Inter-limb coordination in a novel pedalo task: a comparison of children with and without Developmental Coordination Disorder

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Highlights

- Children with DCD and their TD peers completed a novel pedalo task
- Movement outcome and inter-limb coordination was different in children with DCD
- Inter-limb variability of the upper body was higher in TD children
- The relationship between group and movement outcome was mediated by inter-limb variability
- Movement difficulties in DCD may be due to a less optimal exploration of motor solutions.

Abstract

Children with Developmental Coordination Disorder (DCD) have been shown to have different coordination patterns on some tasks compared to their typically developing peers. However, it is unclear whether these differences are driven by the fact that typically developing children tend to be more practiced at the task on which coordination is being measured. The current study used a novel pedalo task to measure coordination in order to eliminate any practice differences. Thirty children (8 years -16 years), 15 with DCD and 15 without were recruited for this study. Children pedalled along an 8m line 20 times. Movement of the 7th Cervical Vertebra, shoulders, elbows, wrists, hips, knees, ankles and toes was recorded. In terms of outcome measures, pedalling speed was not different between the groups but the coefficient of variation of speed was higher in the children with DCD indicating a less smooth movement. Coordination was measured by calculating angles at the shoulder, elbow, hip, knee and ankle. A higher correlation coefficient (more tightly coupled movement) and a greater variation in joint angle was seen in the typically developing children for specific joint segments. The relationship between group and movement outcome (smoothness of movement) was mediated by inter-limb coordination variability. Therefore, the poor coordination and slower learning generally reported in children with DCD could be due to a slower or less optimal exploration of motor solutions.

Keywords: Inter-limb coordination, Intra-limb coordination, Joint angle, coordination pattern

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1.1 Introduction

Most adults are highly skilled at moving around the environment and carrying out complex every day motor tasks with little attention or effort. However, even the simplest of motor tasks requires coordination between different body parts. In this sense 'coordination' refers to the ability to organise different parts of the body to achieve a specific goal. The constraints-based approach to motor control posits that coordination is an emergent property of movement and that any given coordination pattern is constrained by the task, the individual and/or the environment (Newell, 1986). If we take the example of a simple task such as walking, the way in which the limbs of the body are coordinated during this task may be different if we change the task (walking forwards vs. walking backwards), the individual (a child vs. an adult) or the environment (walking in the light vs. walking in the dark). Although subtle, the way in which body segments are coordinated will differ according to these constraints. Importantly, however, there is no direct mapping between the way in which individual moving body parts, or 'degrees of freedom' are coordinated and the outcome (or success) of the movement. The term degrees of freedom (a term coined by Bernstein, 1967) refers to the number of possibilities within the system which are free to vary. This includes position possibilities of anatomical features such as joints and muscles, kinematic features such as displacement, velocity and acceleration and neurophysiological features such as motor neurons. When reaching forward to grasp a cup, the upper trunk, the shoulder joint, the elbow joint, the wrist joint and the finger joints are all free to move independently from each other and these are the degrees of freedom. Bernstein suggested that in order to simplify a motor task we can keep some elements still or rigidly coupled in order to reduce the degrees of freedom, this describes 'freezing' degrees of freedom. In this example, the degrees of freedom could be reduced by keeping the upper trunk still. With practice, a mover starts to ‘free’ degrees of freedom; this describes Bernstein’s later stage of motor learning when changes improve the movement solution. As an extension to this, Turvey (1990) proposed the idea of coordinative structures which describes how body segments (or degrees of freedom) are linked together such that they are then constrained to act as one functional unit, which simplifies the complexity of movement. These coordinative structures are thought to emerge naturally following movement experience with motor learning being a process of discovering these coordinative structures (Turvey, 1990). A key part of Turvey’s account is that the number of coordinative structures does not denote skill, i.e. fewer coordinative structures do not necessarily infer greater skill. This is especially important as research studies are very mixed in terms of providing evidence for Bernstein’s account of freezing and then freeing degrees of freedom during learning of a new motor skill (Newell & Vaillancourt, 2001). In fact, a recent meta-analysis reviewed 13 studies which focused on coordination in learning for adults (Guimarães, Ugrinowitsch, Dascal, Porto, & Okazaki, 2020). The review concluded that for discrete tasks (such as dart throwing, kicking a ball and pointing to a target) the objective of the task was important; tasks emphasising accuracy showed freezing of degrees of freedom to promote learning while those emphasising speed showing freeing of degrees of freedom. In comparison continuous tasks (such as marching, skiing on a simulator and handwriting) were all favourable to the freezing hypothesis apart from one (Ko, Challis, & Newell, 2003) which emphasised balance as the only outcome, this study provided no evidence for the freezing of degrees of freedom. This review highlights that both the type of task and the focus of the task (accuracy versus speed) are important in terms of the way in which limbs are coordinated during learning.

