Level walking in adults with and without Developmental Coordination Disorder: an analysis of movement variability

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1. Introduction

Developmental Coordination Disorder (DCD) is characterized by difficulties in the execution and coordination of body movements which cannot be accounted for in terms of an intellectual impairment or identifiable physical or neurological disorder (APA., 2013). Children with DCD display difficulties with fine and/or gross body movements such as handwriting, doing up shoelaces, participating in ball sports and riding a bicycle. Studies have demonstrated persistence of the condition, with a majority of individuals continuing to show motor difficulties throughout adolescence and into adulthood (Kirby, Edwards, & Sugden, 2011). These include frequent tripping and bumping into things, which have a negative impact on everyday life, including playing sports and moving in the environment (Kirby, et al., 2011). Despite the evidence to suggest that DCD is a life-long condition, there is a paucity of research exploring the movement patterns of basic skills, such as walking, in adults with DCD. The only study on motor difficulties in adults with DCD to have reported relevant data on this was conducted by Cousins and Smyth (2003). They tested 19 adults with DCD, and found that they were slower and made more errors when walking backwards on a line and were slower than controls in avoiding obstacles. However no further details of walking performance were reported.

Walking has been examined in children with DCD and is anecdotally reported to be poorly executed in these children (Gillberg & Kadesjö, 2003). Woodruff et al. (2002) devised a one-dimensional measure of gait which combined the typical foot placement measures that describe gait (step length, step width, double support time, etc.). This classified six out of seven children with DCD as having an 'abnormal' pattern. However, this does not pinpoint the exact nature of the problem and combining variables in this way may statistically increase small differences. Deconinck et al. (2006) examined the same foot placement measures in children with DCD while walking on a treadmill and found that children with DCD took shorter steps and walked at a higher frequency than their peers. They concluded that these children adapt their walking pattern to compensate for difficulty with balance control. However, these findings could be an artifact of treadmill walking, which forces a consistent and possibly artificial walking speed. Two further studies have considered gait patterns of children with DCD while walking on level ground, both of which reported no quantitative differences between DCD and typically developing (TD) groups in terms of walking speed, cadence, stride length, step width or percentage of time in double support (Cherng, Liang, Chen, & Chen, 2009; Deconinck, Savelsbergh, De Clercq, & Lenoir, 2010).

To date, therefore, our understanding of the walking pattern of children and adults with DCD is limited. In contrast, there has been considerable research on gait in the ageing population in an attempt to better understand what underlies the increased incidence of falls in older adults. In addition to foot placement variables, studies on older adults have investigated the coordination of whole body motion during normal walking (Marigold & Patla, 2007; Mazzà, Iosa, Pecoraro, & Cappozzo, 2008; Menz, Stephen, & Fitzpatrick, 2003; Woledge, Birtles, & Newham, 2005). These studies have indicated that the reduced walking stability of older adults seems to be reflected by a different acceleration pattern of various segments of the body. The position, velocity and acceleration of the centre of mass (CoM) of the whole body are also crucially important for body balance when walking (Hof, Gazendam, & Sinke, 2005). Hernández, Silder, Heiderscheit, & Thelen (2009) examined velocity and acceleration of the estimated CoM, in younger and older adults. They found that despite walking at a similar speed to younger adults, older adults showed a significant reduction in the medio-lateral CoM acceleration during double support that was not coupled to changes in anterior-posterior and vertical CoM acceleration. This may be due to decreased ankle power output, and an associated loss of control of medio-lateral stability (Hernández, et al., 2009). Other studies on older adults have considered the variability of movement during walking, i.e. how consistently a participant can control their movements, with increased variability being a sign of impaired motor control (Moe-Nilssen & Helbostad, 2005). In these cases variability is measured by determining the standard deviation across the steps of an individual participant. Increased variability of step length and time in double support have been found to be associated with an increased risk of falling in elderly participants (Maki, 1997). It has also been reported that elderly walkers show a significantly higher step length variability and step width variability compared to younger walkers (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005; Hausdorff, Rios, & Edelberg, 2001; Menz, et al., 2003; Woledge, et al., 2005). This suggests that the increased variability could be related to a reduced ability to maintain upright stability. Moreover, the variability of acceleration at the pelvis has been considered as an indicator of poor balance control during gait (Menz, et al., 2003), with medial-lateral acceleration of the trunk found to be increased in older adults (Marigold & Patla, 2007; Woledge, et al., 2005). These studies on the older population demonstrate the importance of looking beyond traditional measures of foot placement, and it may be that these measures will better describe the ‘atypical’ walking patterns that are reported for individuals with DCD.

