC group compared to the TD group for girls, when performing the STW. This is difficult to explain, as the expectation in a population with MC deficits would produce shorter stride lengths more often seen in immature or pathological gait patterns [110]. One explanation for a larger stride length in low MC group may be attributed to the greater amount of asymmetry in step length seen in this population [124]. This may manifest in, adolescents taking a longer step after a relatively normally step due to problems with postural and balance control. As previously mentioned children with low MC find it more difficult controlling their CoM in the medial-lateral plane when crossing an obstacle and Rosengren *et al.,* [287] indicated that children with low MC have greater difficulty in controlling lower limb stability in stance phase, thus affecting balance, and so causing an overreaching step. In addition, this difference may be too small to produce a functional difference even though a significant difference has been reported.

The difference in stride length variability for boys when performing the CMI walk shows similar findings to previous studies. Gait variability has been used as a measure of motor control in older populations [311] and is higher in children with low MC [292] when performing a concurrent task [111, 287, 292]. This may be explained in part by the nature in which children can cope with performing two tasks simultaneously. It has been hypothesized that children with low MC require more cognitive capacity to produce typical walking patterns compared to their typically developed peers when performing a concurrent walking task [294]. When a greater cognitive load is placed on this capacity to control walking, then deficits in walking parameters (e.g. variability) or, the second task (alternate letters of the alphabet) or both may be reported [112]. Children with typical MC levels have shown increased automation in the control of walking and are affected less when a concurrent task is performed compared to the low MC group [112, 294].

There were within-subject main effects for the CMI walk across all gait parameters for boys and girls, with changes in performance and variability, except for girl's walk ratio (total MC) and boy's stride length variability (Bal MC). These results are widely reported across previous studies, with changes in gait parameters due to the addition of a second task [236, 294, 305, 312]. However, walk ratio is a relatively new gait measure which has not been widely studied in children or adolescents with low MC. Walk ratio is a speed independent measure [313, 314] and has been described as a simple way to assess gait maturity [315], motor control [316] and spatial-temporal coordination in walking [317]. As this is a new measure with limited investigation in this population is it difficult to assess its meaning in this study. However, what we can conclude is that there is no difference between low MC and TD groups when walking in the STW and the CMI condition, but the walk ratio does increase between SWT and CMI walk for both MC groups for boys but not girls and reduces in variability for both sexes and MC groups when performing the CMI walk.

The increase in walk ratio for boys can be explained by the effects of the CMI on cadence and step length. Both cadence and step decreased when the CMI was introduced to both Low MC and TD groups for boys. However, the average percentage difference for the Low MC and TD group showed cadence (9.4%) reduced more than step length (7.8%) causing walk ratio to increase. For girls, the average percentage difference for cadence (10.9%) and step length (9.8%) were closer which, may indicate no within-subject differences for walk ratio. These differences between sexes may be explained by the maturation of gait and how cadence and step length are controlled.

Evidence suggests that normalised cadence is matured in boys and girls around 14 years of age. But other gait parameters such as double support, single support, base of support, normalised step length and lower limb length all mature around 14.9 years or younger in girls whereas, boys these parameters all mature 15.6 years or older [116]. As the present study assessed adolescents between 13 and 14 years of age it could be hypothesised that more girls with mature gait parameters were assessed than for the boys allowing for better control of cadence. In addition, step length is largely controlled by leg length [109] and is less affected when there are changes in walking speed. The frequency of stepping (cadence) has shown to adjust more with changes in walking speed, which may be exacerbated with immature gait parameters [109, 315, 318]. Even though there is an increase in walk ratio when performing a CMI walk for boys, caution is required as this increase may be within the normal range for this population, as supported by adult walk ratios [316]. Future research is thus needed to clarify this question.

5.6 Limitations

There are a number of limitations that should be highlighted when interpreting these results. The walk ratio was not normalised according to leg length. This is a relatively new measure in gait analysis and is not normalised across all studies in the same way, with different methods used when normalising for adults compared to children [240, 241, 313, 316]. It was deemed appropriate to analyse this variable without normalisation as a starting point to understand walk ratio in adolescence and focus on the comparisons between and within groups. However, normalised non-dimensional walk ratio data were analysed but not reported. The CMI task used concurrently with walking to elicit change in walking parameters may not have been hard enough to stress the low MC group to a level, which would have caused a greater reduction in walking parameters compared to the TD group. Previous studies which reported significant interactions, are in children much younger than the present study [112]. Therefore, future research should assess which concurrent task is most valid for adolescents.

5.7 Conclusion

This study indicated that there is a significant interaction between measures of balance MC and spatial-temporal gait measures under cognitive-motor interference conditions. However, these interactions are masked when MC is measured with the inclusion of other MC subsections such as manual dexterity and hand-eye coordination. This suggests that understanding systematic differences in spatial-temporal gait parameters in adolescents requires measures of MC which are necessary for walking control. These results in addition to Chapter 4, highlight the possibility that walking control and balance MC may provide valid models for their relationship to PA durations and intensities.

Chapter 6 The Relationship between Spatial-Temporal Gait Parameters, Motor Competence and Physical Activity levels in Adolescents

6.1 Summary

Chapter 4 found adolescents with low MC spent less time in MVPA and VPA and Chapter 5 found that adolescents with low balance MC have altered walking parameters compared to their typically developed peers. The combination of assessing specific balance skills and walking parameters may provide a better method in determining adolescents at greatest risk of reduced PA due to reduce MC. Therefore, this chapter will assess the relationship of walking performance and MC level on time spent in MVPA and VPA.

6.2 Introduction

Walking is a fundamental aspect of PA in children and adolescents. It is uniquely placed, as it can be used to measure movement quality and quantity [4, 312]. It has shown to provide a large percentage of overall MVPA in adolescents and has been used in interventions to increase PA levels amongst children and adolescent [125]. Evidence from Chapter 4 has shown adolescents with low balance MC perform lower amounts of PA and Chapter 5 has shown evidence that there are differences in walking control in adolescents with reduced balance MC. This suggests that low balance MC affects walking control which, may combine to cause a reduction in PA. Therefore, walking control may provide a link between movement quality and quantity especially if walking control can provide has a significant relationship with PA.

Previous evidence has assessed the link between movement quality, MC and PA in young and pre-school children [319-322]. Clark *et al.,* [322] concluded that there was an agreement in the relationship between movement quality and PA when spectral purity was used to assess movement quality in ambulatory children during school playtime [320]. This suggests that the assessment of walking quality in children may be related to PA. However, no analysis was conducted on the relationship between walking quality and PA duration or intensity or how this might differ between PA intensities.

To the author's knowledge, there have been no studies reporting the relationship of walking control and PA levels in adolescents. However, there has been evidence reporting the predictive capacity of MC ability on PA levels [323]. Evidence from Jaakkola *et al.,* [323] reported fundamental movement skills in young adolescents have a predictive capacity of PA levels in later adolescents. Further evidence from Lopes *et al.,* [73] concluded that locomotor skills in children aged 6-10 years were an important predictor of PA levels. This evidence has not been consistent as data reported by Barnett *et al.,* [285] stated that only object control was a predictor of PA in children, with locomotor skills not showing any significant predictive capacity on PA levels. These inconsistencies arise from multiple methods for assessing MC and PA which span different ages [75, 134, 285, 324, 325], with limitations in measures of PA intensity [134] and new movement battery tests continually being developed [9, 325]. Therefore, assessing movement quality in an everyday task such as walking control which can impact PA may provide a clearer understanding of MC and its predictive capacity on PA.

Furthermore, there is little understanding of how different measures of MC can best predict different levels of PA intensities. Evidence from Chapter 4 indicates that balance measures provide better discrimination for more vigorous levels of PA which can be explained by vigorous PA requiring more advanced balance control. This higher intensity of PA involves moving at higher velocities and accelerations which generally involve whole body mass movements. Therefore, the requirement for higher levels of PA intensities is different when compared to lower levels of intensities such as walking, and may be reported in walking analysis. Providing evidence on the predictive capacity of balance MC and walking analysis measures which are linked to higher and lower levels of PA may indicate a better way to assess the relationship between low MC on PA. It may also provide a better method in targeting adolescents who are at the highest risk of not performing the adequate amount of PA due to low levels of MC and may be able to provide information on which MC skills are needed to promote more vigorous levels of PA.

Therefore, this study is the first to explore the relationship models of walking parameters and MC measures which, assess the building blocks of locomotor skills, with MVPA and VPA in adolescents. This chapter tests the hypothesize that walking quality may provide significant relationships with lower intensities of PA, while more dynamic measures of MC may provide significant relationships with higher intensities of PA.

6.3 Methods

6.3.1 Participants

This cross-sectional study assessed 13-14 year old adolescents, from a single mainstream secondary school in Oxfordshire. This sample of adolescents was taken from the overall sample presented in Chapter 4 and Chapter 5, as seen in Figure 4. Inclusion and exclusion criteria are presented in section 3.2 Participants.

6.3.2 Procedure

Data collection took place in two settings, information gathered from the school screening sessions supplied data on MC, health-related fitness measures and all anthropometrics, as seen in 3.6 Procedure. PA data were collected during free-living conditions over 7 consecutive days, as seen in Chapter 4. Further information is presented in 3.6 Procedure.

6.3.3 Anthropometrics

As seen in Chapter 5

6.3.4 Motor Competence

As seen in Chapter 4, Chapter 5 and General Methods Section 3.8.1 Motor Competence (MC).

6.3.5 Gait Analysis

Gait variables used in this study were selected from the significant interactions reported in Chapter 5, when the balance subsection was used to measure MC, while under CMI walking conditions. The methods used to obtain these gait parameters are discussed in the General Methods section 3.8.3 Gait Analysis.

6.3.6 Physical Activity

As seen in Chapter 4 and General Methods Section 3.8.2 Physical Activity (PA).

6.3.7 Health-Related Fitness Measures

Aerobic capacity, grip strength and lower limb explosive power as seen in General Methods Section 3.8.4 Health-Related Fitness Measures.