The constraints-based approach to understanding motor behaviour is a useful way to describe and understand movement in children with Developmental Coordination Disorder, DCD (Sugden & Wade, 2013). DCD describes a condition in which motor coordination is below the level expected given an individual’s age and opportunity for learning (APA, 2013). Almost 2% of children in the UK present with DCD (Lingam, Hunt, Golding, Jongmans, & Emond, 2009), displaying fine and/or gross motor difficulties (Sugden, 2006) which persist into early adulthood, continuing to have a negative impact on everyday life (Kirby, Edwards, Sugden, & Rosenblum, 2010). Despite its diagnostic term, we still understand very little about the nature of *coordination* in individuals with DCD. Missiuna (1994) observed coordination during a computer mouse control movement, increased tension within the hand, across the wrist, elbow and shoulder joints were seen in the children with DCD. These observations led them to the conclusion that this may be due to the children with DCD trying to reduce or ‘freeze’ the degrees of freedom (Missiuna, 1994). In terms of actually measuring kinematics, studies focusing on coordination in children with DCD have been varied; some studies have considered discrete tasks while others have focused on continuous tasks. These studies are described below.

Firstly in terms of discrete movements the majority of studies have considered the coordination of joint angles during a ball catching task in children with DCD. A higher inter- and intra-limb coupling of body segments was found in children with DCD compared to typically developing matched controls in one (Asmussen, Przysucha, & Zerpa, 2014) and two-handed catching (Astill & Utley, 2006; Przysucha & Maraj, 2013). The tight coupling of inter-limb pairings in children with DCD was reduced when balls were presented to the left or right side rather than the midline (Astill, 2007) and when ball speed was increased (Przysucha & Maraj, 2014). One final ball catching study found that children with DCD demonstrate a greater level of inter-limb asymmetry in elbow flexion-extension compared to their peers (Sekaran, Reid, Chin, Ndiaye, & Licari, 2012). Many of these ball catching studies also considered variability of coupling (i.e. the standard deviation of correlation coefficients between angle segments across trials). The majority of studies which considered this found elevated variability in coupling of intra- and inter-limb coordination in children with DCD (Asmussen et al., 2014; Astill, 2007; Przysucha & Maraj, 2013). However, one study found no difference (Przysucha & Maraj, 2014) and another found elevated variability in the typically developing children (Astill & Utley, 2006). On the surface these findings seem to support the notion of children with DCD ‘freezing’ degrees of freedom to simplify movement patterns, with some studies finding intra-limb and others inter-limb group differences (the differences here could simply be due to methodological details). However, these studies also highlight situations where patterns of coordination are similar across children with and without DCD. A further study considering a discrete movement examined the coupling of the hand, torso and head during pointing (Elders et al., 2010). This study showed tighter temporal coupling between the head and torso in children with DCD compared to controls, but weaker coupling between the head and hand.

In terms of continuous tasks, studies initially considered the coupling of movement to an external stimulus such as an auditory beat, with the focus being accuracy of timing coordination. These studies all demonstrated an increased variability in the coupling of movements made by children with DCD compared to their peers (Volman & Geuze, 1998a, 1998b; Whitall et al., 2008). Studies have also considered how well children with DCD can coordinate the timing of their movement with studies considering bilateral finger tapping (Roche, Wilms-Floet, Clark, & Whitall, 2011) and tapping of a hand and foot (Volman, Laroy, & Jongmans, 2006). In both cases, a higher variability of coupling between the fingers / limbs was seen in the children with DCD. Studies considering more complex tasks have examined the coordination of clapping and marching (Mackenzie et al., 2008), clapping and jumping (de Castro Ferracioli, Hiraga, & Pellegrini, 2014) and clapping and walking (Whitall et al., 2006). Here we also see that patterns of coordination in the children with DCD are characterised by a heightened variability in the coupling of two actions; with the positioning of the 'clap' within the cycle of the other movement varying across claps. Finally, the movement of the thigh and shank while walking was modelled using Elliptical Fourier Analysis and fit (sum of squared error, SSE) was compared across a full fit (using 500 harmonics) and reduced fit (using 10 harmonics) (Rosengren et al., 2009). A more complex movement was characterised by a higher SSE. Furthermore, phase portraits were calculated for each gait cycle and the linear displacement of the centroid of each cycle was compared as a measure of variability, as was the standard deviation of the radius of all points in the cycle. Children with DCD had a higher complexity of movement and generally displayed much more variability in their gait compared to the typically developing peers. No group differences were seen in the symmetry of movement. We cannot draw conclusions from these studies regarding the freeing or freezing of degrees of freedom as this was not specifically examined in these studies.