The aims of the current study were, firstly to consider the walking pattern of adults with DCD using similar foot placement measures to those previously used in children with DCD (Cherng, et al., 2009; Deconinck, et al., 2006; Deconinck, et al., 2010); and secondly to examine velocity and acceleration of the body and measures of movement variability which have previously been considered in older adults but not in work on DCD. Given the previous research with children with DCD we would not expect any overt differences in foot placement measures on level-ground walking. However, given that these adults show differences in measures of dynamic balance and obstacle avoidance (Cousins & Smyth, 2003), we would expect some movement differences and this may be apparent in the measures of velocity and acceleration of the body and variability of the measures.

2. Methods

2.1. Participants

Fifteen adults with DCD, 6 female and 9 male (mean age 25.3 years) and 15 gender and age-matched typically developing (TD) adults (mean age=25.4 years) were recruited to take part in the study. Adults with DCD were recruited from two sources: (1) from a group known to the authors since having a diagnosis of DCD in childhood and; (2) from workshops run for a local support group for individuals with coordination difficulties. We followed the most recent UK guidelines for the assessment of adults with DCD (Barnett, Hill, Kirby, & Sugden, 2014), which are based on the DSM-5 criteria for children (APA., 2013). A number of different assessments were used to address the four diagnostic criteria in DSM-5. Since there is no motor assessment for individuals over 16 years of age that has UK norms, we addressed Criterion A by using two assessment instruments; the test component of the Movement Assessment Battery for Children second edition (MABC-2, Henderson, Sudgen, Barnett, & Petermann, 2007), which has UK norms for individuals up to 16 years of age and the Bruininks-Oseretsky Test of Motor Proficiency, Second Edition, Brief Form (Bruininks & Bruininks, 2005), which has US norms for individuals up to 21 years. The participants with DCD all scored below the 5th percentile on the MABC-2 and below the 18th percentile on the BOT-2 Brief. The Adult Developmental Coordination Disorder Checklist (Kirby, Edwards, Sugden, & Rosenblum, 2010) and a telephone interview with the participant was used to determine that the motor impairment significantly impacted on activities of daily living (criterion B) and that the onset of these difficulties was during childhood (criterion C). In the telephone interview it was also confirmed that the difficulties were not due to a known neurological impairment or intellectual disability (criterion D).

The 15 TD participants were recruited from the local area. They were age (to within 12 months) and gender matched to each participant with DCD. None of these participants reported any movement difficulty either in childhood or adulthood, as ascertained by the self-report Adult Developmental Coordination Disorder Checklist (ADC) and a detailed telephone interview.

Given the common co-occurrence of ADHD and DCD, and the impact that inattention may have on motor skill, the Conners' Adult ADHD Rating Scales (Conners, Erhardt, & Sparrow, 1999) was used to assess ADHD symptoms. None of the DCD or TD participants scored above average on the ADHD index of the CAARS, indicating no overt attention or impulsivity difficulties.

2.2. Apparatus and procedure

A VICON Nexus 3D motion capture system with 12 cameras running at 100Hz was used to track the movement of reflective spherical markers (9.5mm in diameter) attached to the skin at six bony landmarks: the seventh cervical vertebrae, the sacral wand, the second metatarsal head on the left and right foot, and the ankle on the left and right foot.

An 11m long by 1m wide walkway made with high-density foam sports mats was constructed to provide a comfortable walking surface. Participants were instructed to walk at a comfortable pace up and down the length of the walkway for one minute. Movement data were captured during the middle 4m only in order to eliminate periods of acceleration and deceleration.