6.3.8 Statistical Analysis

An independent t-test assessed the differences in group characteristics between MC level (significance set at <0.05). Cohen's d effect size was interpreted as small 0.2 – 0.5, medium >0.5 – 0.8, large > 0.8 [273]. Multiple linear regressions assessed the relationships between PA levels (MVPA and VPA) and measures of MC (MABC2, Balance subsection of the MABC2), spatial-temporal gait parameters and spatial-temporal gait variability parameters, as assessed by the previous two studies (Chapter 4 and Chapter 5). The independence of residuals where assessed by the Durbin-Watson statistic with a value close to two indicating independence. Homoscedasticity was assessed by studentised residuals plotted against unstandardised predicted values. Linear relationships were assessed collectively (plotting studentised residuals against unstandardised predicted values) and individually (Pearson's correlations) against the independent variable. Multicollinearity was assessed using the tolerance statistic, whereby, <0.1 may indicate collinearity between independent variables. No outliers were removed as none were ±3SD from the mean. Q-Q plots assessed PA, gait parameters and MC measures for normally distributed data (Appendix H). All assumptions for multiple linear regressions were met. Significance of the overall model fit was assessed by the ANOVA at an α level $p < 0.05$. Effects from individual variables on the dependent variable were assessed using Standardized Beta Coefficients at an α level of $p < 0.05$. All data analysis was performed using IBM SPSS v.25. Further analysis was conducted on the mediating effects of the health related fitness measures (VO2max, Broad jump, Grip strength) on the relationship between MC and walking control with PA. However, the overall sample size was not large enough to provide adequate power for this type of analysis. Furthermore, adding them into the regression analysis violated the multicollinearity assumption as the three independent health related fitness variables reported high collinearity (Tolerance value < 0.1). Therefore, this data were not presented.

6.4 Results

A total of 166 participants took part in this study (aged 13-14 years), however, due to missing data from MC (n=9), gait (n=15), and students not meeting the required wear time for PA (n=94), 48 participant were analysed for the study (as seen in Figure 4). Due to a relatively small sample size and providing adequate power all analysis was conducted with genders combined into one group. Descriptive statistics for total MC score and total balance MC score are presented in Table 14 and Table 15 respectively.

6.4.1 *Total MC Score*

The TD group had significantly better performance on the broad jump test, with a greater average jump distance of 16.6cm ($t_{(47)}$ = 2.22, p = 0.031, 95%CI -31.7 -1.5, Cohen's d = 0.66, 95%CI 0.058 – 1.25), a greater VO_2max score of 6.1mL.kg^{-1}.min^{-1} ($t_{(47)}$ = 2.13, p = 0.038, 95%CI -11.8 -0.34, Cohen's d = 0.63, 95%CI 0.034 – 1.22), and a higher MABC2 score by 34 percentile ($t_{(30.8)}$ = 10.1, p < 0.01, 95%CI -40.6 -27.0, Cohen's d = 2.98, 95%CI 2.031 – 3.91). The Low MC group reported greater stride variability by 2.0% when performing the CMI walking task ($t_{(47)}$ = 2.47, p = 0.017, 95%CI 0.31-3.8, Cohen's d = 0.73, 95%CI 0.128 – 1.32) (see Table 14).

6.4.2 *Total Balance MC Score*

The low balance group had higher weight by 10.9kg ($t_{(47)}$ = 2.64, p = 0.01, 95%CI 2.6-19.0, Cohen's d = 0.84, 95%CI 0.19 – 1.48), and higher BMI by 2.8 kg.m^{-2} ($t_{(47)}$ = 2.35, p = 0.02, 95%CI 0.4-5.2, Cohen's d = 0.75, 95%CI 0.102 – 1.38) compared to the TD group. The TD group reported higher VO_2max by 7.1 mL.kg^{-1}.min^{-1} ($t_{(47)}$ = 2.41, p = 0.02, 95%CI -13.0 -1.2, Cohen's d = 0.77, 95%CI 0.12 – 1.4), greater time spent in MVPA by 8.9mins ($t_{(47)}$ = 2.22, p =0.03, 95%CI -17.0 -0.84, Cohen's d = 0.71, 95%CI 0.063 – 1.34), and VPA by 1.6mins ($t_{(47)}$ = 2.82, p = 0.007, 95%CI -6.1 -1.0, Cohen's d = 0.90, 95%CI 0.24 – 1.54), and higher levels of total balance MC score by 45 percentile ($t_{(47)}$ = 5.98, p < 0.001, 95%CI -57.2 -33.2, Cohen's d = 1.9, 95%CI 1.16 – 2.62) compared to the low balance group (see Table 15).

6.4.3 *MVPA*

The overall model for MVPA was significant (Table 16) with 20% of the variance explained by the model (see Table 17). Even though the overall model was significant, only one variable reported a significant β coefficient. The data suggests that a decrease in stride length variability may relate to increases MVPA in adolescents (see Table 18).

6.4.4 *VPA*

The overall model for VPA was significant (Table 16) with 23% of the variance explained by the model (see Table 17). Even though the overall model was significant, only one variable reported a significant β coefficient. The data suggests that an increase in balance performance as measured by the MABC2 may relate to higher levels of VPA (see Table 19).

Table 14: Descriptive Characteristics of Participant's Anthropometric, PA, Total MC Score, and Gait Parameters

Total MC Score	TD n=29		Low MC n=19	
	mean±SD	95% CI	mean±SD	95% CI
Height [cm]	167.9±8.4	164.8-171.1	167.3±16.4	159.6-175
Weight [kg]	54.5±13.5	49.4-59.7	61.7±13.9	55.2-68.2
BMI [$kg.m^{-2}$]	19.2±3.8	17.8-20.7	23.2±11.1	18-28.4
Broad Jump [cm]*	168.1±27.7	157.6-178.6	151.5±22.7	140.9-162.1
Grip Strength [kg]	26.6±7.3	23.8-29.4	24.7±5.2	22.3-27.1
VO_2 max [$mL.kg^{-1}.min^{-1}$]*	53.1±9.3	49.5-56.6	47.0±10.6	42.0-51.9
MVPA [mins]	31.7±13.7	26.5-36.9	24.2±12.1	18.5-29.9
VPA [mins]	5.8±4.4	4.2-7.5	3.4±4.1	1.5-5.3
MABC2 Total Score [Percentile]**	40±18	33-46	6±3	4-7
Walking Speed CMI [ND]	0.34±0.05	0.32-0.36	0.37±0.05	0.34-0.39
Stride Length CV CMI [%]*	5.1±2.7	4.1-6.1	7.1±3.1	5.5-8.5

TD = Typically Developed, Low MC = Low Motor Competence, BMI = Body Mass Index, MVPA = moderate-Vigorous Physical Activity, VPA = Vigorous Physical Activity, MABC2 = Movement Assessment Battery for Children 2nd Edition, CMI = Cognitive Motor Interference, CV = Coefficient of Variation, ML = Medial-Lateral, ND = Non-Dimensional.
Difference between Motor Competence groups: * $p < 0.05$
Difference between Motor Competence groups: ** $p < 0.01$

Table 15: Descriptive Characteristics of Participant's Anthropometric, PA, Total Bal MC Score, and Gait Parameters

Total Bal MC score	TD n=34		Low Bal n=14	
	mean±SD	95% CI	mean±SD	95% CI
Height [cm]	168.1±7.8	165.4-170.8	166.7±19	156.2-177.2
Weight [kg]*	54.2±13.2	49.6-58.8	65.0±13.1	57.7-72.2
BMI [$kg.m^{-2}$]*	19.1±3.8	17.7-20.4	21.9±3.5	19.8-23.9
Broad Jump [cm]	163.7±27.4	154.1-173.3	156±25.3	142-170
Grip Strength [kg]	25.4±5.9	23.3-27.4	26.8±7.9	22.4-31.2
VO_2 max [$mL.kg^{-1}.min^{-1}$]*	53.1±7.8	50.4-55.9	46.0±12.2	39-53.1
MVPA [mins]*	31.4±12.6	27-35.8	22.5±13.7	14.9-30
VPA [mins]*	5.9±4.7	4.3-7.6	2.4±2	1.3-3.5
MABC2 Balance[Percentile]**	51±28	41-60	8±2	6-9
Walking Speed CMI [ND]	0.4±0.1	0.3-0.4	0.3±0.1	0.3-0.4
Stride Length CV CMI [%]	5.9±3.0	4.8-6.9	6.1±3.2	4.3-7.8

TD = Typically Developed, Low MC = Low Motor Competence, BMI = Body Mass Index, MVPA = moderate-Vigorous Physical Activity, VPA = Vigorous Physical Activity, MABC2 = Movement Assessment Battery for Children 2nd Edition, CMI = Cognitive Motor Interference, CV = Coefficient of Variation, ML = Medial-Lateral, ND = Non-Dimensional.

Difference between Motor Competence groups: * $p < 0.05$

Difference between Motor Competence groups: ** $p < 0.01$

Table 16: Overall model fit for MVPA and VPA

		SS	df	Mean Square	F	p-value
MVPA	Regression	2337.99	4	584.50	4.03	0.007
	Residual	6379.93	44	145.00		
	Total	8717.92	48			
VPA	Regression	271.27	4	67.82	4.62	0.003
	Residual	645.79	44	14.68		
	Total	917.06	48			

MVPA = Moderate to Vigorous Physical activity, VPA = Vigorous Physical Activity, SS = Sum of Squares, df = degrees of freedom, F = F statistic

Table 17: Variance in MVPA and VPA explained by independent variables

	R	R^2	Adj R^2	Standard Error of the Estimate
MVPA	0.52	0.27	0.20	12.04
VPA	0.54	0.30	0.23	3.83

MVPA = Moderate to Vigorous Physical activity, VPA = Vigorous Physical Activity, R = Pearson's correlation, R^2 = R square, Adj R^2 = Adjusted R square

Table 18: Coefficients relating to MVPA in adolescents

	Unstandardized β	$SE_β$	Standardized β	p-value
Variable				
Intercept	26.889	12.482		0.037
Total MABC2	0.039	0.122	0.062	0.752
Bal MABC2	0.158	0.085	0.356	0.068
Stride Length CV CMI [%]	-1.293	0.599	-0.291	0.036
Walking Speed CMI [ND]	7.131	34.155	0.028	0.836

Unstandardized β = Unstandardized coefficients, $SE_β$ = Standard error, Standardized β = Standardized coefficient, ND = Non-Dimensional, MABC2 = Movement Assessment Battery for Children 2nd Edition, Bal = balance

Table 19: Coefficients relating to VPA in adolescents

	Unstandardized β	$SE_β$	Standardized β	p-value
Variable				
Intercept	6.445	3.971		0.112
Total MABC2	0.0003	0.039	0.002	0.994
Bal MABC2	0.068	0.027	0.472	0.015
Stride Length CV CMI [%]	-0.313	0.19	-0.217	0.108
Walking Speed CMI [ND]	-6.545	10.867	-0.078	0.55

Unstandardized β = Unstandardized coefficients, $SE_β$ = Standard error, Standardized β = Standardized coefficient, ND = Non-Dimensional, MABC2 = Movement Assessment Battery for Children 2nd Edition, Bal = balance

6.5 Discussion

The main findings indicated that reduced walking quality and lower MC are associated with lower PA levels in adolescents. The data indicates that lower stride length variability under CMI walking conditions is associated with greater amounts of MVPA. Furthermore, balance seems to be an important factor in VPA durations.