The collection of studies described above highlight potential differences in the coordination between children with DCD and typically developing children across a variety of tasks and using a variety of different measures. Furthermore, one commonality among these tasks is that they were all familiar to the children and given the nature of DCD we would expect they were more practiced in the typically developing group. Therefore, the coordination patterns which were compared do not necessarily reflect similar stages of learning. To that end, the aim of the current research study was to document movement performance (outcome) and coordination of a **novel** task in children with and without DCD. Furthermore, we aimed to investigate the possible link between movement coordination and movement outcome. A novel task was chosen as we wanted to 'even the playing field' between the children with DCD and the typically developing children in terms of familiarity and practice. Furthermore, we wanted to choose a task which children could complete at a self-selected pace rather than having to coordinate their movement to an external stimulus as this was considered more common-place in daily life. For this purpose a pedalo task was chosen, which requires the mover to coordinate movement in such a way that they can maintain dynamic balance, which can be a particular difficultly for children with DCD. In the current study we were primarily interested in the initial stages of organisation of coordination. As this task requires coordination of multiple body segments we considered joint angles between segments in line with research focusing on kinematics of coordination in this group. Our specific research questions were:

1. How does *outcome* compare across a DCD and a TD group in a novel balance task? We expected that the TD group would have a more successful movement outcome in terms of fewer errors (i.e. fewer occurrences of stepping off the pedalo) and smoother pedalling action.

2. How is *movement coordination* different across a TD and a DCD group? Although previous studies have not looked at novel tasks in a population with DCD we would expect differences in joint angle coordination between these groups given the nature of DCD, however, whether this is an increase in variability of the coordination of the limbs is not clear.

3. What factors mediate the relationship between group and o*utcome*?

1.2 Method

1.2.1 Participants

15 individuals with DCD and 15 age and gender matched controls were recruited for this study. Individuals with DCD were an opportunistic sample recruited from a database of individuals held by the researchers at Oxford Brookes University. Participants ranged from 9 to 16 years of age. All participants in the DCD group held historic diagnoses of DCD / Dyspraxia (which satisfies all of the DSM-5 criteria for DCD), however these participants also completed the MABC-2 Test and their parents completed the MABC-2 Checklist to ensure DSM-5 criteria A and B for the diagnosis of DCD were still met. All participants in the DCD group fell below the 15th percentile on the MABC-2 Test and below the 5th on the MABC-2 Checklist. Typically developing (TD) controls were gender and age matched to within six months of each participant with DCD. TD controls did not complete the MABC-2 Test, but they and their parents confirmed they had no suspected motor difficulties. Participant details can be found in Table 1. All participants were asked about their previous experience on similar balance activities to the pedalo task used in this study, for this

participants were presented with eight related activities as asked if they have any experience (the eight were: riding a bike, uni-cycling, scooting, staking, skate-boarding, skiing, snowboarding and surfing). None had previous experience with a pedalo. Participants were awarded 3 points for similar activities they reported to do regularly, 2 points for those they did every now and again, 1 point for those they had tried and 0 points for a task they had never tried. Therefore, if participants did all eight activities regularly they would have scored the maximum score of 24, if they had never tried any they would score the minimum score of 0.

1.2.2. Procedure

The task for participants was to pedal forwards along an 8 m line using a Pedalo© classical pedal racer (Holz-Hoerz, Germany). Foam mats were placed either side of the 'runway' for safety. Each participant started with their self-selected preferred foot on the 'up' pedal and their non-preferred foot on the 'down' pedal (see Figure 1). No instructions were given regarding how to pedal or what to do with the upper body. Participants were instructed to move at their self-selected speed but to step off if they felt they were going to fall. One practice trial was given with the experimenter walking alongside the participant for encouragement and safety. After this participants were asked to judge how well they felt they would be able to use the pedalo (1 = 'Not well at all', 2 = 'Not very well', 3 = 'Well', 4 = 'Very well'), this provided a measure of self-efficacy, which can be found in Table 1. Following this judgement all participants completed 20 trials (pedalling forwards 20 trials from one end of the runway to the other). Trials where the participant stepped off the pedalo before the end of the runway were terminated but were counted as a trial. In order to measure movement and coordination, 18 retro-reflective markers were tracked by a six-camera VICON system (running at 120Hz). These were placed on bony landmarks: the middle of the forehead, the 7th cervical vertebra (C7), bilaterally on the acromion process (shoulders), lateral epicondyle (elbows), radial styloid process (wrists), iliac crest (hips), lateral femoral epicondyle (knees), lateral malleolus (ankles), head of the second metatarsal (toes). Markers were also placed on the front of each pedal.

Figure 1. The pedalo with markers placed on the feet and each pedal of the pedalo.

Table 1. Participant group data for both the TD and DCD group.

