Gait patterns in children with Developmental Coordination Disorder

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Abstract

Previous research has shown that adults with Developmental Coordination Disorder (DCD) show increased variability of foot placement measures and movement of the centre of mass (CoM) while walking. The current study considered the gait patterns of young and older children with DCD. Fourteen young children with DCD (7-12 years), 15 older children with DCD (12-17 years) and 29 age and gender matched typically developing children took part. Children were asked to walk up and down a flat 10m long pathway for one minute while the movement of their feet and trunk was recorded using motion analysis. The gait pattern of children with DCD was characterised by wider steps, elevated variability in the time spent in double support and stride time and greater medio-lateral velocity and acceleration compared to their peers. An elevated variability in medio-lateral acceleration was also seen in the young but not the older children with DCD. In addition, the young children showed a greater variability in velocity and acceleration in all three directions compared to the older children. The data suggest that the high incidence of trips and falls seen in children with DCD may be due to differences in the control of the centre of mass.

Keywords: Developmental Coordination Disorder, Gait, Movement Variability, Centre of Mass, Children

Introduction

Walking from place to place while avoiding tripping or falling over is an essential skill needed in everyday life. However, there are some individuals who find this skill difficult. Amongst these are children with Developmental Coordination Disorder (DCD). DCD is characterised by difficulties with fine and gross motor skill in the absence of an intellectual impairment or identifiable physical/neurological disorder. The skills usually cited as problematic for this population are handwriting, doing up shoelaces, participating in team sport and riding a bicycle. A UK population based study showed a prevalence rate of approximately 2% (Lingam, Hunt, Golding, Jongmans, & Emond, 2009) while other research demonstrates that the majority of children with DCD continue to have problems with motor skill in adolescence and early adulthood (Kirby, Edwards, Sugden, & Rosenblum, 2010). Researchers and therapists working with children with DCD often comment that these children seem to have a different gait pattern from typically developing (TD) children (Gillberg, 2003). Furthermore, children with DCD are reported to be awkward in their gait, frequently stumbling and bumping into objects in their pathway (Gillberg, 2003; Parker &

Larkin, 2003). Despite this there remains a paucity of data concerning the exact nature of walking in children with DCD. What has been done is described below.

In an attempt to capture the gait patterns of children with DCD, Woodruff et al. devised a one-dimensional measure of gait which combined the usual foot placement measures into one value of gait. This measure classified six out of the seven children with DCD as having an 'abnormal' gait pattern (Woodruff, Bothwell-Myers, Tingley, & Albert, 2002). Although this study seems to capture what researchers and therapists commonly observe, it fails to identify which aspects of gait are abnormal. Subsequent studies which have tried to do this have produced mixed results. Deconinck et al. (2006a) examined the same foot placement measures in a group of 10 children with DCD while they walked on a treadmill. This study found that children with DCD walked with shorter steps and at a higher frequency compared to their peers. It was concluded that the shorter step length was due to a difficulty with balance control. However, given that a treadmill enforces a specific walking speed this difference may be an artefact of the task rather than descriptive of walking in DCD. Two further studies have considered the walking patterns of children with DCD while walking on level ground and both reported no quantitative difference between children with and without DCD (Cherng, Liang, Chen, & Chen, 2009; Deconinck, Savelsberg, De Clercq, & Lenoir, 2010). In a recent study Du, Wilmut, & Barnett (2015) found no differences between adults with and without DCD in terms of absolute measures of foot placement (step length, step width, time in double support, stride time). However, this study also considered the *variability* of these measures by determining the standard deviation across the steps for individual participants. The adults with DCD showed higher variability in normalised step length, normalised step width, double support and stride time compared to their matched controls (Du et al., 2015). Along similar lines, Rosengren et al. (2009) used elliptical Fourier analysis (EFA) to examine differences in the variability of gait in children with DCD. Generally, changes in joint angular position vs. velocity (phase portraits) represents an elliptical shape, EFA allows quantification of both complexity and variability of these phase portraits. Complexity is measured by identifying the number of harmonics needed in the Fourier series to describe the shape of the phase portrait while variability measures are based on the change in phase portrait centroid location between consecutive gait cycles. Rosengren et al. (2009) found that children with DCD exhibited larger variation in the movement patterns of the right and left lower limbs as compared to their TD peers (for more detail on EFA see Hsiao-Wecksler Polk, Rosengren, Sosnoff & Hong, 2010). Although Rosengren et al.