As previously discussed in Chapter 5, reduced postural control and increased difficulty in controlling lower limbs when walking may explain an increased CMI stride length variability [123, 287, 302]. As walking provides a substantial amount of daily activity [4, 125] it could be reasoned that low postural control, as measured by stride length variability, may make it more difficult for low MC adolescents to walk for longer periods of time thus reducing overall PA. However, this may be masked when walking is performed as a single task. It could be that adolescents with low MC can match the walking performance of their typically developed peers when walking is performed as a single task but requires increased attentional resources [109]. As a second task is introduced and the attentional capacity has been reached, there may be an increase in stride length variability [109]. This is important for everyday functioning, as walking almost always involves a secondary attentional task such as talking, assessing spatial surrounds or other interactions with the environment, which is not always present in lab-based assessments. Therefore, with this increased workload on the attentional capacity of adolescents with low MC when walking may produce a behavioural habit to avoid walking and further disengagement with PA. This may have been developed in early childhood before adequate mastery of fundamental movement skills had been developed for locomotor and balance movements, which would progress into adolescence [47, 58, 85, 326].

Increased variability in stride length may also indicate reduced automatisation of movements in adolescents with low MC [287, 294, 304]. It has been suggested that children with low MC find it more difficult to perform rhythmical tasks consistently, compared to TD peers [123]. This may reduce their economy of movement and therefore, find it more energetically demanding and stop exercising sooner than TD peers [327-329]. As walking is modelled on the inverted pendulum, which describes the position of the CoM throughout the gait cycle (1.4.1 Definitions and Terminology) and requires exact and consistent timings of specific events to produce efficient locomotion, it could be hypothesised that this inability to automate a complex sequence of events is causing increased stride length variability [123]. This could lead to inadequate transfer from potential energy into kinetic energy within the gait cycle causing a decrease in efficient walking gait. This may cause an increase in metabolic cost in children with low MC compared to typically developed peers [105, 326, 330]. Then create a negative feedback loop which would have developed in young children, as real-world walking will provide a more complex environment what will challenge walking control more and may cause reduced PA levels [49]. This would further lead to less time walking and the opportunity to practise walking with a concurrent motor or cognitive task. A combination of increased difficulty in postural control and reduced movement automatisation may decrease the motivation to perform even moderate intensities of PA, which could be further exacerbated when higher intensities of PA are targeted [331].

More vigorous forms of PA generally require better control of body limbs and the body's CoM than moderate forms of PA [332], as increased forces and acceleration are produced which, differ between MC groups [328]. This may explain why the balance subsection of the MABC2 was significantly associated with VPA in adolescents. These MC measures which make up the balance subsection test the participant's movements and can be considered more representative of skills required when performing VPA compared to walking analysis. This may indicate that improving balance skills in adolescents may equip them better to perform VPA, however, there is a paucity of evidence assessing this relationship [85]. Previous studies have assessed MC as a predictor of PA in children [72]. Larsen *et al.,* [72] indicated that fitness-related motor performance significantly predicted MVPA in children aged 6 to 12 years old, with a stronger relationship for boys compared to girls. They reported significant coefficients for shuttle run test, vertical jump, Andersen test, the z-score for health-related fitness (grip test and Andersen test) and the z-score of performance-related fitness (vertical jump, shuttle run, backward balancing and precision throw). However, they reported no significant coefficient for balance measured individually. These differences between the present and previous study could involve the different age groups and the MC test used to measure balance. The previous study used one balance test from the KTK [72] which, may be less valid compared to the complete subsection of the MABC2 which was used in the present study. Walking backwards on different width balance beams may not adequately test dynamic balance which is required for many vigorous physical activities.

There are many movement battery tests which measure different aspects of MC and populations (as seen in Table 2). However, there are very few tests that measure specific MC ability with different intensities of PA in adolescents [75]. This may be beneficial as a screening tool to target adolescents who have low MC and are not completing the recommended levels of PA. The advantages of using walking as a measure of MC ability firstly gives a quick and easy method to assess many participants in a short period of time. Secondly, walking is a FMS which is developed in early childhood along with other FMS such as object control and balance. Therefore, it may be plausible to conclude that if there is a deficit in walking control there could also be a deficit in other FMS [111, 122]. Thirdly, low MC is associated with low PA and if movement quality can be measured from walking this could link quality of movement and quantity of movement and how to improve both. Finally, walking is a skill that does require practice and is performed every day even in those with very low PA levels. This then increases the validity when assessing the MC level. In the DSM-5 [14] manual which defines DCD, it states that the diagnosis of DCD requires low motor coordination to be below that of typically developed aged-matched peers, who have had the opportunity for use and practice. This could be problematic with many movement battery tests assessing skills which could be out of date and less well practised compared to when they were developed (see Table 2). However, walking can negate this problem as it is easy to practice and there is ample opportunity for it to be performed on a daily basis, but can still determine differences in MC ability [110, 111, 122, 123, 322] and is further supported in Chapter 5 where new evidence highlights the differences in CMI gait performance in adolescents with low and TD MC levels.

This method could be improved with the addition of dynamic and static balance measures which have indicated different motor learning strategies in TD compared to low MC groups [300]. The present study highlights balance measures are related to VPA, which may be explained by higher intensities associated with sports and competitive games which also require advanced dynamic balance control. These findings could be used to screen children and adolescents for MC affecting more vigorous intensities of PA or trying to engage adolescents in sports and team game activities. VPA has shown better health outcomes compared to moderate levels of PA and less time is required to gain these benefits [101]. Then this efficient way of performing PA is more desirable and should be assessed to target improvement in children and adolescents. As previously indicated children and adolescents are not meeting the recommended daily levels of PA, with the majority achieving around 30mins per day, independent of MC level. Therefore, increasing the intensity of PA could then reduce the overall time children and adolescents need to spend in PA without the loss of the health benefits. Currently, there is little evidence indicating the minimum required time for VPA to produce significant health benefits in children and adolescents [101], however, it is likely to follow adult guidelines with reduced time spent in VPA compared to MPA while maintaining similar health outcomes [79].

Previous research has assessed the direct relationship between MC and PA in children and adolescents [49, 64, 75]. More recently other variables have been added to this relationship to better understand the effect of certain physiological and psychological behaviours which may mediate this relationship. Fitness levels, body fatness, and self-perception of MC have all been shown to significantly mediate the relationship between MC and PA [3, 65, 333, 334]. Lima *et al.,* [335] also indicates that children with low MC are more likely to have higher levels of body fatness and lower level of fitness over time. This relationship remained constant for girls but strengthened over time for boys before becoming constant in adolescents. However, assessing the relationship between MC and PA, using movement battery tests could be masking the complex interaction between these two constructs. More recent research has investigated the application of raw accelerometry signals in assessing movement quality [319-322]. Clark *et al.,* [322] have used spectral purity to derive movement quality from ambulatory gait, in free-living environments such as playtime at school. Spectral purity is a set fundamental frequency which possesses low signal noise and harmonics. It assesses the frequency component of the ambulatory gait acceleration signals and determines how tightly they are distributed. As spectral purity increases in ambulatory gait acceleration signals, then a smoother and more consistent movement pattern is derived. This has been linked to better motor control in pre-school children [319]. Even though the present study has different methods and variables measured in the assessment of gait quality, it does support the hypothesis that movement quality from gait analysis (stride variability) is related to movement quantity and adds that locomotor MC skills (balance subsection MABC2) are associated with more vigorous intensities of movement quantity.

This movement quality analysis as measured by spectral purity has been assessed in young and pre-school children with low and TD levels of MC [319, 321]. The data indicates that spectral purity is an effective measure in identifying low and TD MC levels in free play conditions [322]. Cluster analysis reported by Clark *et al.,* [322] suggests that the MABC2 score was more closely linked to spectral purity compared to integrated acceleration (physical activity counts), even though both were significantly clustered to the MABC2. This indicates that walking quality has the potential to measure MC and its effects on PA levels. The present study further adds to this by suggesting that gait quality and locomotor skills measured by the balance subsection of the MABC2 are associated with MVPA and VPA in adolescents. Therefore, this could be used as a screening tool to assess which adolescents are not meeting the required guidelines due to low levels of MC ability. Evidence from Clark *et al.,* [321] highlights the ability that gait analysis may be an adequate measure to understand the effects of MC on PA through ambulatory walking assessment. Furthermore, assessing adolescent MC through gait quality and introducing a second cognitive task may differentiate low MC to TD more comprehensively (as seen in Chapter 5). Even though the current thesis utilizes different methods in order to assess walking movement quality and PA, it does support the hypothesis that gait and MC could be used in order to assess low levels of PA in adolescents.