	TD	DCD
N	15	15
Mean age	12.60 years	12.79 years
Gender ratio (M:F)	13:2	13:2
MABC-2 test percentile score mean (range)	-	3.51 (0.1 – 9.0)
% of children <5th centile on MABC-2 test		80%
% of children <5th centile on MABC-2 checklist	-	100%
Rating of related previous experience (possible maximum of 24)	9.00 (4.14) Range 5-17	3.67 (2.09)* Range 0-7
Self-efficacy rating (on scale of 1 to 4)	2.93 (0.42)	2.63 (0.72)

* A significant group effect was found p < .01

1.2.3. Data processing

Trials where the participant stepped off the pedalo before the end of the runway were not included when considering the outcome of the task or the limb coordination even if the start of the trial had useable data[2]. VICON movement data were filtered using an optimised low pass Woltring filter with a 12Hz cut off point and then analysed using tailored matlab routines. For each trial only the middle three periods or cycles of pedalling were analysed (to remove the start and end of movement and in line with previous research using this task; Chen, Liu, Mayer-Kress, & Newell, 2005). The start of a cycle was determined by eyeballing the z coordinates of the pedals over time. The start of a cycle occurred when the z coordinate of one of the pedal markers was at a minimum while the other pedal marker was at a maximum (as the pedals are yoked these events always co-occurred), the end of the cycle was the next time at which that same point was reached. Variables describing movement outcome and variables describing movement coordination were extracted, as described below.

1.2.3.1. Variables describing movement outcome

This included: times stepped off the pedalo, referred to as the number of errors (%), which is the number of trials on which the participant stepped off the pedalo as a percentage of the number of trials completed, speed (ms^{-1}), the average speed of movement, and coefficient of variation of speed (CV of speed = standard deviation of speed / mean of speed)

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[2] These were removed as coordination in the ‘incomplete’/’failed’ trials may be qualitatively different to that in the successful trials.

giving an indication of the 'smoothness' of movement within each trial. These were determined from the mid-point of the pedalo markers across all three dimensions of movement.

1.2.3.2. Variables describing movement coordination

Joint angle was used as a measure of limb movement with the angles at five bilateral joints calculated. These were the angle at the shoulder (calculated as the angle created between the elbow, shoulder and hip), elbow (calculated from the shoulder, elbow and wrist), hip (from the shoulder, hip and knee), knee (from the hip, knee and ankle), and ankle (calculated as the angle created between the knee, ankle and toe). An increase in angle of the knee indicated extension (moving the foot away from the body) while an increase in angle of the shoulder indicated abduction (moving the arm away from the body), a decrease in the elbow angle indicated flexion (pulling the upper arm up towards the head) and a decrease in the ankle angle indicated dorsiflexion of the foot (moving the toes towards from the body). Joint angle was calculated for each frame within each trial and then Pearson cross correlation coefficients were calculated between pairs of joints and then a Fisher's z transformation applied. Inter-limb correlations were calculated between left-side and right-side joints. A correlation close to ±1 indicates a close coupling of joint movement, while a correlation close to 0 indicates no coupling of joint movement. The standard deviation across these correlations was also calculated as a measure of inter-limb coordination variability. This method of using cross correlations to assess coordination has been used previously (Guimarães et al., 2020) including in populations with DCD (for example see Astill, 2007 and Astill & Utley, 2006).

1.2.4. Statistical analysis

Statistical analyses were carried out using IMB SPSS Statistics 25. Each of the variables specified above were calculated for each trial. One-way ANOVA was used to compare the measures of self-efficacy, experience, and the measures of movement outcome (error, speed and CV of speed) between the DCD and TD group. In line with Lakens (2013) partial eta squared is reported as a measure of effect size. For movement coordination, the individual correlations between pairs of joint angles and the variability of these angles MANOVA (group) was used and then, where appropriate followed up with univariate tests. Pillai's trace is reported. Finally, in a bid to determine factors which were important in the relationship between group and the outcome variable of coefficient of variance, a mediation analysis was conducted. Mediation variables were chosen from our selection of variables measuring coordination which had demonstrated group difference, these were: a combined measure of inter-limb coordination at the knee and ankle joint and a combined measure of inter-limb variability at the shoulder and elbow (these combined measures were calculated by taking an average). Error was also included as a mediator variable. For all the statistical analyses an alpha level of 0.05 was used for significance.

1.3. Results

1.3.1. Description of movement outcome

Three variables were considered in the description of the outcome of the movement; error, speed and the CV of speed. Data can be found in Table 2 and is also graphically illustrated in Figure 2 across the 20 trials. Participants with DCD showed a higher error percentage than TD participants (*F* (1,28) = 7.78, *p* = .009, η^2_p = 2.17). A significant effect of group was also found for CV of speed, *F* (1,28) = 9.13, *p* = .005, η^2_p = .25, with individuals with DCD showing a higher CV of speed. No effect of group was found for speed.

Table 2. Error, speed and CV of speed for TD and DCD groups, standard deviation is given in brackets.