identified an increased variability in children with DCD, it is not clear whether it is all aspects of locomotion or just some aspects which show an increase in variability in this population. Variability of movement is commonly measured in gait research in the elderly, with increased variability commonly taken as a sign of impaired motor control (Moe-Nilssen & Helbostad, 2005). Specifically, elderly walkers tend to show a higher step length variability and step width variability compared to young walkers (Brach, Berlin, Van Swearingen, Newman, & Studenski, 2005; Menz, Stephen, & Fitzpatrick, 2003; Woledge, Birtles, & Newham, 2005). Furthermore, an increased variability in step length and time spent in double support is linked with an increased risk of falling in older adults (Maki, 1997). Other measures which have been widely used in studies of the ageing population during normal walking are velocity and acceleration of the centre of mass (CoM). With studies highlighting an increase in medio-lateral (ML) trunk movement and acceleration with increasing age along with an associated increase in variability of acceleration in the ML direction (Marigold & Patla, 2007; Woledge et al., 2005). Furthermore, similar studies have highlighted that increased variability in these measures is associated with an increased risk of falls in older adults (Maki, 1997).

O'Connor & Kuo (2009) considered control of movement during walking, their study was initially motivated by the observations that there is more ML compared to AP variability in walking (Bauby & Kuo, 2000) and that removal of visual feedback results in a larger increase in ML but not AP variability. They found that an artificial visual perturbation moving in a ML direction while walking increased ML variability (illustrated by an increase in step width variability), however, neither visual perturbations in the AP or ML direction influenced AP variability. This suggests that visual feedback is needed in the control of ML movement but not AP movement. O'Connor & Kuo (2009) concluded that walking is dynamically unstable in the ML direction and is therefore actively stabilised using sensory feedback (sensory information is used when determining foot placement). In contrast walking is passively stable (regulated by propriospinal control) in the AP direction and so little control is needed for foot placement in this direction. Supplementing this finding is an earlier study by Courtine, De Nunzio, Schmid, Beretta, & Schieppati (2007) which demonstrated that proprioceptive perturbations had very little influence on AP control while walking (despite a large influence on AP control while standing still). In terms of the findings from the ageing population the increase in ML velocity and acceleration suggests a loss of control in this direction which may be a direct result of a difficulty integrating sensory feedback.

Du et al's study (2015) which focused on adults with DCD was the first to consider such measures in this population. No differences were found in the absolute measures of velocity and acceleration of CoM. However, adults with DCD showed a higher variability in the AP velocity of CoM, the vertical velocity of CoM and the vertical acceleration of CoM compared to their peers. Du et al. (2015) concluded that adults with DCD may be able to integrate visual information well to control gait in the ML direction, but may have some difficulty in controlling gait in the AP direction due to some difficulty at the propriospinal level.

Although previous studies have shown that DCD persists into adolescence and adulthood (Kirby et al., 2010; Losse et al., 1991) the presentation of the condition changes with age. In a series of studies focusing on reach-to-grasp, adults with DCD showed a more mature pattern of movement compared to children with DCD although this was still different to the typical adult level (Wilmut & Byrne, 2014; Wilmut, Byrne, & Barnett, 2013). Therefore, it cannot be assumed that children with DCD will perform in the same way as adults with DCD. In the current study we considered gait patterns of children with DCD, how these differ from typically developing children and how they compare to the pattern of results from our previous paper which considered adults with DCD. Firstly we considered the absolute measures of foot placement variables that have previously been considered in this population. Given no group differences have been seen in these measures while walking on flat terrain we expected no group differences in the current study. We then extended these foot placement measures to consider the variability with which they are executed. In a previous study it was found that that adults with DCD exhibit higher levels of variability in these measures (Du et al., 2015), furthermore, children with DCD have been shown to exhibit higher variability in movement patterns compared to their peers (Rosengren et al., 2009). Therefore, we expected to see differences in these measures, whereby the children with DCD show an elevated variability in these foot placement measures compared to their typically developing peers. Finally, we considered the measures of trunk movement (velocity and acceleration) in the medial-lateral, anterior-posterior and vertical directions. Du et al. (2015) found that adults with DCD showed no differences in the absolute measures of these compared to their peers but that they showed an elevated variability in the velocity and acceleration of the trunk in the anterior-posterior and vertical direction(Du et al., 2015). Whether this pattern is mirrored in children with DCD remains to be seen.