This could also be an effective method in targeting interventions in children who are not meeting the required PA guidelines due to low MC. Even though there are many constructs which affect PA levels it is important to address the major limitations affecting PA, with MC showing a considerable effect on PA from childhood into adulthood. This study highlighted that only 20-23% of the variance in MVPA and VPA are explained by stride length variability and balance performance. Evidence has indicated that increasing FMS in children leads to increased MC and increased levels of MVPA [336-338]. Sit *et al.,* [338] undertook a randomised control trial assessing the effects of a FMS intervention on MC and PA level in children with and without DCD. Their results concluded that improvements from the FMS intervention through reduced error learning training had a similar effect to improvements in MC when compared to the control group. As the control group performed normal school-based PE lessons which involved similar FMS training to the intervention group, it is clear why both groups would have improved equally over the study period. However, they do report that FMS training significantly increased MVPA in the DCD group compared to the conventional PE lessons. This was in addition to increased enjoyment in PA within the DCD group after the FMS intervention. Therefore, this highlights the importance of MC and the promotion of PA in children and adolescents and the need for a quick and simple method for screening young populations who may be missing out on the health benefits of PA due to inadequate MC ability [338].

6.6 Limitations

There are a number of limitations that require highlighting when deriving conclusions from this study. The relatively small sample size and age range does limit this study's capacity to convey the results into the wider population of adolescents and children. The cross-sectional study design also limits the studies ability to predict PA levels over time, which would provide more information to the importance of MC and quality of gait movement predicting PA. Vertical CoM motion was used to assess gait quality. It may have been more appropriate to add in measures of medial-lateral motion which are important in locomotive and dynamic control [111]. This may have produced an increased variance percentage within the models used to predict VPA. As previously stated the relationship between PA and MC may be reciprocal in adolescents. However, this is not tested within this study, as the main aim was to understand the relationship between MC and walking control with PA durations and intensities in adolescents and therefore we assigned PA as the dependent variable in this relationship. This study may have lost granularity when assessing PA as a one-second epoch were used to calculate time spent in PA [322]. Further evidence has also indicated that the validity of the MABC2 in assessing MC for children and adolescents in the present day, may be out of date [339]. As this test procedure was developed over 10 years ago and the tasks used to assess MC may not be in touch with modern movement skill requirements [74].

6.7 Conclusions

This study provides novel findings that walking control is significantly related with moderate levels of PA, while more complex balance MC is important for higher intensities of PA. This allows new methods to assess adolescents who are not performing adequate levels of different PA intensities due to low MC.

Chapter 7 General Discussion

7.1 Summary

This thesis aimed to investigate the effects of MC on PA levels and walking control in adolescents and assess the relationship to PA duration and intensity. Chapter 4 found adolescents with low MC performed lower amounts of PA with balance MC showing a greater discriminative ability than overall MC. Chapter 5 reported interactions between walking control and balance MC, with the low balance MC group showing greater alterations in walking control than their typically developed peers. Finally, Chapter 6 reported that balance MC and walking control significantly relate to MVPA and VPA. More specifically, walking control is associated to lower intensities of PA and balance MC is associated to higher intensities of PA. This chapter will provide an overview of the discussions and their relevance in understanding and helping the improvement PA from the previous chapter's main findings.

7.2 Main Findings

7.2.1 Physical Activity and Motor Competence in Adolescents

The importance of MC especially balance MC promotes higher levels of PA duration and intensities was confirmed by the study reported in Chapter 4. Whilst previous studies [340-342] and theories (as seen in section 1.2 Motor Development Theories) have sought to elucidate this relationship, empirical evidence is limited. Only a few studies investigating the effects of reduced MC ability on PA using objective measures in adolescents [343], which is an important age for consolidation of future PA. Furthermore, there is little evidence assessing the effects of total MC and balance MC on different intensities of PA in adolescents and what level of MC is required to produce higher levels of PA (1.3.3 PA Recommended Guidelines). Chapter 4 has provided clear evidence that higher levels of balance MC in adolescents is an important skill set required to not only perform the recommended levels of PA but is also able to increase participation in higher intensities of PA. Improving balance MC may be the most efficient way to improve adolescents PA levels from low levels to the recommended levels and further increase them into higher intensities, such as sports and game-based activities. In addition, this is the first study to report evidence that a higher level of balance MC (31st percentile) is required in order to achieve these increases in PA compared to the arbitrary cut-off of 15th percentile. As this study provides data which directly relates to PA it can now be used by physical education teachers and health care professional who are interested in improving PA levels and who require movement specific targets in order to achieve this goal. In order to provide targeted interventions to improve balance MC and PA then an adequate screening process is required which incorporates an assessment of balance MC and is part of daily physical activity. This has led to the assessment of differences in walking performance in adolescents with low and typical levels of balance MC (Chapter 5).

7.2.2 Motor Competence and Walking Performance in Adolescents

Previous studies have assessed walking performance in children and adolescents with low and TD MC. However, there is inconsistent data on how gait differs between these two groups [111, 122, 123, 294] (1.4.2 Spatial-Temporal parameters). Previous studies have reported children and adolescents with low MC have performed similarly to TD peers, but have hypothesized that they require greater cognitive processes compared to more automated processes in TD groups [296-298]. Therefore, studies have introduced a cognitive-motor interference task or a dual task to further stress unautomated movement control in low MC populations [112]. However, many assessments of MC use manual dexterity measures which may mask the true effect of MC skills required for movements more closely related to walking which may be responsible for these inconsistent results [111]. The present study revealed that when MC was measured using the balance subsection of the MABC2 then there was a reported interaction for walking speed and stride length variability. This indicates that low MC as measured by the balance subsection does negatively influence walking performance under CMI conditions more so than TD peers. This further highlights the masking effect of the total MABC2 score over the individual subsections such as balance. As balance is important for many aspects of controlled walking it is clear to measure MC levels in skills which are important to the functional task of interest such as PA (Chapter 4) or movement quality of walking (Chapter 5). Therefore, this study highlights that balance is reflective in walking control while under CMI even though this is well a practised movement skill even in those with low balance MC. This indicates walking analysis can be used as a method to provide information not only on balance MC but also on the possibility that it will negatively affect PA levels. This has led to further analysis of the relationship between balance MC, walking performance and PA duration and intensities. The combination of specific MC skills (balance) and functional movement assessments (walking performance) may provide a better method for detecting adolescents at risk of low PA duration and intensities due to specific MC deficits (Chapter 6).

7.2.3 Relationship of Motor Competence and Walking Performance with Physical Activity Duration and Intensity

Currently, no evidence exists with regards to the relationship of movement quality as measured by functional (walking performance) and specific movement skills (balance) to different durations and intensities of physical activity. It is important to understand this relationship as it may provide further information on identification and targeted interventions in order to improve PA which has shown to be drastically low in the current adolescent population (1.3.3 PA Recommended Guidelines). The final part of this thesis (Chapter 6) reported that spatial-temporal gait parameters and MC as measured by the total MABC2 and the balance subsection were significantly related to time spent in MVPA and VPA, with 20% and 23% of the variance explaining the change in MAPA and VPA respectively. Even though this equates to a relatively small influence on MVPA and VPA, it may represent enough meaningful change in the duration of different intensities of PA to elicit some health benefits and provide a stepping stone for a further increase in PA levels (section 1.3.3 PA Recommended Guidelines) [79, 82, 100]. Further analysis indicated that reduced stride length variability under CMI conditions were related to MVPA. This indicates that movement quality as measured through walking parameters may be used by physiotherapists and other clinicians to assess adolescents who are at danger of not meeting the recommended guidelines of PA due to deficits in MC. The utilisation of a method which can differentiate MC level through a common form of PA is especially valuable for its efficiency and ability to quickly target why low levels of PA are being performed. However, this was different when VPA was individually assessed as the dependent variable. The data reported that an increase in balance performance in adolescence related to higher durations of VPA. This may be as a result of higher intensity activities requiring skills which involve the control and movement of an individual's body mass such as in the MABC2 balance subsection, which may be masked when this subsection is combined with other movement skills. Therefore, the use of spatial-temporal gait parameters may provide a useful screening tool to identify adolescents with reduced PA due to low MC, with the addition of using balance MC to screen for adequate levels of high PA intensities.

7.3 Limitations

Each study chapter was cross-sectional by design and cannot infer causality. Specific limitations are reported in respective study chapters, however, there are some general limitations which should be addressed and considered in relation to the overall conclusions. The MABC2 used to assess MC is a measure which has been designed to capture children and adolescents with low MC. The test has an upper limit on the highest achievable score, resulting in a ceiling effect. This may have resulted in some participants reaching the maximal score on some of the test items, which might not truly capture their actual MC ability. This could lead to skewed data and reduce the effects of MC on walking control and PA levels [344]. This may be further exacerbated as boys and girls are assessed from the same reference tables. Evidence indicates there are gender differences in MC across manual dexterity, object control and locomotor skills (as seen in section 1.1.2). This could cause a higher prevalence reported in one gender compared to the other, but actually, be as a result of inaccurate reference values.

The walking assessment may be limited in fully understanding free-living walking control as both single walking and cognitive-motor interference conditions were performed in straight-line walking. As normal daily living involves changing direction, stopping and starting and changing speeds, it may have been more appropriate to involve some of these free-living walking requirements to test the effects of MC on free-living walking in this population which, may have indicated clearer differences between low MC and TD groups [294]. However, the practicalities of this were unachievable within the screening sessions at each school. Time constraints and space limited the ability to carry out this methodology.

Limitations associated with measuring PA over a relatively short time can ultimately cause inaccuracies in the estimation of actual PA levels. This thesis measured students over 7 school days within the Autumn/Winter months. Measurement at this time may be different from PA measured within the summer months and/or when the students are on their school holidays. Within school term time there are limitations on the available time students can perform PA as lessons require students to sit for long periods, which may be further limited by weather and daylight restrictions. Therefore, the PA measurements taken within this thesis may be representative of the lowest amount of PA performed in this population. Further limitations from this study which were reported in Chapter 4 has already highlighted a large amount of data lost due to inadequate wear time necessary to be included in the study analysis. However, as previous studies have used imputation to increase their sample size, this was inappropriate for this thesis. Adolescent PA may not be as routine as adult PA [345] and using methods which impute from the average of previous day's PA may be completely inaccurate for adolescents as PE lessons are most commonly twice a week and differ over a two-week timetable. This resulted in analysing only participant's raw data that met the criteria for minimum wear time.

