Altered postural control strategies and sensory organization in children with developmental coordination disorder

Shirley S.M. Fong, William W.N. Tsang*, Gabriel Y.F. Ng
Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong

*Correspondence to**:**
William W.N. Tsang, PT, PhD
Department of Rehabilitation Sciences
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
Tel: (852) 27666717
Fax: (852) 23308656
Email: william.tsang@inet.polyu.edu.hk

Abstract

The postural control of children with and without developmental coordination disorder (DCD) was compared under conditions of reduced or conflicting sensory input. Twenty-two children with DCD (16 males, 6 females; mean age 7 years 6 months, SD 1 year 5 months) and 19 children with normal motor development were tested (13 males, 6 females; mean age 6 years 11 months, SD 1 year 1 month). Standing balance, sensory organization and motor control strategy were evaluated using the sensory organization test (SOT). The results reveal that children with DCD had lower composite equilibrium scores ($p < 0.001$), visual ratios ($p = 0.005$) and vestibular ratios ($p = 0.002$) than normal children in the control group. No significant between-group difference in their average somatosensory ratio was observed. Additionally, children with DCD had lower motor strategy scores (swayed more on their hips) than the normal children when forced to depend on vestibular cues alone to balance ($p < 0.05$). We conclude that children with DCD had deficits in standing balance control in conditions that included reduced or conflicting sensory signals. The visual and vestibular systems tended to be more involved in contributing to the balance deficits than the somatosensory system. Moreover, children with DCD tended to use hip strategy excessively when forced to rely primarily on vestibular signals to maintain postural stability.

Key words: Balance deficits, clumsy children, sensory organization, movement strategy

1. Introduction

Developmental coordination disorder (DCD) is a fairly common disorder, affecting approximately 6% of children of primary school age (APA, 2000). Common symptoms include marked delays in achieving motor milestones, clumsiness, poor balance, poor coordination and poor handwriting (APA, 2000; Cermak & Larkin, 2002). These motor impairments significantly interfere with the child’s academic achievements and activities of daily living and cannot be explained by any other medical or intellectual condition (APA, 2000). Previous studies have reported that 73% to 87% of children with DCD have balance problems (Macnab, Miller, & Polatajko, 2001). Their suboptimal balance is important and needs to be tackled, because any impairment in postural control may limit the children’s activity and participation, increase the risk of falling and injury, and affect their motor skills development (Fong, Lee, & Pang, 2011a; Grove & Lazarus, 2007).

Postural control requires the ability to integrate inputs from the somatosensory, visual and vestibular systems and to utilize the integrated sensory signals in generating coordinated motor actions to maintain body equilibrium (Nashner, 1997). A few studies have examined sensory organization for balance control in children with DCD but the results have been inconsistent (Cherng, Hsu, Chen, & Chen, 2007; Grove & Lazarus, 2007; Inder & Sullivan, 2005; Przysucha & Taylor, 2004). For example, Inder & Sullivan (2005) first reported wide-spread impairment in sensory organization in four children with DCD using computerized platform posturography. Their somatosensory, visual and vestibular ratios were all below the norm. Grove and Lazarus (2007) replicated Inder & Sullivan’s testing methods with a larger sample (16 and 14 children in the DCD and control groups, respectively) and found that the ability to utilize vestibular information for balance was ineffective (significantly lower vestibular ratio) in children with DCD. Somatosensory and visual inputs were therefore weighted more heavily in postural control. Later, Cherng’s group used the modified Clinical Test of Sensory Interaction and Balance and found that there was no difference in the three sensory ratios between children with and without DCD (Cherng et al., 2007). So the sensory organization deficits that contribute to the balance problems of children with DCD remain elusive. Moreover, these findings only reflect their postural performance of the DCD participants with co-morbidities such as attention deficit hyperactivity disorder (ADHD). Since co-morbidities may significantly influence the nature and severity of sensorimotor deficits (Pitcher, Piek, & Barrett, 2002; Shum & Pang, 2009), it is important to use a relatively homogenous group of children when studying DCD.