This study included children aged from 7 to 17 years of age. A seminal study by Sutherland, Olshen, Cooper, & Woo (1980) describes the development of gait in typical children aged from 1-7 years and in adults. Sutherland et al. (1980) argue that there are five determinants of mature gait; duration of double-support, walking speed, cadence, stride length and step width. Of the five measures identified by Sutherland et al. (1980) the only measure that matured after 7 years of age in typically developing (TD) children was the ratio of pelvic span to step width, (typically maturing after 10 years) which is wider in children than adults. A more recent study found data which mirrored that of Sutherland's, with no maturational changes in normalised velocity, cadence, step length and step width after 5 years of age (Dusing and Thorpe, 2007). Our measures of foot placement (step length, step width, double support and stride time) directly map onto these five measures with the cadence and walking speed measures of Sutherland being represented by stride time and step length. Therefore, we would not expect to see any developmental difference in the foot placement measures for the typically developing population. To date there have been no studies on the developmental time course of the movement of the CoM while walking and so any age differences in these measures will be described.

Method

Participants

This project was approved by Oxford Brookes University Research Ethics Committee and was performed in line with the ethical standards as laid out in the 1964 Declaration of Helsinki. Twenty nine participants with DCD took part, divided into a young and an older child group: the young group (N=14) were aged between 7 years 8 months to 12 years 5 months and; the older group (N=15) were aged between 12 years 8 months to 17 years 10 months. In addition 29 age (to within 6 months) and gender matched typically developing (TD) individuals took part. Details regarding these participants can be found in Table 1. Participants with DCD were recruited from a group known to the authors from previous studies and from a local support group for individuals with DCD and their families. All participants with DCD were assessed and selected in line with the DSM-5 criteria for DCD and with recent UK guidelines (Barnett, Hill, Kirby, & Sugden, 2015). For criterion A the test component of the Movement Assessment Battery for Children second edition (MABC-2; Henderson, Sugden, & Barnett, 2007) was used to determine motor skill below the level expected for the individual's chronological age. Participants with DCD scored below the 16th percentile on this test. The MABC-2 Checklist, the Developmental Coordination Disorder

Questionnaire (DCD-Q Wilson, Kaplan, Crawford, Campbell, & Dewey, 2000) and a telephone interview with the parent were used to determine that the motor impartment significantly impacted on daily living (criterion B) and that the onset of the motor difficulty was in early childhood (criterion C). The telephone interview was also used to determine that the difficulties were not due to a known neurological impairment or intellectual disability (criterion D). Parents of the typically developing participants completed a telephone interview, the MABC-2 Checklist and DCD-Q to confirm that no movement difficulties were present.

Given the co-occurrence of motor difficulties and attention difficulties all parents completed the Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997). We focused on the inattention/hyperactivity subscale and used the classifications specified by the test. Ten of the participants with DCD had high or very high scores on this subscale compared to none of the typically developing participants. Running analyses both with and without these children with high or very high scores did not alter the outcome of the findings and so these individuals were included in the study.