7.4 Future Directions

Data from this thesis provides new and supporting evidence to the importance of balance MC and its effect on walking control and meaningful PA levels in adolescents. Future investigations should use evidence from this thesis to assess the effect of a balance MC intervention on PA. Improving balance MC may provide the necessary skills order for more adolescents to participate in sports activities which is more likely to evolve higher levels of engagement and adherence into adulthood. The addition of running control could further highlight the differences in adolescents with low MC as this locomotor skill is much more difficult to control due to the higher limbs speeds and greater dynamic control of their whole body mass. This, in addition to the evidence provided by this thesis, could further improve the identification of children and adolescents with deficits in motor control and targeting specific interventions aimed at improving MC and PA levels. It may provide further rationale for utilising dynamic balance measures as the main indicator of low MC affecting higher PA intensities which could be a way to progress MC to a level that is appropriate for sports and game-based activities. Screening tests aimed at identifying children and adolescents should involve an individual section which covers balance to not only acquire if there is an MC deficit but more importantly to highlight if they are at further risk of low PA.

7.5 Conclusion

The results from this thesis indicated that balance MC has a significant effect on PA levels in adolescents especially high intensity PA. Balance MC was also reflective in walking performance as, adolescents with low balance MC reporting a greater alteration in their walking performance compared to their typically developed peers. Furthermore, this thesis highlighted the significant relationship of MC measures and walking control under cognitive-motor interference condition on PA durations and intensities. This may allow measures of walking control and balance to be used as a simple, quick and effective method in screening large samples of adolescent who may not be achieving the recommended levels of PA due to low MC. This could improve targeted interventions for balance, designed to improve PA levels. Introducing this in adolescents may improve participation in PA which could be maintained into adulthood, and contribute to the reduction of non-communicable diseases that are associated with inactivity.

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Appendix

Appendix A – Ethical Approval

OXFORD BROOKES UNIVERSITY

Dr Patrick Esser
Senior Research Fellow Movement Science Group
Department of Sport and Health Sciences Faculty of Health and Life Sciences Oxford Brookes University
Gipsy Lane Headington

7 October 2016 Dear Dr Esser
UREC Registration No: 161033 (resubmission)
Engagement participation inclusion confidence in physical activities EPIC 2

Thank you for your email of 6 October 2016 outlining your response to the points raised in my previous letter for your study and attaching the revised documents.

Once available please forward copies of the permission letters from the Head teachers based on the example given and as the participant information sheets are updated to explain further about the research study itself after the screening process, copies should be forwarded to Louise Wood for an adequate audit trail. On this basis I am pleased to give 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 7 October 2018. If you need the approval to be extended please do contact me nearer the time of expiry.

Should the recruitment, methodology or data storage change from your original plans, or should any study participants experience adverse physical, psychological, social, legal or economic effects from the research, please inform me with full details as soon as possible.

Yours sincerely

Dr Sarah Quinton
Chair of the University Research Ethics Committee

cc Helen Dawes and Ben Weedon, Co-investigators Anne Delextrat, Research Ethics Officer
Louise Wood, UREC Administrator

Appendix B – Example of School Acceptance Letter

Head
Jolie Kirby, BA, NPQH

Cheney School
Cheney Lane, Headington
Oxford OX3 7QH

T: 01865 765726 F: 01865 767399
E: office@cheney.oxon.sch.uk
W: www.cheney.oxon.sch.uk

Think for yourself, act for others

CHENEY SCHOOL OXFORD

Mrs J Kirby, Head Teacher

22 November 2016

To the Movement Science Group, Oxford Brookes University

We are pleased to confirm that Cheney School will allow access to members of the Movement Science Group to conduct their research activities relating to the EPIC2 project with Year 9 pupils.

Signed

Mrs J Kirby Head Teacher Cheney School

Appendix C – Opt-Out Consent Form

Dear Parent,

Title of Project: Engagement participation inclusion confidence in physical activities (EPIC 2)

Your child has been invited to participate in a fitness screening research study organized and run by Oxford Brookes University, funded by Sport England, at your child's school.

Your child will be taking part in exercises that test aspects of your child's fitness, including their muscle strength, power, motor skills, speed, endurance and flexibility using standardized exercise tests as part of their PE lesson and curriculum. We are aiming to measure fitness across this year group to gain an understanding of strengths, and areas for improvement, in order to better understand physical activity and sports participation. In addition, this screening will be undertaken to determine who might benefit from a planned study looking at performance and learning of motor skills in sport.

We will give feedback to your child and information of local sporting activities, and we would like to be able to store and use the results of the tests for reference. Any personal information such as their name will be removed and the data stored anonymously.

However, if you **do not** wish your child to take part and would like to have your child op-out **then please sign and have this form returned**.

We look forward to meeting your child and hope they find the day enjoyable and rewarding.

Student Name:…………………………………………………………………….. Date:………… (Please print)

Parent/Guardian:……………………………………………………………….. Date:……….. (Name and signature)

Kind Regards,

The Movement Science Group

Headington Campus, Gipsy Lane, Oxford OX3 0BP

Dr Patrick Esser Tel: 01865 483833

@: pesser@brookes.ac.uk

Prof Helen Dawes Tel: 01865 483293

@ hdawes@brookes.ac.uk

Mr Ben Weedon Tel 01865 483272

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OXFORD BROOKES UNIVERSITY

Appendix D – Participant information sheet – Adolescent

12+ yrs Copy

Research Project Title:
Engagement participation inclusion confidence in physical activities (EPIC 2)

We are inviting you to take part in a research study. Before deciding whether or not you would like to take part we would like you to understand why the research is being done and what it would involve. Please take time to read the following information carefully.

What is the study about?
Physical activity and exercise improves health and well-being, has a beneficial effect on mood and behaviour, and enhances performance in school. Young people aged 12-14yrs are recommended to participate in moderate to vigorous physical activity for at least 60 minutes a day. This research study is set out to train the coordination of young people and examine the changes that take place in their brains as their skills improve. This may enable us to develop better training strategies for those children who find it difficult to acquire new exercise techniques and motor skills.

Why have I been invited to participate?
You have been invited to participate because you took part in a skills and fitness screening session held at your school. Following the screening, your results suggest you have the potential to improve your performance in certain areas and we would like to help you do this by inviting you to our EPIC training club. This is a great opportunity to receive personal training in a well kitted-out gym and to improve your overall movement and coordination skills. If you do decide to take part you are free to withdraw at any time without giving a reason.

We may ask if you'd like to volunteer to have your brain scanned. This will enable us to monitor changes to your brain as you proceed through the training programme. The methods we use are painless, very safe and easy to use. The methods are described in more detail on pages 2 and 3. It is really important to understand that the brain scan is entirely optional. You can choose to be involved in the exercise training only.

Exclusion criteria
You will be required, together with your parents, to complete a health screening questionnaire. This will help us to identify any obvious reasons why you shouldn't take part in this study. For instance, if you have a long-term degenerative muscular condition such as muscular dystrophy, you will not be able to take part in the study. However, if you have asthma, diabetes or epilepsy, you would be able to participate so long as your condition was stable. In these cases we will ask for you

to bring your medications with you to the sessions. So if you have asthma, we would expect you to bring an inhaler.

Do I have to take part?

It is up to you to decide whether or not you want to take part. Take time to think about it and please don't hesitate ask any questions that you may have. If you have any of the medical conditions stated above and you have concerns about participating you may wish to discuss this with a parent. Your safety and well-being is our top priority. If the research team feel that you should be checked by the GP prior to testing, we would like to be able to tell you so. Once it's been determined that it is safe for you to take part we will schedule a suitable day for you to start. You will also be asked to sign an informed consent form. Your involvement in the study won't compromise any on-going or future treatment you may be receiving, nor will it affect your progress at school.

What will happen to me if I take part?

The EPIC project is designed to improve skills and coordination. You will be encouraged to attend 8 weekly sessions during or after school. Each session lasts approximately 60 mins and will involve:

- Cardiovascular exercise (i.e. cycling, treadmill running or a group warm-up) for 25-30 mins within a 65-90% target heart rate (HR) zone.
- Strength, resistance and coordination training will also be incorporated under the supervision of a qualified and experienced coaches focusing on volume and intensity of resistance training based on your fitness level and abilities.

Brain Scanning

We may ask if you would like to volunteer to visit the Oxford Brookes University Movement Science Laboratory or the Warne ford hospital on on <u>two</u> separate occasions lasting approximately 1-1.5 hours each. There is an additional 45 minutes added if you volunteer for the fMRI scanner at the Warneford hospital. During the assessments we will assess the following:

- Height, weight, blood pressure and maturity
- <u>Health questionnaires:</u> general health screening questionnaires specifically for young people
- <u>Movement:</u> coordination and physical activity level measurements measured by a monitor you wear for 7 days
- <u>Confidence and motivation:</u> Self-perception measurements to assess how you perceive your sporting ability
- <u>Cognition</u>, a computerised reaction time task.
- <u>Brain measures:</u> brain measures will be recorded during performance of the coordination skill using two brain imaging methods; 1) by non-harmful

laser light (fNIRS) and 2) via magnetic imaging (MRI). During the laboratory visits you will be asked to wear the fNIRS cap in which you can move freely (see Figure 1-a on page 3). The MRI method will require you to lie inside a scanner and perform foot movements (See Figure 1-b on page 3).

Figure (1): a- Functional Near Infrared Spectroscopy (fNIRS) b- functional Magnetic Resonance Imaging (fMRI).

Stepping Task

During the stepping task, a motion sensor will be attached to your lower back with non-allergic double adhesive tape. This will allow us to track, in very high detail, how the rhythmic task is being performed.

The testing is safe and will be monitored by a trained researcher to ensure that you are comfortable and confident with all tasks. We will also make sure you warm-up and properly cool-down before and after exercise.

How much time does this study require?