	TD	**DCD**
Error (%)	7.33 (7.99)	18.67 (13.56)*
Speed (ms^{-1})	5.11 (1.81)	4.15 (2.60)
CV of speed	.77 (.14)	.95 (.18)*

* Denotes a significant group effect prior to addition of covariate

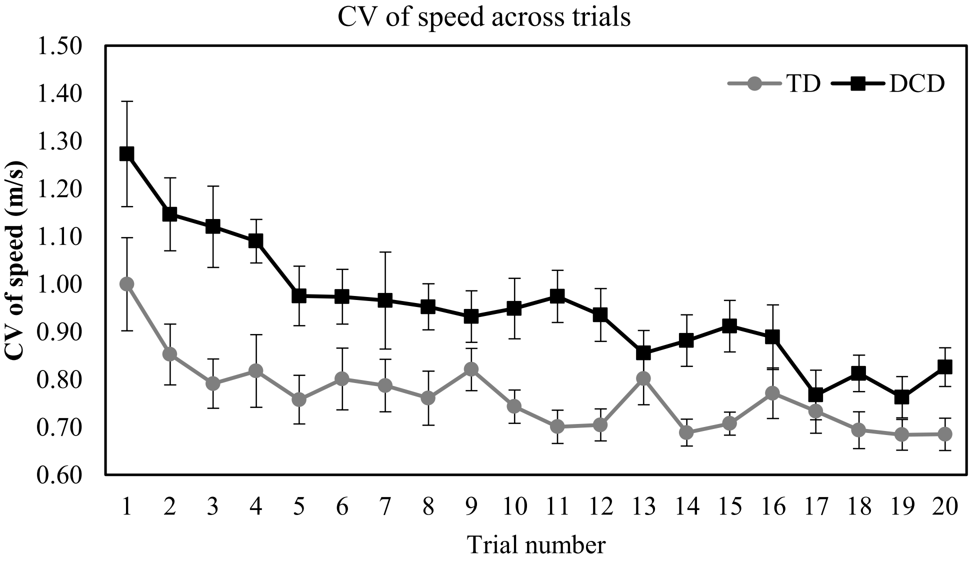

Figure 2. An illustration of CV of speed across the 20 trials for the TD group and group with DCD.

1.3.2. Description of Inter-limb coordination

Inter-correlations between left and right angles and the variability of those correlations (shoulder, elbow, hip, knee, ankle) were considered using MANOVA (group). The overall MANOVA was significant for both the correlations (*F* (5,24) = 2.80, $p = .040$, $\eta^2_p=.37$) and the variability of those correlations (*F* (5,24) = 3.69, $p = .013$). Follow up univariate tests demonstrated group differences for correlations between the knees (*F* (1,28) = 5.33, $p = .029$, $\eta^2_p=.16$) and the ankles (*F* (1,28) = 4.96, $p = .034$, $\eta^2_p=.15$), in both cases correlations were higher in the typically developing children. For variability, differences were seen for the angles at the shoulders (*F* (1,28) = 14.83, $p < .001$, $\eta^2_p=.35$) and elbows (*F* (1,28) = 10.07, $p = .004$, $\eta^2_p=.27$) only, with the TD children showing a higher level of variability compared to the children with DCD. Data regarding the correlations can be found in Table 3 and angle plots can be found in Figure 3.

Table 3. Transformed inter-limb correlations between right and left shoulder, elbow, hip, knee and ankle joint angles across TD and DCD groups, standard deviation is given in brackets.

	Average correlation		**Correlation variability**	
	TD	**DCD**	**TD**	**DCD**
Shoulders	.04 (.27)	.008 (.27)	.54 (.08)	.39 (.13)**
Elbows	-.01 (.23)	.004 (.23)	.50 (.06)	.41 (.09)*
Hips	-.33 (.26)	-.28 (.26)	.51 (.11)	.47 (.21)
Knees	-1.33 (.39)	-.98 (.43)*	.39 (.10)	.36 (.21)
Ankles	-1.08 (.25)	-.80 (.28)*	.36 (.09)	.31 (.07)

The values in this table represent correlations which have been transformed to z scores, correlations below 0.5 show very little change under this transformation while high correlations change far more. For example a Pearson's correlation coefficient of 0.2 would be transformed to 0.202, one of 0.5 would transform to 0.54, one of 0.75 would transform to 0.97 and one of 0.95 would transform to 1.83.