INSERT TABLE 1 HERE

Apparatus and procedure

Participants completed a single walking task during which they walked bare foot on a surface made from high-density foam sports mats. Movement was tracked using a VICON Nexus 3D motion capture system with 16 cameras running at 100 Hz. Six reflective markers (9.5 mm in diameter) were attached to the skin at bony landmarks: the seventh cervical vertebrae, the sacral wand, the second metatarsal head (toe) on the left and right foot, and the lateral malleolus (ankle) of the left and right foot. Participants walked at a comfortable pace up and down an 11 m long by 1 m wide walkway for one minute. Movement data were captured during the middle 4 m of the 11 m walkway in order to eliminate periods of acceleration and deceleration. Data capture was initiated when the participant starting walking and then stopped and re-started each time the participant reached the end of the walkway; in this way we obtained one trial for each 11m length that the participant completed.

Data analysis

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 stride we classified heel strike (HS) and toe off (TO) events, based upon the foot velocity algorithm (FVA, C. M. O'Connor, Thorpe, O'Malley, & Vaughan, 2007). The FVA identifies TO and HS using peaks and troughs in the vertical velocity of the midpoint between the heel and toe marker. This method was compared against force plate data in a data set of 54 typically development children and errors in the order of ±15ms were found, furthermore, when compared to other kinematic methods the FVA was favourable (C.M. O'Connor et al., 2007). One major advantage of this method is that it requires first derivates only compared to other methods which use second derivates and therefore may include an inherent error due to higher order derivative estimation.

We analysed the maximum number of strides we had for each participant in order to maximise our dataset. This resulted in an average of 43 strides for the older children with DCD compared to 41 strides for the TD older children and 43 strides for the young children with DCD compared to 38 strides for the TD young children. No age or group effect was seen in terms of the number of strides. Four measures pertaining to foot placement were determined, these are described below and are in line with those used by Du et al. (2015): Step length ratio: the AP distance between the ankle marker of the front foot and the toe marker of the back foot at each HS, normalized by leg length. A measure between ankle and toe was taken so to remove the length of the foot as a factor given that this may have been different for the two groups; Step width ratio: the ML distance between the two ankle markers at each HS, normalized to hip width; Stride time (s): the time between subsequent HS with the same foot; Double support (%): the proportion of stride time that both feet are in contact with the floor during that stride. For each step, sacral root mean squared velocity (ms^{-1}) and acceleration (ms^{-2}) was calculated over the three axes of movement: ML; AP; and vertical (V). Due to the wide age range and hence height of our participants all velocity and acceleration measures were normalised to leg length (in line with the methods used by Hsue, Miller, & Su (2009). For the foot placement measures and the velocity and acceleration of CoM we report the average value of the measures for each participant across the trials (indicating the absolute measures) and we report the standard deviation across trials for each participant (indicating variability measures).

Results

Absolute measures

The absolute value of each variable was considered across age and group using a two-way ANOVA (age x group). Data can be found in Table 2. For the measures of foot placement an effect of group was found for normalised step width [$F(1,54)=4.47$ $p=.039$ $\eta^2=.10$], whereby the participants with DCD had a larger normalised step width compared to the TD participants. In addition, a main effect of age was found [$F(1,54)=10.42$ $p=.002$ $\eta^2=.16$] with the young children showing a higher normalised step width compared to the older children. A main effect of age was also found for stride time [$F(1,54)=36.63$ $p<.001$ $\eta^2=.40$], with the young children showing a significantly longer stride time compared to the older children. No significant group or age effects were found for the normalised step length or double support ($F<1$).

For the normalised measures of velocity and acceleration of CoM a main effect of group was found for ML velocity [$F(1,54)=5.44$ $p=.023$ $\eta^2=.09$] and acceleration [$F(1,54)=4.40$ $p=.041$ $\eta^2=.08$].The participants with DCD showed a higher normalised velocity and acceleration compared to the typically developing participants. No other significant group differences were found for the AP or V direction. Main effects of age were found for all velocity [ML $F(1,54)=33.60$ $p<.001$ $\eta^2=.38$, AP $F(1,54)=52.87$ $p<.001$ $\eta^2=.50$ and V $F(1,54)=29.39$ $p<.001$ $\eta^2=.35$] and acceleration [ML $F(1,54)=21.33$ $p<.001$ $\eta^2=.28$, AP $F(1,54)=22.26$ $p<.001$ $\eta^2=.29$ and V $F(1,54)=34.23$ $p<.001$ $\eta^2=.39$] measures. In all cases this was due to a higher velocity and acceleration in the young children compared to the older children.