2.3. Data analysis

VICON movement data were smoothed using an optimized low-pass Woltring filter with a 12 Hz cut-off point and were then processed using tailored Matlab routines. Initially full strides were identified by classifying heel strike (HS) and toe off (TO) events, based upon the foot velocity algorithm (O'Connor, Thorpe, O'Malleya, & Vaughana, 2007). A stride consists of two steps each of which includes one TO event and one HS event. Within each 4m data capture period the maximum number of full strides were identified and isolated, each stride was then treated as an individual event (using this method allowed us to extract a mean of 42.13 strides for the adults with DCD and 42.00 strides for the TD adults). Four measures pertaining to foot placement were determined: *Step length ratio*: the anterior-posterior distance between the front ankle marker and the back toe marker at each HS, normalized by leg length (leg length was measured from the Iliac crest to the floor when participants stood straight); *Step width ratio*: the medio-lateral distance between the two ankle markers at each HS, normalized to hip width (hip width was measured between the two Iliac crests); *Stride time (s):* the time between the first TO and the last HS of each stride; *Double support (%)*: the proportion of stride time that both feet are in contact with the floor during that stride (feet are in contact with the floor between the first HS and the second TO).

The ageing studies mentioned in the introduction used a variety of different methods to determine 'body' movement; some track the movement of the body CoM (Hernández, et al., 2009), while others track the movement of the entire trunk (Marigold & Patla, 2007; Menz, et al., 2003). Studies which have primarily considered forward velocity and acceleration of body movements have usually used CoM, whereas the trunk is typically used when roll, pitch and yaw of the upper body are of interest. In this study, therefore, we report movement of the

CoM. There are a range of basic methodologies for calculating CoM motion during walking utilizing kinematic data from markers placed on the body. In this study we used one of the simplest kinematic methods, a single marker placed on the sacrum, to approximate CoM motion. This single marker method has been shown to be an effective, inexpensive, and reasonably accurate estimate in the vertical direction at slower walking speeds (Gard, Miff, & Kuo, 2004; Saini, Kerrigan, Thirunarayan, & Duff-Raffaele, 1998; Thirunarayan, Kerrigan, Rabuffetti, Croce, & Saini, 1996), as well as in the medio-lateral and frontal direction to analyze simple movement activities without trunk flexion or limb bending (Mapelli et al., 2014). For each step sacral root mean squared velocity (ms^{-1}) and acceleration (ms^{-2}) was calculated over the three axes of movement: medio-lateral (ML); anterior-posterior (AP); and vertical (V).

For both the foot placement measures and the trunk velocity and acceleration we report the average value of the measures for each participant across the trials (indicating the absolute values) and we report the standard deviation across trials for each participant (indicating variability values).

3. Results

Firstly the absolute variables were considered. Independent *t*-tests (group) were used to determine whether any group differences were present. All data can be found in Table 1. No significant differences were found between the DCD and TD group.

(insert Table 1 here)

Secondly we considered the measures of individual variability for each of the foot placement and CoM velocity and acceleration variables. These data can be found in Table 2. Once again independent-samples *t*-tests were used to look for significant group differences. In terms of foot placement measures, significant group differences were found for all of the measures of variability: step length ratio [*t*(28)=2.49, *p*=.02], step-width ratio [*t*(28)=2.74, *p*=.01], double-support [*t*(28)=4.12, *p*<.001] and stride time [*t*(28)=2.41, *p*=.03]. In each case the adults with DCD showed greater movement variability compared to the TD participants. In terms of the movement of the CoM, significant group differences were found in the individual variability of velocity in two of the three directions [anterior-posterior: *t*(28)=2.93, *p*=.007 and vertical: *t*(28)=3.12, *p*=.004], in each case the velocity was more variable for the adults with DCD compared to the TD adults. Finally, for acceleration a significant group difference was found for the vertical direction only [*t*(28)=3.47, *p*=.002], once again with the DCD group showing greater variability in acceleration.

(insert Table 2 here)

4. Discussion

The present study attempted to identify whether adults with DCD differed from typically developing peers in their gait. It was found that individuals with DCD showed similar gait patterns in terms of step length, step width, double support time and stride time. Individuals with DCD also showed similar velocity and acceleration of the CoM in all directions compared to their TD peers. However, individuals with DCD exhibited greater variability in both foot placement and CoM velocity and acceleration measures.