- The training sessions take place over 8 weeks. Each session lasts 60 minutes.
- The assessments at baseline (week 0) and at the end of week 8 will take between 1hr and 1.5hrs of your time. However, if you volunteer for the MRI scan at the Warneford Hospital this time will be extended by another 45 minutes. If you are brain scanned, the whole assessment will take place at the Warneford Hospital for which no additional travel time has to be added.

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Gipsy Lane, Headington, Oxford, OX3 0BP, +44 (0) 18765 483272

We will plan the assessments (week 0 & 8) to suit your diary. If it’s easier, we can even test you during weekends . The breakdown of the study is as follow:

	Week 0	Week 1	Week 2	Week3	Week4	Week5	Week6	Week7	Week 8	Week 9
Baseline Assessment (1.5hrs)										
Optional MRI Scanning (45mins)										
Training 2x60minutes					16 hours in total					
Final Assessment (1.5hrs)										
Optional MRI Scanning (45mins)										

Whereby the accumulative time can be broken down as:

What	Time Required	Accumulative
Baseline Assessment	1.5hrs	1.5hrs
Intervention	2x60minutes	3.5hrs
Intervention	2x60minutes	5.5hrs
Intervention	2x60minutes	7.5hrs
Intervention	2x60minutes	9.5hrs
Intervention	2x60minutes	11.5hrs
Intervention	2x60minutes	13.5hrs
Intervention	2x60minutes	15.5hrs
Intervention	2x60minutes	17.5hrs
End of Study Assessment	1.5hrs	19hrs
MRI Scanning when opted-in	2x45minutes	20.5hrs

Is there anything I need to do before the sessions?

We will ask you to complete several questionnaires so that we are confident you are in good general health and capable of performing the exercise tasks during the study.

What type of clothing should I wear for exercise sessions?

You should bring comfortable shoes and sportswear or PE kit clothing (e.g. shorts, T-shirt, trainers) that you can wear for the exercise sessions. If you wear orthopaedic shoes or orthotics in daily life we would ask you to wear these during the exercise session. If you are taking part in the fMRI study, the clothing that can be worn in the scanner is described in detail on page 5.

What are the possible benefits of taking part?

The benefits of participating include specialist coaching with a personal trainer who will teach you the proper techniques for strength and resistance training. You will also get taught how to use cardiovascular training machines (eg treadmill, bike, rower) to achieve higher fitness levels.

Are there any risks in taking part?

The procedures and tests in this study are routinely used for assessing a young person's health, fitness and skill sets. However, exercising is not without risk and some individuals may find exercising uncomfortable or unpleasant. If you do not regularly take part in physical activity, you may find the training and exercise tests very tiring and your muscles may ache the next day after the session. This is perfectly normal and is a sign that you have worked your muscles hard. The researchers are fully trained first aiders. Your heart rate and breathing will be monitored throughout the assessments as well as during training. You would be able to stop at any time without giving a reason.

fMRI part

MRI is safe and non-invasive and does not involve any ionizing radiation (x-rays). However, because it uses a large magnet to work, MRI scans are not suitable for everybody. Because of this, you will be asked pre-screening safety questions to help determine if you are able to take part. For example, if you suffer from claustrophobia, you could not be scanned. Normally, MRI scanning for research purposes would not be performed without further investigation if you have a heart pacemaker, mechanical heart valve, mechanical implant such as an aneurysm clip, hip replacement, or if you carry other pieces of metal that have accidentally entered your body. While there is no evidence to suggest that MRI is harmful to unborn babies, as a precaution, the Department of Health advises against scanning pregnant women unless there is a clinical benefit. We do not test for pregnancy as routine so if you think you may be pregnant you should not take part in this study. As some of the scans are noisy, we would give you earplugs or headphones to make this quieter for you. It is important that these are fitted correctly as they are designed to protect your hearing.

What type of clothing should I wear for fMRI sessions?

In preparation for your fMRI scan and for your comfort and safety we may ask you to change into pocket less and metal free "pyjama-style" top and trousers, which are available in a range of sizes. You may keep your underwear and socks on but we would ask ladies to remove underwired bras, if you have a suitable non-wired bra you may wear this instead. Please avoid any fabrics that contain metallic threads or have been silver impregnated (often marketed as anti-microbial/bacterial or anti-odor/stink). Metal jewellery including body piercing must also be removed. Eye shadow and mascara must also be avoided, since some types contain materials that can interact with the magnetic field. If you wish to wear eye makeup to your scan we can provide makeup removal wipes but you are advised to bring your own makeup to reapply. Lockers are provided to secure your personal belongings and clothing.

It is important to note that we do not carry out scans for diagnostic purposes, and therefore these scans are not a substitute for a doctor's appointment. Our scans are not routinely looked at by a doctor, rather our scans are intended for research purposes only. Occasionally a possible abnormality may be detected. In this case, we would contact your GP, who may suggest a follow-up scan. We would inform you in the event that the GP is contacted.

What will happen if I don't want to carry on with the study?
It is entirely up to you to decide if you want to continue with the study. You can withdraw from any part of the study.

What if there is a problem?
If you have a concern about any aspect of this study, you should contact the researchers who will do their best to answer your questions. If you have any concerns about the conduct of the research you may contact the Chair of the University Research Ethics Committee on ethics@brookes.ac.uk. If you require any independent support for this study you may contact Jaroslaw Semeniuk on jaroslaw.semeniuk@oxfordhealth.nhs.uk

What happens when the research study stops?
The study ends after completion of the 8 week training programme. However the aim of the pathway is to promote long term physical activity and you would therefore be able to continue for longer if you please. We also hope to provide you with a connection to a sport or physical activity that you enjoy and for you to carry on with for longer-term participation. You would still be free to contact any of the researchers with any question or queries you may have regarding the study. The results from the study will be presented at academic conferences and published in peer reviewed sources.

What will happen to the findings of this study?
The results from your performance and any data we collect will be kept in a safe place. Your name will not be used, but instead you will be given an ID number. All information collected will be retained in accordance with the University's policy on Academic Integrity and will be destroyed when no longer needed.

Who should we contact if I have some more questions?

Mr Ben Weedon Tel 01865 483272
@: b.weedon@brookes.ac.uk

Dr Patrick Esser Tel: 01865 483833
@: pesser@brookes.ac.uk

Prof Helen Dawes Tel: 01865 483293
@ hdawes@brookes.ac.uk

Who is organising and funding the research? This study is organised by researchers in the Movement Science Group and funded by the Community Sport Activation Fund (CSAF).

Who has reviewed the study? It has been reviewed and ethical permission approved by the University Research Ethics Committee.

If you are interested and/or have any questions regarding the study, please contact the Supervisory team using the contact details at the top of the page. We would be more than happy to speak with you. Thank you for taking time to read this information sheet.

Oxford Brookes University, Movement Science Group,
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Appendix E – Physical Activity Readiness Questionnaire (PAR-Q)

ID # Date: / / .

Physical Activity Readiness-Questionnaire (PAR-Q)

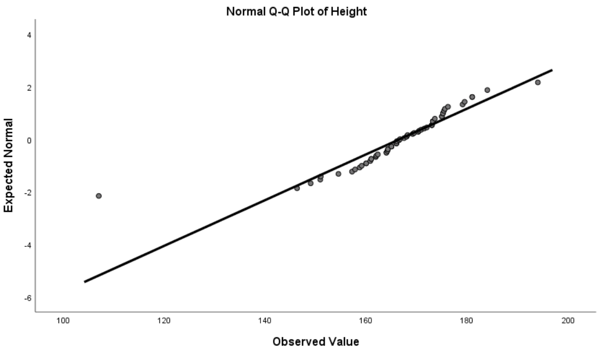
Please read the following carefully and answer as accurately as possible by ticking the appropriate box for each question.

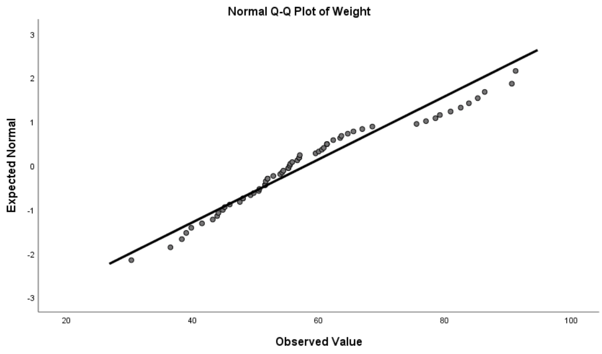
	Yes	No
1. Has a doctor ever said you have heart trouble?		
2. Do you ever suffer frequently from chest pains?		
3. Do you often feel faint or have spells of dizziness?		
4. Has a doctor ever said you have epilepsy?		
5. Has a doctor ever said you have high blood pressure?		
6. Has a doctor ever said you have diabetes?		
7. Has a doctor ever said you have asthma?		
8. Do you have a bone, joint or muscular problem which may be aggravated by exercise?		
9. Do you have any form of injury?		
10. Are you currently taking any prescription medications?		
11. Have you suffered from a viral illness in the last two weeks?		

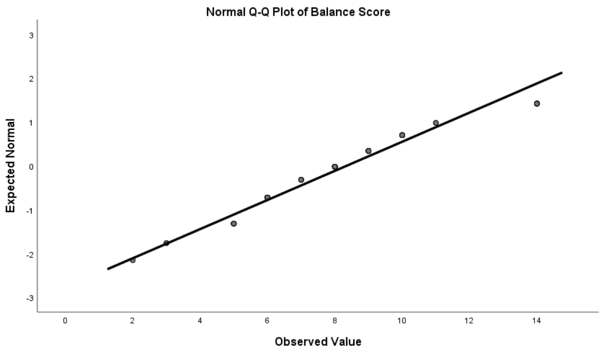
If you have answered YES to any of the above questions, or know of any possible reason (physical or psychological) that might affect the safety or accuracy of the tests - please inform a member of staff.