No significant interactions between age and group were found for either the measures of foot placement or the measures of velocity and acceleration of CoM.

INSERT TABLE 2 HERE

Variability measures

The standard deviation (or variability measure) of each variable was compared across age and group using a two-way ANOVA (age x group). Data can be found in Table 3. For the foot placement measures an effect of group was found for double support [$F(1,54)=10.46$ $p=.002$ $\eta^2=.16$] and stride time [$F(1,54)=10.408$ $p=.002$ $\eta^2=.16$]. These effects demonstrate a higher variability in time spent in double support and a higher variability in stride time in the participants with DCD compared to the TD participants. In addition a main effect of age was

found for normalised step length variability [$F(1,54)=13.16$ $p<.001$ $\eta^2=.20$], normalised step width variability [$F(1,54)=16.52$ $p<.001$ $\eta^2=.08$], double support variability [$F(1,54)=10.77$ $p=.002$ $\eta^2=.17$] and stride time variability [$F(1,54)=7.16$ $p=.01$ $\eta^2=.12$]. The young children showed a higher variability in normalised step length, normalised step width, time spent in double support and stride time compared to the older children.

In terms of the measures of velocity and acceleration a main effect of group was found for normalised ML acceleration variability [$F(1,54)=5.41$ $p=.024$ $\eta^2=.08$].The participants with DCD showed a higher variability in the velocity and acceleration compared to the typically developing participants. A main effect of age was found for normalised velocity and acceleration variability in all three directions [Velocity: ML, $F(1,54)=66.75$ $p<.001$ $\eta^2=.35$, AP, $F(1,54)=33.50$ $p<.001$ $\eta^2=.38$, V, $F(1,54)=64.65$ $p<.001$ $\eta^2=.55$. Acceleration: ML, $F(1,54)=48.66$ $p<.001$ $\eta^2=.47$, AP, $F(1,54)=39.47$ $p<.001$ $\eta^2=.42$, V, $F(1,54)=100.51$ $p<.001$ $\eta^2=.65$]. For each of these measures this was due to a higher variability in the young children compared to the older children. In addition, an interaction was seen between group and age for normalised ML acceleration variability [$F(1,54)=4.10$ $p=.048$ $\eta^2=.07$]. Simple main effects tests indicated that this was due to a group difference for the younger children [$F(1,54)=9.34$ $p=.003$ $\eta^2=.15$] but not the older children [$F<1$].

No other significant interactions between age and group were found for either the measures of variability of foot placement or the measures of variability of velocity and acceleration of CoM.

INSERT TABLE 3 HERE

Discussion

This study considered a range of measures to examine walking in young and older children with DCD. In terms of foot placement measures the participants with DCD showed a higher normalised step width and a higher level of variability in time spent in double support and stride time compared to their peers. Previous research which has considered absolute foot placement measures in children with DCD has had mixed findings. Cherng et al. (2009) and Deconinck et al. (2010) found no differences in absolute foot placement measures when walking over a flat terrain between a group of children with DCD and age matched peers.

Using similar measures we recently found no difference between adults with DCD and age-matched controls. The increased step width found in children with DCD in the current study suggests a need for a wider base of support which in turn may suggest dynamic balance difficulties in this population. In support of this conclusion Deconinck et al. (2006a) found that children with DCD bend further forward at the waist while walking which he attributed to a need to lower the CoM due to balance difficulties. However, these difficulties were not demonstrated in terms of an increase in normalised step width in the Deconinck et al. (2006a) study which is in contrast to the current study. This difference may be due to the smaller sample size in their study (N=10) and the different task whereby the children with DCD in Deconinck's study walked on a treadmill. In addition to these differences in the absolute measures of foot placement we also saw group differences in the variability of foot placement measures. Specifically, the children with DCD in the current study showed an increase in variability of the time spent in double support and variability in stride time compared to their peers. In a study focusing on typically developing children Hausdorff, Zemany, Peng, & Goldberger (1999) found an increase in stride-to-stride variability (i.e. the difference between stride time for one stride as compared to the subsequent stride) which was higher in younger compared to older children. These findings demonstrate that the temporal structure of gait is not fully developed in 7 year-old children (Hausdorff et al. 1999). Hausdorff et al. (1999) suggested that given locomotion is a complex system the dynamics of mature locomotion may only arise when all of the interacting individual components are fully developed. They propose that components that may affect stride dynamics include biomechanical and neural properties that are known to mature at a later age. . This explanation could also hold true for children with DCD who may show an immature pattern of locomotion until all component parts have matured, a process that could simply take longer for children with DCD compared to their typically developing counterparts.