* Denotes a significant group effect p < .05

** Denotes a significant group effect p < .001

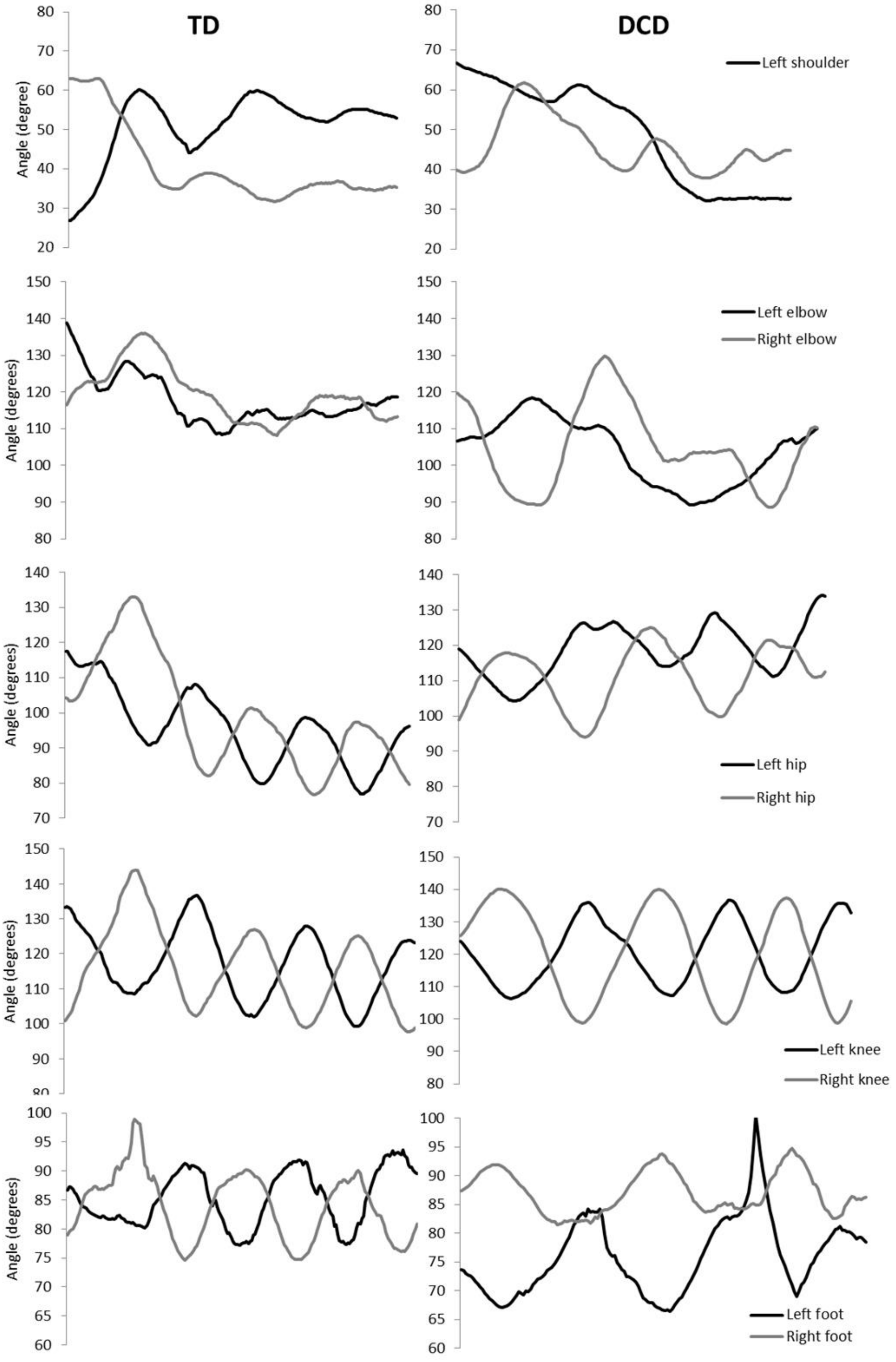

Figure 3. Angle plots for a single trial with an example from a TD participant on the left and an example from a participant with DCD on the right, shown for the shoulder, the elbow, the hip, the knee and the foot. Time elapsed within the trial is plotted along the x-axis and angle on the y axis. The left side of the body is represented by the black line and the right side by the grey line. Shown

1.3.3. Factors which mediate the relationship between group and outcome

The mediation analysis confirmed a significant predictive relationship between group and each mediator variable ($p < .05$). It also confirmed that prior to mediation there was a relationship between both group and CV of speed ($F(2,27) = 5.55$. $p = .0096$. $R^2 = .29$) which was not significant after mediation ($p > .05$). Only the combined variability of shoulder and elbow was a significant mediator between group and CV of speed with the upper and lower confidence intervals both falling below zero indicating a negative relationship (Indirect relationship: CI = -.221 -.038, $\beta = -.36$, $p = .005$). See Figure 4 for a path diagram, this illustrates the beta values for each component relationship, the only indirect relationship which was significant is indicated by bold lines.