The lack of group differences in all of the absolute foot placement measures is consistent with earlier findings from children with DCD during level-ground walking (Cherng, et al., 2009; Deconinck, et al., 2010). The finding also suggests that the group difference between children with DCD and their peers while walking on a treadmill (Deconinck, et al., 2006) may be an artifact of the task demands. Walking on a treadmill may force a consistent and possibly artificial walking speed rather than be indicative of any differences apparent in natural level-ground walking. To confirm this additional studies considering level-ground walking in children with DCD are needed. In addition, the current study showed no differences in the CoM velocity and acceleration measures across the two groups. This is in contrast to the change seen in older adults whereby medio-lateral movements and acceleration of the body increase in older compared to younger adults (Hernández, et al., 2009; Maki, 1997; Woledge, et al., 2005). This suggests that atypical pattern of gait in adults with DCD does not reflect the gait of a typical ageing population.

Despite the lack of differences in the absolute measures described above, the current study found clear group differences in measures of variability of movement. This includes group differences in all of the foot placement variability measures (step length ratio variability, step width ratio variability, double support time variability and stride time variability) and some of the CoM velocity and acceleration variability measures (variability of velocity in the anterior-posterior direction and the vertical direction, and variability of acceleration in the vertical direction). In all cases the adults with DCD showed a higher variability than their controls. There is evidence that greater walking variability may be due to a slower walking speed (England & Granata, 2007). However, with our data, there was no significant difference between the velocity of the two groups, which suggests the greater variability in DCD participants could not be attributed to slower walking speed.

The results from this study support more general findings within this population that individuals with DCD exhibit a greater variability during walking tasks. Rosengren et al. (2009) reported that children with DCD exhibit greater overall variability in the pattern of both shank and thigh movements than TD children, suggesting that children with DCD have more difficulty controlling their lower limbs as they walk. Furthermore, in a recent study we have shown that, compared to age-matched controls, adults with DCD show a greater variability in lateral trunk movement as they walk towards and pass through an aperture (Wilmut, Du, & Barnett, 2015).

Studies on the ageing population have demonstrated that movement variability is higher in elderly adults compared to young adults. For example, studies found that step length variability and step width variability was elevated in an older population (Hausdorff, et al., 2001; Menz, et al., 2003; Woledge, et al., 2005), and this has been identified as an indicator of fall risk in older adults (Maki, 1997). Furthermore, other studies have shown that the variability of body acceleration is different in older compared to young adults, with increased medio-lateral movement in older adults (Marigold & Patla, 2007; Woledge, et al., 2005). These differences have been linked to reduced postural stability in older adults, leading to an inconsistency in foot placement. The nature of variability of movement seen in our adults with DCD is not the same as that previously demonstrated in an elderly population suggesting that the underlying mechanisms are not the same. It has been suggested that medio-lateral movements during walking relies on the central motor control system which integrates information from visual, vestibular and proprioceptive systems; whereas anterior-posterior movements during walking relies more on lower-level reflex actions generated in the spinal cord (Bauby & Kuo, 2000; O'Connor & Kuo, 2009). It is suggested that this is because the medio-lateral direction is orthogonal to the moving direction and so forces such as inertia and momentum have little influence and so there is a greater dependence on active control for foot placement (Bauby & Kuo, 2000). Based on the analysis of medio-lateral compared to anterior-posterior control which is detailed above it may be that adults with DCD have a well-functioning central motor control system (no differences in variability in the medial-lateral direction) but a atypically functioning lower level motor-control system (increased variability in the anterior-posterior and vertical direction). Further studies more directly considering this hypothesis are needed.

Our study is the first to investigate the movement of CoM and movement variability in individuals with DCD. Our results suggest that greater variability of movement while walking may explain the anecdotal reports of poor gait control in individuals with DCD and tripping and bumping into things reported by adults.