Postural stability not only requires reliable sensory information, but also appropriate motor responses to position the center of gravity (COG) within the base of support (BOS) (Cherng et al., 2007). The motor responses can be coordinated into hip and ankle strategies which maintain anteroposterior (AP) stability in fixed stance (Cherng et al., 2007; Nashner, 1997). The ankle strategy shifts the centre of gravity while maintaining foot placement by rotating the body as an approximately rigid mass about the ankle joint. It appears to be used most commonly when the external perturbation is small and the support surface is firm (Horak & Macpherson, 1996; Nashner, 1997). Hip strategies involve postural movements centered about the hip joints with opposing ankle joint rotations. The COG shifts in the direction opposite to the hip joint because of the inertia of the trunk, generating an opposite horizontal shear reaction force against the support surface. Hip strategies are commonly used to restore equilibrium in response to larger and faster perturbations, or when the support surface is compliant or shorter than the feet (Horak & Macpherson, 1996; Nashner, 1997). Normal individuals typically use combinations of these two strategies to maintain standing balance when the feet are stabilized (Horak & Macpherson, 1996; Nashner, 1997; Shumway-Cook & Woollacott, 2007).

In children with DCD it is well known that motor control strategies for regulating muscle activity are less uniform and consistent than in children following the normal developmental milestones (Williams, 2002; Huh, Williams, & Burke, 1998). For example, Johnston, Burns, Brauer and Richardson (2002) reported that the timing and pattern of postural muscle activation used to maintain posture were altered during goal directed reaching in children with DCD. This echoes Williams (2002), who reported that the normal distal-to-proximal muscle activation sequence in perturbed standing was substituted by a proximal-to-distal pattern of activation. Moreover, Geuze (2003) found that children with DCD and balance problems showed more co-activation of the leg muscles when standing on their non-preferred leg. All these neuromuscular deficits may affect the motor strategies such children use for postural control. However, no study has investigated their motor control strategies, including their hip and ankle strategies, in detail. Studying the motor strategies used for balance is important from a diagnostic perspective because any change in body posture will alter the type of sensory feedback available and will thus further influence postural stability (e.g., changing the head position during postural corrections may alter the visual and vestibular feedbacks for balance control) (Black, Shupert, Horak, & Nashner, 1988; Horak, Nashner, & Diener, 1990).

The objectives of the present study were (1) to compare the standing balance ability of children with and without DCD, (2) to investigate the postural sway when children rely on somatosensory, visual and vestibular inputs, and (3) to compare the motor control strategies used by children with and without DCD.

2. Methods

2.1 Participants

Twenty-two children with DCD but with no indications of autistic disorder or ADHD were recruited from a local child assessment centre which provides assessment service for children. A formal diagnosis of DCD was made by an interdisciplinary team according to the DCD criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR) (APA, 2000). To warrant a diagnosis of DCD the child had to demonstrate motor coordination substantially below normal for their age (i.e. a gross motor composite score <42 as measured by the Bruininks-Oseretsky Test of Motor Proficiency) (Bruininks, 1978) which interfered with the child's activities of daily living and academic performance. Each child also underwent a neurological screening performed by a paediatrician to rule out other causes of motor deficits. In addition, each child was required to have normal intelligence (Shum & Pang, 2009; Hung & Pang, 2010).

Children who had recently been diagnosed with DCD were then screened by the primary investigator to determine whether the following criteria were fulfilled: (1) aged between six and nine years, and (2) studying in a regular education framework without demonstrating significant physical or psychosocial disability. Children were excluded if they had any of the following: (1) a history of any neurological condition; (2) any other movement disorder; (3) a vision, hearing or vestibular function deficit: (4) a formal diagnosis of autistic disorder or ADHD; or (4) significant musculoskeletal or cardiopulmonary conditions that might influence balance performance.

Nineteen children with normal development were recruited from the community as control participants. They had to fulfill the same inclusion and exclusion criteria set for the DCD group, except that they had no history of DCD.

2.2 Procedures and measures

Ethical approval was obtained from the human subjects ethics review subcommittee of the Hong Kong Polytechnic University. The study was explained to each child and at least one parent, and written informed consent was obtained from the parent. A medical history and information on exercise habits were obtained by interviewing the parent and child. Each child's physical activity level was estimated by asking the parents about the type of extracurricular physical activity that the child had most actively engaged in during a typical week within the past year. This factor was considered because previous research has shown that physical training can improve motor skills in children with DCD (Hung & Pang, 2010). The physical activity level, in metabolic equivalent (MET) hours per week, was calculated based on the exercise intensity, duration, frequency and the assigned MET value of the activity according to the Compendium of Energy Expenditures for Youth (Ridley, Ainsworth, & Olds, 2008).