In our previous study, adults with DCD showed an elevated pattern of variability in all of the foot placement measures (normalised step length, normalised step width, double support and stride time) (Du et al., 2015). In the current study this pattern is only seen in two of the four foot placement measures. The wide-spread group difference seen in adults may only emerge once variability in the typical population decreases, i.e. the higher variability which is seen in typical children compared to typical adults may be masking this effect.

In terms of the measures of velocity and acceleration of the CoM the children with DCD exhibited a greater velocity and acceleration in the medio-lateral direction. Du et al. (2015) found no differences between the adults with DCD and their peers in terms of absolute measures. This is the first study to consider these variables in children with DCD. Research on an ageing population has shown that medio-lateral trunk movement velocity and acceleration both show an increase with increasing age (Marigold & Patla, 2007; Woledge et al., 2005). From this it may be possible to draw parallels between balance difficulties in an ageing population and in children with DCD which are demonstrated by these subtle differences in CoM movement. However, in our recent study on adults with DCD these absolute velocity and acceleration differences were not present which suggests that the adults with DCD may have adopted a more mature way of controlling their CoM which brings their behaviour in line with their peers. In terms of variability Du et al. (2015) demonstrated that adults with DCD showed a higher variability in the vertical and anterior-posterior direction for velocity and in the vertical direction for acceleration. Du et al. (2015) concluded that adults with DCD may be able to integrate visual information sufficiently in order to control gait in the ML direction, but may show a deficit in the control of gait in the AP direction due to some difficulty at the propriospinal level. This was on the basis that previous studies have suggested that medio-lateral movement during walking relies on the integration of sensory information while anterior–posterior movement relies on lower-level propriospinal actions (O'Connor & Kuo, 2009). In contrast, in the current study we have demonstrated an elevated variability in medio-lateral acceleration in children with DCD compared to their peers. These current findings are in line with what is seen in an ageing population (Marigold & Patla, 2007; Woledge et al., 2005) and would suggest a difficulty or a deficit in the integration and use of sensory information to control gait. Previous work in children with DCD has demonstrated a difficulty with the integration of multiple sources of sensory feedback (i.e. vision and proprioception) which leads to an over-reliance on visual information. For example, children with DCD show a poorer control of gait when the availability of visual information is reduced (Deconinck et al. 2006b) and show a greater postural sway when the eyes are closed compared to open (Cherng, Hsu, Chen, & Chen, 2007; Tsai, Wu, & Huang, 2007). Although it is difficult to draw parallels between these types of motor control given that clinical tests of posture do not always predict gait control (Visser, Carpenter, van der Kooij, & Bloem, 2008; Shimada, Obuchi, Kamide, Shiba, Okamoto, & Kakurai, 2003) it would seem that a common finding is that these children have some difficulty in integrating sensory information to make accurate movements. This explanation does not preclude that of

Hausdorff et al. (1999), it may simply be that the immature gait pattern seen in the children with DCD in this study is a consequence of a difficulty integrating sensory information into their control of gait and it is this component of walking which needs to be fully matured before a mature pattern of gait can be seen.