This provides a possible starting point for future research, to investigate postural stability and control in adults with DCD in more detail. For example, with a more accurate estimate of CoM(Hof, et al., 2005), the relationship between movement of CoM and the base of support in DCD could be examined, which could reveal more details of the higher variability on anterior-posterior and vertical movements as shown by adults with DCD in the current study. We see from research on children with DCD that they show difficulties with postural control (Geuze, 2005) which has previously been used as an explanation for their differing walking pattern (Deconinck, et al., 2006). This would sit well with the idea that a reduced postural stability may influence the variability of walking as suggested in the ageing literature. This deficit in postural control and different walking patterns may be explained by some of the neuromuscular deficits seen in children with DCD, such as problems of muscle strength and power, and increased co-activation of muscle groups during knee flexion tasks (Raynor, 2001). Other work examining limb control has reported that children with DCD are more variable than TD peers in the timing and force of muscle contractions, both in rhythmic and discrete tasks (Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Piek & Skinner, 1999). Children with DCD have also been found to demonstrate altered activity in shoulder muscles, anterior and posterior trunk muscles (Johnston, Burns, Brauer, & Richardson, 2002; Kanea & Bardena, 2012), which suggest altered postural muscle activity may contribute to poor trunk stability and movement control. Our findings suggest that those neuromuscular problems may persist into adulthood and lead to the differences in variability of foot placement and body velocity and acceleration as reported.

In conclusion, our results have confirmed that difficulties in movement control persist into adulthood, and that adults with DCD demonstrate an increased variability of movement while walking compared to peers. Previous research has suggested that adults may develop compensatory mechanisms for dealing with their coordination impairments in simple motor tasks (Kirby, et al., 2011). However our results indicate that adults with DCD show a different movement pattern in basic motor activities such as level walking, and their greater variability and inconsistent movement may contribute to the difficulties they experience in daily life.

Acknowledgements

This research was supported by an ESRC grant awarded to Wilmut and Barnett (ES/J02015X/1).

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Table 1. Table showing the absolute measures of foot placement and trunk movement for the DCD and TD groups. Standard deviation is given in brackets.

	DCD	**TD**
Measures of foot placement		
Step length ratio	0.56(0.07)	0.55(0.05)
Step width ratio	0.56(0.08)	0.59(0.09)
Double support (%)	13.09(1.64)	13.56(2.16)
Stride time (s)	0.93(0.06)	0.89(0.06)
Measures of trunk movement		
ML velocity (ms^{-1})	0.13 (0.04)	0.11 (0.03)
AP velocity (ms^{-1})	1.35 (0.12)	1.37 (0.17)
V velocity (ms^{-1})	0.21 (0.04)	0.19 (0.04)
ML acceleration ($ms\text{-}^{2}$)	1.51 (0.42)	1.42 (0.48)
AP acceleration ($ms\text{-}^{2}$)	1.45 (0.24)	1.55 (0.30)
V acceleration ($ms\text{-}^{2}$)	2.56 (0.52)	2.51 (0.62)

Table 2. Table showing the variability of the foot placement and trunk movement measures for the DCD and TD groups. Standard deviation is given in brackets. *p* values are given where a significant group effect was found.

	DCD	**TD**	***p* value**
Foot placement measures			
Step length ratio SD*	0.03 (0.02)	0.02 (0.01)	.02
Step width ratio SD*	0.11 (0.03)	0.09 (0.02)	.01
Double support SD (%)***	1.29 (0.2)	1.01 (0.17)	<.001

Stride time SD (s)*	0.02 (0.01)	0.01 (0.01)	.03
Trunk movement measures			
ML velocity (ms^{-1})	0.03 (0.01)	0.02 (0.01)	-
AP velocity (ms^{-1})**	0.07 (0.02)	0.05 (0.02)	.007
V velocity (ms^{-1})**	0.03 (0.01)	0.02 (0.01)	.004
ML acceleration (ms-^{2})	0.31 (0.17)	0.22 (0.09)	-
AP acceleration (ms-^{2})	0.20 (0.08)	0.21 (0.11)	-
V acceleration (ms-^{2})**	0.35 (0.12)	0.23 (0.06)	.002

*p<0.05; ** p <0.01