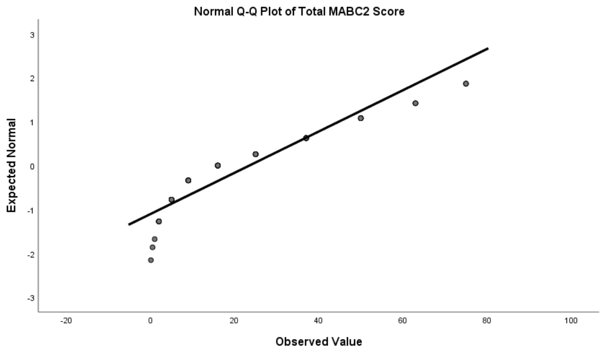
Anything else you feel that we should know about:

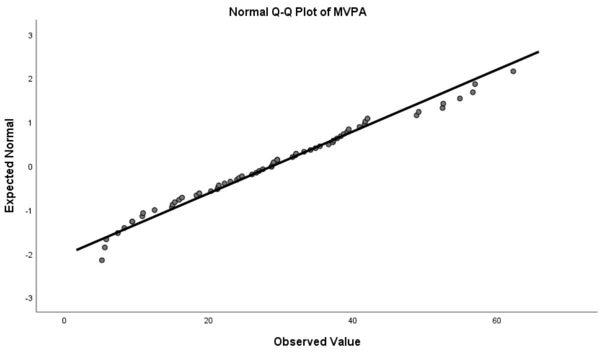
Appendix F - Q-Q plots Chapter 4

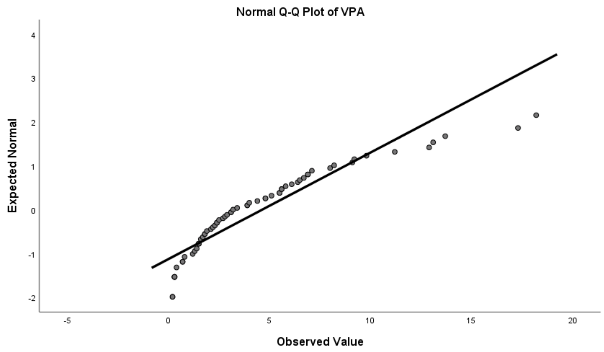




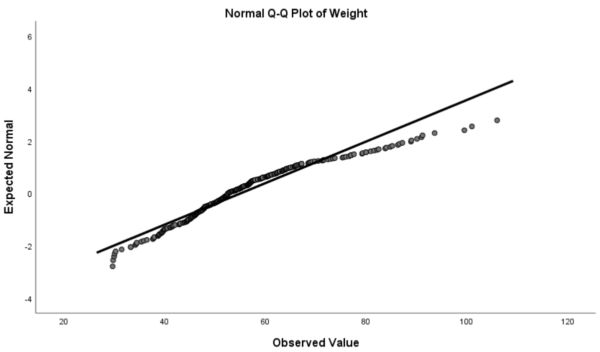


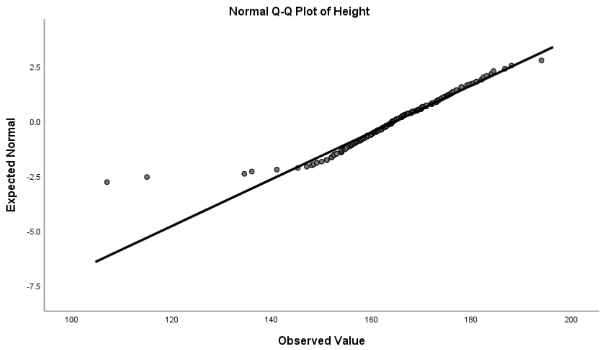


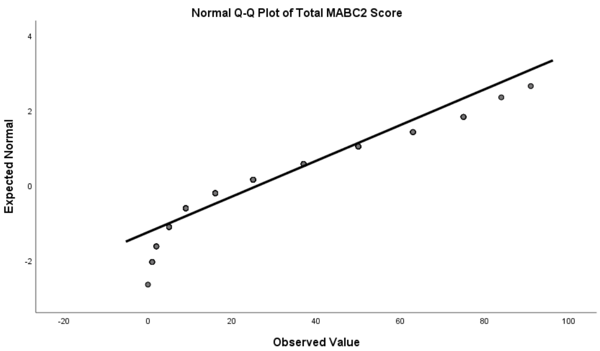


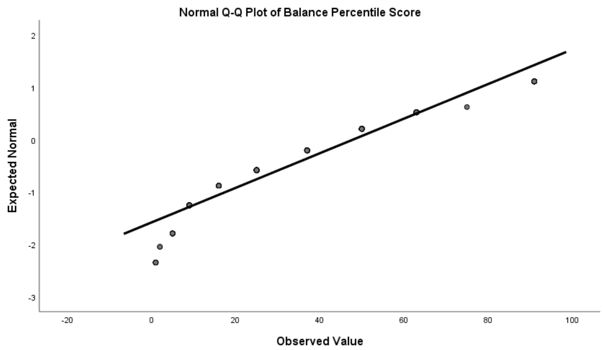


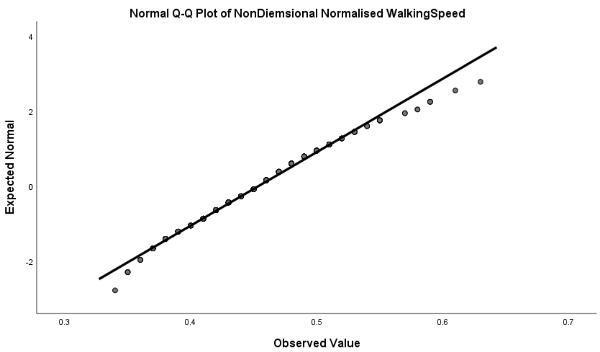
Appendix G – Q-Q plots Chapter 5

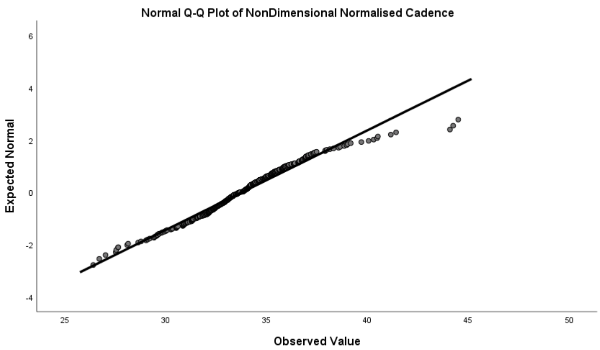


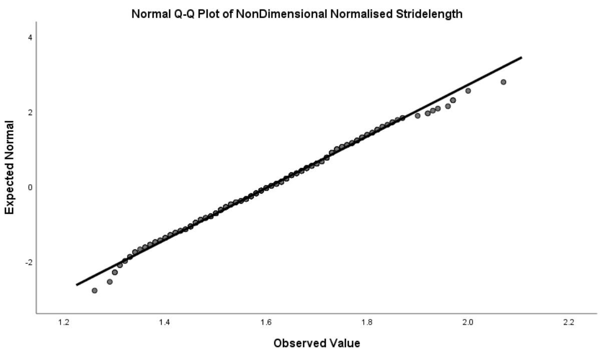


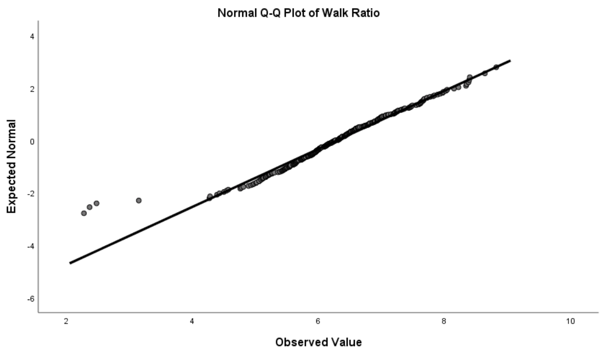


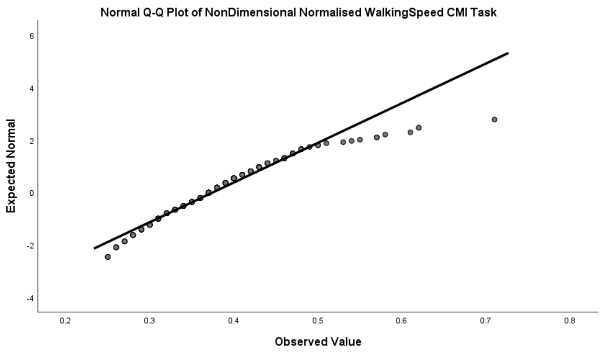


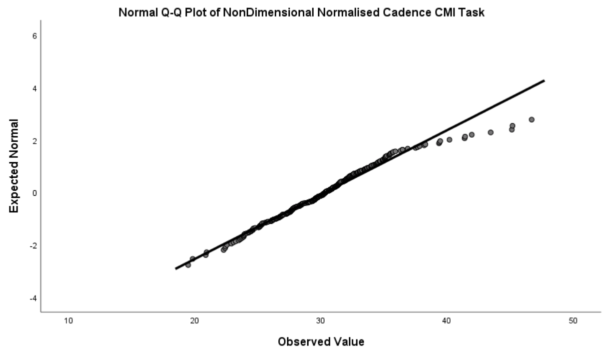


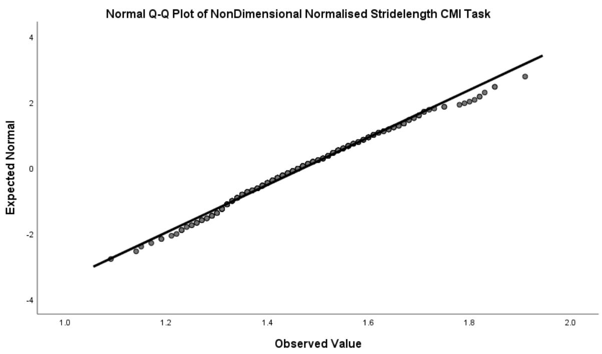


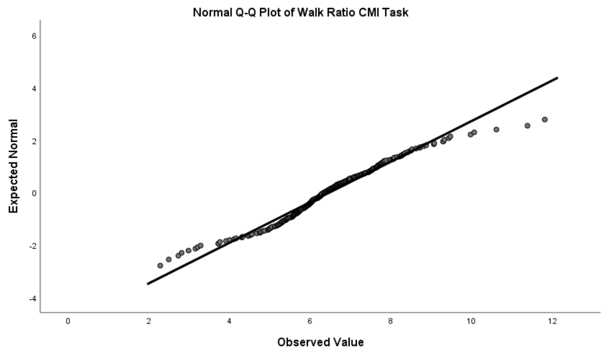




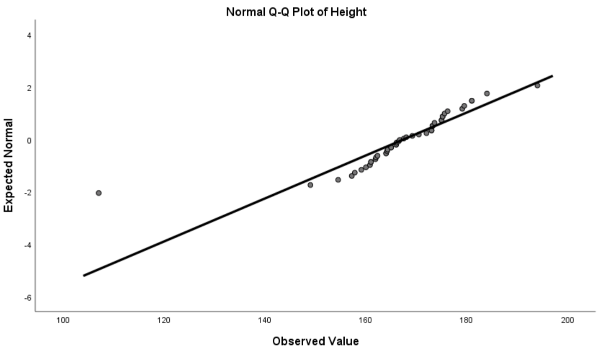

Normal Q-Q Plot of NonDimensional Normalised WalkingSpeed CMI Task
Expected Normal
6
4
2
0
-2
-4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Observed Value