The intriguing finding here is that in the current study we have found a difficulty with control of movement in the ML direction in children with DCD while our previous study found a difficulty in the control of movement in the AP direction in adults. Using the O'Connor and Kuo explanation this would suggest a well-functioning propriospinal control in children while the use of sensory information is poor and then a relatively poor functioning propriospinal control in adults when the use of sensory information is good. Some support for the conclusion that children with DCD mature their gait pattern and reduce medio-lateral acceleration as they get older is provided by the interaction we found between group and age for variability of medio-lateral acceleration; this interaction demonstrates increased medio-lateral acceleration variability in young children with DCD compared to their peers, but not older children with DCD compared to their peers, thus a move towards a mature medio-lateral control in older children with DCD. However, this does not explain why we then see a loss of control in the AP direction in adults with DCD compared to their peers. There are two explanations for this: AP control improves in typical adults and that the development of the adults with DCD does not reflect this; or that some aspect of development in the adults with DCD leads to a loss of control in the AP direction. A full developmental trajectory of the control of movement while walking in typical individuals is needed before we can rule out the first explanation. However, in terms of the second explanation it is possible that after individuals with DCD start effectively using sensory feedback to control movement in the ML direction while walking this is then also adopted for control of movement in the AP direction, i.e. moving away from using propriospinal control. Individual trajectories of development across these age groups are needed to address these possible explanations.

In addition to the group findings outlined above we also saw age differences in both the foot placement and the CoM movement measures. The young children showed a greater normalised step width and stride time compared to the older children and they showed a greater velocity and acceleration of the CoM in all three directions compared to the older children. In previous work Sutherland et al. (1980) suggested that all aspects of gait aside

from step width ratio were fully developed by 7 years of age. However, Sutherland only measured four foot placement measures (normalised step length, normalised step width, double support and cadence). This is the first study to have considered development of the movement of the CoM and we have demonstrated development between 7-17 years of age in terms of CoM control. As suggested above it is possible that these developments in dynamic balance of typically developing children are in line with the development of static balance. Previous studies have demonstrated that younger children are less efficient in the control of static balance with adult-like balance strategies beginning to appear at around 7-8 years of age (Kirshenbaum, Riach, & Starkes, 2001) which is explained by refinement of muscle activity (Williams, Fisher, & Tritschler, 1983) and an improvement in feedback-based control of balance (Hatzitaki, Zisi, Kollias, & Kioumourtzoglou, 2002).

In addition to the age difference described above we also saw an elevated level of variability in all of the measures in the young compared to the older children. Generally, children show a greater variability of movement compared to adults in reach-to-grasp (Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002), sit-to-stand (Guarrera-Bowlby & Gentile, 2004) and gait (Hausdorff et al., 1999), this pattern is once again replicated here. As described above, Hausdorff et al. (1999) saw a higher variability in stride time variability while walking in younger children (6-7years) compared to older children (11-14years). We have found a similar result in the current study and have also replicated this with additional foot placement measures such as normalised step length, normalised step width and percentage of time in double support. In the ageing population an increase in variability has been linked to an increased risk of falls in older adults (Maki, 1997).

One possible explanation for these age differences may be the difference in gender ratio seen between the younger and the older age group. Some studies which have aimed to explore the maturational changes in gait patterns have ensured an equal gender ratio in every age group (for example see Hausdorff et al. 1999) although this is not true of them all (for example see Dusing et al. 2007). Given that the main aim of the current study was to consider gait patterns of children with and without DCD our gender ratio was driven by the availability of our clinical population and therefore is not equal across age groups. However, given that previous research has demonstrated difference in gait across adult males and adult females (Nigg, Fisher, & Ronsky, 1994) it is important for future research to exclude this as an explanation for these possible developmental differences.

In conclusion, in this study measurements of CoM movement and measures of variability have highlighted several differences in the control of gait in children with DCD compared to a typical population. Specifically we see wider steps, elevated variability in the time spent in double support and stride time and greater medio-lateral velocity and acceleration compared to their peers. Furthermore, an elevated variability in medio-lateral acceleration was also seen in the young but not the older children with DCD. In addition, the young children showed a greater variability in velocity and acceleration in all three directions compared to the older children. The data suggest that the high incidence of trips and falls seen in children with DCD may be due to differences in the control of the centre of mass which may be due to a difficulty with the integration of sensory information for the control of gait.