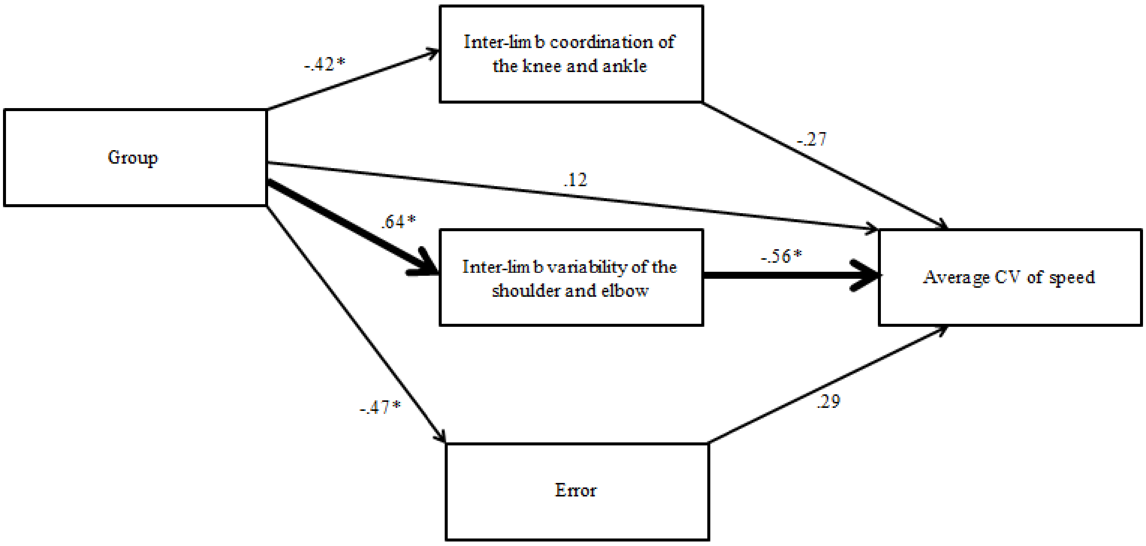

Figure 4. An illustration of the indirect and direct relationships between group and related experience and the outcome of the movement. Beta values are provided between each relationship with asterisks indicating significant relationships.

1.4. Discussion

Our study had three main aims, firstly to examine movement outcome on a novel task in children with and without DCD, secondly to examine coordination patterns for the same task and thirdly to look at factors which mediated the relationship between group and movement outcome. Each of these aims and related findings are discussed below.

Firstly, in terms of movement outcome we see differences between the groups in terms of the number of times they stepped off the pedalo (error) and the smoothness of the pedalling action (CV of speed), both of which were worse (higher error and lower smoothness) in the children with DCD compared to their typical peers. Both of these measures denote a less successful movement outcome in the children with DCD. Although many studies have shown similar findings (for example see Asmussen et al., 2014; Astill, 2007; Astill & Utley, 2006; Wade & Kazeck, 2018; Wilmut, Du, & Barnett, 2016; Wilson, Caeyenberghs, Dewey, Smits-Engelsman, & Steenbergen, 2018) in movement in individuals with DCD compared to their typical peers, this is often within the context of a task which is more practiced for the typically developing children. Therefore, this finding demonstrates clear differences between children with DCD and typically developing children which are seemingly inherent from the very start of attempting a task.

One important point to note in relation to movement outcome is that of related experience. Although this was a novel task for all participants it is clear that the typically developing group had a greater degree of experience on *related* tasks, i.e. those requiring balance. Therefore, we cannot unpick whether it is group membership or degree of related experience which is the most important factor in movement outcome. Given this relationship a limitation of the current study is that we did not have an experience related matched group which would have allowed us to start to untangle the relationship between related experience and coordination. This is a potential consideration for further research but as we discuss later it does have its difficulties.

Once we had described movement outcome we also considered inter-correlations between angles at different joints. We saw more tightly coupled body segments around the knees and ankles in the typically developing children compared to the children with DCD. These results demonstrated more loosely coupled inter-limb coordination between left and right side of the lower body (knees and ankles) in the children with DCD. In contrast, a greater degree of inter-limb coupling in terms of spatial (Astill & Utley, 2006; Przysucha & Maraj, 2013, 2014) and temporal aspects (Astill & Utley, 2006) of the limb is usually seen between the wrists, elbow and shoulders in children with DCD in catching tasks. The differences here could simply relate to the nature of the task; the task in the current study, like walking is a cyclical tasks where the movement of one lower limb is connected to movement of the other, while a ball catching task is a discrete task and so looser coupling of the target limbs may be very much more appropriate. Previous studies which have modelled pedalo task performance in typical adults have shown that skill mastery is defined by a single unit of movement, i.e. high correlations between all body segments Chen, Liu, Mayer-Kress, & Newell, 2005; Haken, 1996). Although the children in the current study were a long way from skill mastery, we can see clear differences here between the children with DCD and their typically developing peers during the initial stages of task familiarisation (as demonstrated in Figure 2).

An important point to note regarding the inter-limb correlations is that both groups showed much higher cross-correlations for the lower compared to the upper joints. In fact the inter-correlations for the shoulders, elbows and hips were below 0.5 for both groups, while they were much higher for the knees and ankles. This is clearly illustrated in the angle plots in Figure 3. Essentially this may be a consequence of the task given that the pedals were yoked together (as one pedal moved down the other moved up) and so there may have been an expectation that in order to move the pedalo that the left and right ankle, knee and hip joint movements would also be yoked and would thus show a correlated movement. In contrast the shoulder and elbow joints were not influenced by the pedals.