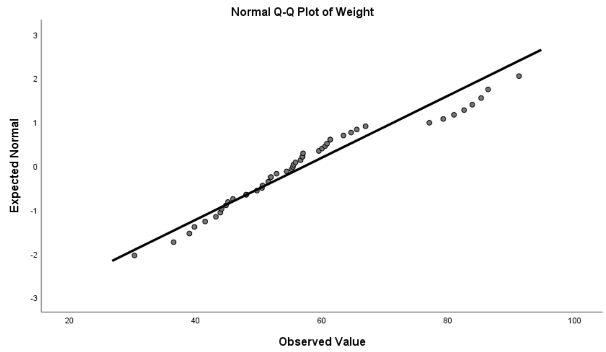

Normal Q-Q Plot of NonDimensional Normalised Cadence CMI Task
Expected Normal
6
4
2
0
-2
-4
10
20
30
40
50
Observed Value

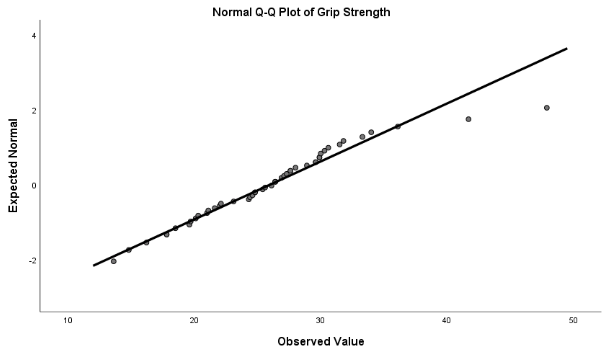

Normal Q-Q Plot of NonDimensional Normalised Stridelength CMI Task
Expected Normal
4
2
0
-2
-4
1.0
1.2
1.4
1.6
1.8
2.0
Observed Value

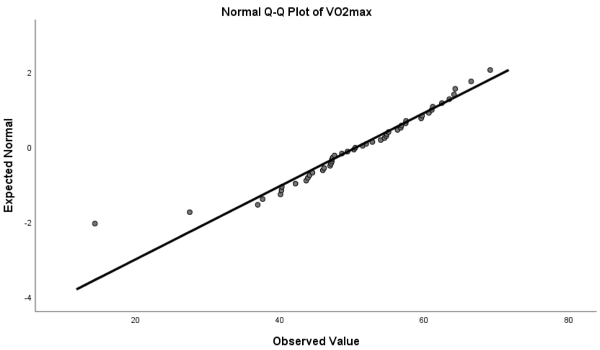

Normal Q-Q Plot of Walk Ratio CMI Task
Expected Normal
6
4
2
0
-2
-4
0
2
4
6
8
10
12
Observed Value

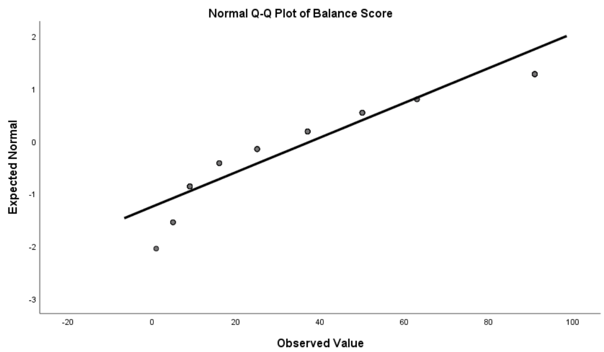
Appendix H – Q-Q plots Chapter 6

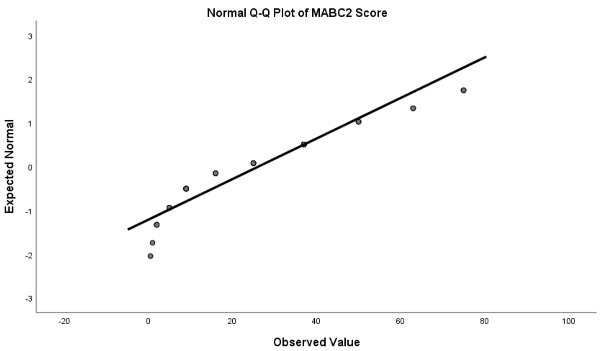


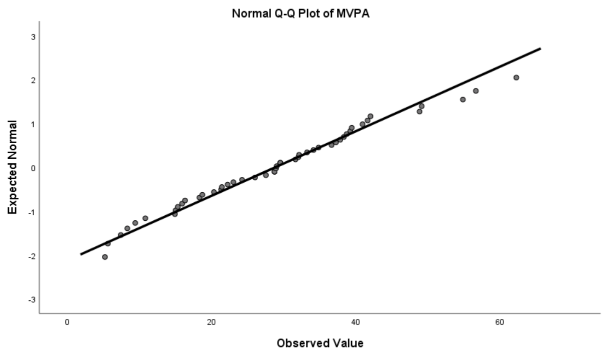


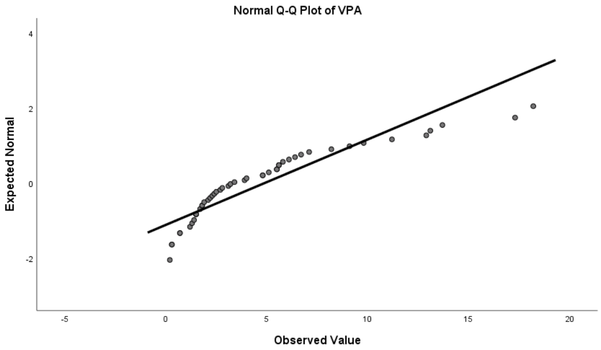


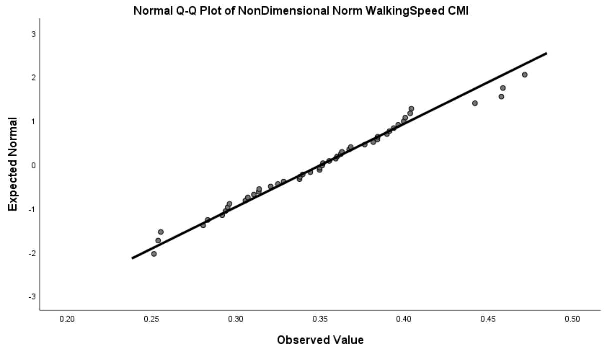


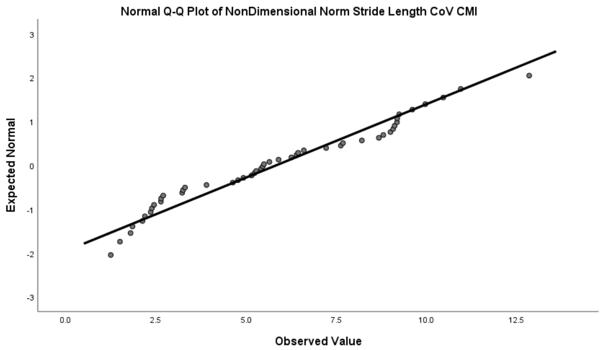







Normal Q-Q Plot of VPA
Expected Normal
Observed Value
4
2
0
-2
-5
0
5
10
15
20


Normal Q-Q Plot of NonDimensional Norm WalkingSpeed CMI
Expected Normal
Observed Value
3
2
1
0
-1
-2
-3
0.20
0.25
0.30
0.35
0.40
0.45
0.50


Normal Q-Q Plot of NonDimensional Norm Stride Length CoV CMI
Expected Normal
Observed Value
3
2
1
0
-1
-2
-3
0.0
2.5
5.0
7.5
10.0
12.5

Appendix I

Number of adolescents meeting MVPA guidelines for gender and MC level for total MABC2 and Balance subsection

	Female		Male		Female		Male	
MVPA	Low MC[%]	TD[%]	Low MC[%]	TD[%]	Low Bal[%]	TD[%]	Low Bal[%]	TD[%]
≥60min	0 [0]	1 [5.5]	0 [0]	0 [0]	0 [0]	1 [5]	0 [0]	0 [0]
≥45min	2 [15.4]	3 [16.7]	1 [6.7]	2 [11.8]	1 [10.0]	4 [19.0]	1 [9]	2 [9.5]
≥30min	3 [23.1]	9 [50.0]	4 [26.7]	11 [64.7]	1 [10.0]	11 [52.4]	3 [27.3]	12 [57.1]
<30min	10 [76.9]	9 [50.0]	11 [73.3]	6 [35.3]	9 [90.0]	10 [47.6]	8 [72.7]	9 [42.9]
Total	13	18	15	17	10	21	11	21

Bal = balance subsection MABC2, TD = Typically Developed, MVPA = Moderate to Vigorous Physical Activity