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Table 1. Descriptive information for the four cohorts.

	Older children		Young children	
	TD	DCD	TD	DCD
N	15	15	14	14
Mean age (yrs:mo)	14:7	14:11	9:3	9:3
Gender ratio (F:M)	1:3	1:3	1:6	1:6
MABC-2 test mean percentile	-	2.55	-	3.71
MABC-2 test percentile range	-	0.1 – 5	-	0.5 – 9
MABC-2 checklist number of children score in lowest range	3	15	0	13
DCD-Q total score	70.2	33.1	65.5	34.6

Table 2. Absolute values for foot placement measures and velocity and acceleration of CoM. Standard deviation is given in brackets.

	Older children		Young children		Sig.		
	TD	DCD	TD	DCD	Group	Age	Group x age
Measures of foot placement							
Normalised step length	0.60 (0.11)	0.54 (0.10)	0.64 (0.08)	0.60 (0.10)	ns	ns	ns
Normalised step width	0.55 (0.11)	0.64 (0.09)	0.67 (0.07)	0.70 (0.09)	p=.039	p=.002	ns
Double support (%)	12.2 (1.24)	12.3 (1.61)	12.1 (1.33)	11.8 (1.14)	ns	ns	ns
Stride time (s)	0.91 (0.04)	0.90 (0.05)	0.81 (0.05)	0.74 (0.15)	ns	p<.001	ns
Measures of velocity and acceleration of CoM (all normalised)							
ML velocity	0.099 (0.02)	0.118 (0.03)	0.163 (0.02)	0.203 (0.09)	p=.023	p<.001	ns
AP velocity	1.380 (0.15)	1.342 (0.20)	1.998 (0.19)	2.345 (0.81)	ns	p<.001	ns
V velocity	0.206 (0.05)	0.196 (0.06)	0.306 (0.08)	0.351 (0.14)	ns	p<.001	ns
ML acceleration	1.427 (0.39)	1.595 (0.46)	2.259 (0.48)	3.195 (1.89)	p=.041	p<.001	ns
AP acceleration	1.521 (0.28)	1.495 (0.19)	2.559 (0.39)	3.728 (2.64)	ns	p<.001	ns
V acceleration	2.643 (0.62)	2.412 (0.77)	4.380 (1.16)	5.473 (2.78)	ns	p<.001	ns

Table 3. Variability values for foot placement measures and velocity and acceleration of CoM. Standard deviation is given in brackets.

	Older children		Young children		Sig		
	TD	DCD	TD	DCD	Group	Age	Group x Age
Measures of foot placement							
Normalised step length	0.03 (0.01)	0.03 (0.02)	0.05 (0.03)	0.05 (0.01)	ns	p=.001	ns
Normalised step width	0.11 (0.03)	0.13 (0.04)	0.16 (0.03)	0.18 (0.06)	ns	p=.041	ns
Double support (%)	1.14 (0.23)	1.43 (0.17)	1.43 (0.49)	1.70 (0.34)	p=.002	p=.002	ns
Stride time (s)	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)	0.03 (0.02)	p=.002	p=.01	ns
Measures of velocity and acceleration of CoM (all normalised)							
ML velocity	0.023 (0.01)	0.030 (0.01)	0.059 (0.01)	0.070 (0.03)	ns	p<.001	ns
AP velocity	0.057 (0.02)	0.067 (0.03)	0.142 (0.10)	0.187 (0.08)	ns	p<.001	ns
V velocity	0.021 (0.01)	0.025 (0.01)	0.054 (0.02)	0.064 (0.03)	ns	p<.001	ns
ML acceleration	0.276 (0.10)	0.295 (0.08)	0.545 (0.19)	0.784 (0.36)	p=.021	p<.001	p<.05
AP acceleration	0.217 (0.08)	0.233 (0.11)	0.497 (0.21)	0.642 (0.34)	ns	p<.001	ns
V acceleration	0.309 (0.10)	0.339 (0.12)	0.786 (0.30)	0.947 (0.24)	ns	p<.001	ns