In addition to the coordination differences we have also demonstrated a greater variability of inter-limb coordination in the typically developing children at the shoulders and elbows. This may be counterintuitive, as research often shows that children with DCD are more variable (Astill, 2007; de, Hiraga, & Pellegrini, 2014; Goleni et al., 2018; Mackenzie et al., 2008; Przysucha & Maraj, 2013, 2014; Roche et al., 2011; Volman & Geuze, 1998a, 1998b; Volman et al., 2006; Whitall et al., 2008 ; Whitall et al., 2006). However, research focusing on walking has highlighted that variability plays a functional role in motor control and is an indication of flexibility and adaptation. In particular they demonstrated reduced variability in patients with Parkinson’s Disease compared to their healthy counterparts which relates to the movement coordination and transition problems in these individuals (van Emmerik, & van Wegen, 2000). These findings mimic what we have seen here in our participants with DCD. Furthermore, the current task was novel to all of our participants. In infants starting to walk (i.e. adopting a novel task) research has shown that although newly walking infants display a similar inter-limb coordination to adults, the variability of this inter-limb coordination is initially high and then decreases and becomes more stable after a few months (Clark, Whitall, & Philips, 1988). It is thought that this high variability may reflect an initial exploration of the possible solutions that enable successful completion of the motor task. Following practice/experience fewer motor solutions (coordinative structures) are needed. This is further supported by the finding that variability decreases with initial practice and then further with short term practice for adults when learning a novel movement (Beerse, Bigelow, & Barrios, 2020). In the current context, the lower variability seen in the children with DCD may be indicative of fewer coordinative structures being explored as solutions to the task at hand during this initial phase of task familiarisation.

Interestingly the group findings in relation to inter-limb coordination were not influenced by previous related experience in the same way as the outcome measures. This may simply support the notion that there are many movement solutions to a single task (Bernstein, 1967) and that the key to learning is to explore the many different movement solutions. The group difference in inter-limb coordination may be a direct consequence of the novel aspect of the task. When coordinating limbs it may be that there is little to be drawn from related tasks, so previous experience is less important than it is for movement outcome. We further explored the relationships between group and movement outcome using mediation analysis. Interestingly although the group difference in performance (as measured by CV of speed) could be explained by their differences in the inter-limb coordination of the knee and ankle *and* the inter-limb variability of the shoulder and elbow it was only the latter of these which mediated the relationship between group and movement outcome. This suggests that although the inter-limb correlations at the knee and the ankle can separate the two groups this is not key in the movement outcome (CV of speed). The importance of high inter-limb variability has been shown to be important in the optimisation of motor control, especially in the early stages of skill acquisition (for example see Black, Smith, Wu, & Ulrich, 2007; Wu, McKay, & Angulo-Barroso, 2009). When considering all factors we see that the variability in the inter-limb coordination of the elbows predicted movement outcome. Specifically, the greater the variability of inter-limb coordination across the right and left elbow the smoother the pedalling movement. This negative relationship tells us that this is not simply a relationship driven by similar levels of variability. Our findings reflect those from typical adult populations which demonstrate that when the goal of motor control is to maintain a steady balance, skilled adults will often use excessive upper limb movements in order to keep balance and compensate for unwanted lower limb movements, in particular in less familiar situations (Hurt, Rosenblatt, & Grabiner, 2011). This supports the notion that a high coordinative variability may be needed for optimal motor control. Our findings suggest that variability of movement around the shoulder and elbow joint contributes to the movement outcome. It is this variability which is more important in movement outcome than previous related experience or group membership.

There are a couple of limitations to the study which need to be considered with regards to the interpretation of the findings. The first is around the finding that inter-limb variability in the shoulder and elbow mediated the relationship between group membership and movement outcome. Group membership is a dichotomous variable and as such may preclude relationships which we may otherwise find if we used a continuous variable of motor competence. A final limitation is that since many different coordination patterns can achieve the same motor outcome it is difficult to determine whether those patterns seen in children with DCD should be viewed as deficient and the reason that they sometimes fail to perform a task well (i.e. step off the pedalo) or whether they are functional compensations to movement difficulties. As such it is difficult in this study to determine whether the differences in coordination lead to a greater number of errors or whether they are simply a different way to master the redundancy of the system.

In terms of implications our study has re-highlighted the importance of considering variability of movement in context and previous assertions that movement variability always denotes poor motor control is an unhelpful way to consider coordination in children and adults with DCD. Our study demonstrates the functionality of movement variability in terms of the variability in the coupling of the shoulder and the elbow. Linked to this, our study also once again highlights the importance of exploring movement options during skill acquisition and those children who did this more (demonstrated by a high variability of inter-limb coordination) demonstrated a better movement outcome (demonstrated by the smoothness of movement). This supports the building blocks that intervention programmes such as CO-OP (Cognitive Orientation to daily Occupational Performance; Polatajko & Mandich, 2004) are built upon; which promotes self-exploration to enhance motor learning.

1.4.2 Conclusion

In conclusion, our findings demonstrate clear differences in the coordination patterns of children with and without DCD and these primarily relate to less coupling of body segments and less inter-limb variability. These differences in inter-limb variability seem to impact directly on the quality of the movement outcome. Therefore, it would seem that the slower and less optimal movement generally reported in children with DCD may be due to a less efficient or less rigorous exploration of possible movement solutions.

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