All of the data was collected by an experienced paediatric physical therapist. The procedures were conducted in accordance with the Declaration of Helsinki. Postural sway was assessed in bipedal stance under normal, reduced or conflicting sensory conditions using the sensory organization test (SOT) (NeuroCom, 2008). The SOT is commonly used to evaluate a participant's ability to make effective use of somatosensory, visual and vestibular inputs and filter out inappropriate sensory information in maintaining balance. It also provides information on the degree of ankle and hip movement under different sensory conditions (NeuroCom, 2008; Nashner, 1997). The results with children have been found to be reliable and valid (Di Fabio & Foundriat, 1996; Fong, Fu, & Ng, 2011b).

During the test, the child stood barefoot on the platform of a computerized dynamic posturography machine (Smart Equitest, NeuroCom International Inc., Clackamas OR, USA) and wore a security harness to prevent falling. Each participant was instructed to stand quietly with both arms resting by the sides of the trunk and eyes looking forward. The child was then exposed to six different combinations of visual and support surface conditions in sequence according to the protocol suggested by the manufacturer of the posturograph (NeuroCom, 2008). Condition 1 was designed to provide accurate somatosensory, visual and vestibular inputs; conditions 2 and 3 provided only accurate somatosensory and vestibular inputs. In these three conditions, the child stood on a fixed platform first with their eyes open, then with their eyes closed, and then with their eyes open in a sway-referenced visual surround. In conditions 4 (provided accurate visual and vestibular inputs), 5 and 6 (provided accurate vestibular input only), the child stood on a sway-referenced platform under the same three visual conditions (Table 1). Sway-referencing involved tilting the support surface and/or the visual surround about an axis co-linear with the ankle joints to directly follow the AP sway of the child's centre of gravity (NeuroCom, 2008). Each participant was tested three times in each condition.

The machine captured the trajectory of the center of pressure (COP) on the platform, which was then used to calculate an equilibrium score (ES) defined as the non-dimensional percentage that compared the participant's peak amplitude of AP sway to the theoretical limits of AP stability (12.5°). The theoretical limit of stability was influenced by the individual's height and size of the supporting base. It represented an angle (8.5° anteriorly and 4.0° posteriorly) at which the person could lean in any direction before the centre of gravity would move beyond the point of falling. The equilibrium score was calculated by the machine's software with the formula

$$12.5° - [(\theta_{max} – \theta_{min})/12.5°] \times 100,$$

where θ_{max} is the largest AP COG sway angle attained by the participant and θ_{min} is the smallest. An ES of 100 represented no sway whereas a score of 0 indicated a sway exceeding the limit of stability which without the restraint would have required the child to move his or her foot or would have resulted in a fall (Nashner, 1997; NeuroCom, 2008).

After obtaining the three ESs in each of the six conditions, the mean in each condition was calculated for each child, and these averaged scores were used to calculate the somatosensory, visual and vestibular ratios (Table 2). These three sensory ratios were then used to represent the contribution of each sensory system, namely somatosensory, visual and vestibular inputs to balance control. High sensory ratio (close to 1) reflected the participant had superior ability in using that particular sensory input for balance (Nashner, 1997). A composite ES was also generated by the machine's software taking into account the ES attained in all the six testing conditions (NeuroCom, 2008). The composite ESs, mean ESs for the six sensory conditions and the three sensory ratios were used in the analysis.

The posturograph also detected shear forces in the AP direction and produced a motor strategy score. That score, like the ES, was calculated by the machine's software. It quantifies the amount of ankle and hip movement used in maintaining balance during each 20-second trial according to the formula

$$\text{Strategy score} = [1 – (SH_{max} – SH_{min}) / 25] \times 100.$$

In this formula, SH_{max} is the greatest horizontal AP shear force observed and SH_{min} is the lowest. Their difference was normalised to 25lb of shear force because 25lbs is the average difference measured with a group of normal participants who use hip sway only to balance on a narrow beam. A strategy score approaching 100 indicated that the child predominantly used an ankle strategy to maintain equilibrium, while a score near 0 revealed that the child predominantly used a hip strategy. Scores between 0 and 100 represented a combination of the two strategies (NeuroCom, 2008). A strategy score was obtained for each trial in each testing condition and the mean score across three trials was calculated. The means in SOT conditions 1 to 6 were used for analysis.

2.3 Statistical analysis

Descriptive statistics were calculated for each variable. The normality of data was checked using Kolmogorov-Smirnov tests. Independent t-tests were used respectively to compare age, height, weight, and physical activity level between the DCD and control groups. A χ^2 test was used for gender. Multivariate analysis of variance (MANOVA) was performed to compare the equilibrium scores (conditions 1 to 6 of the SOT), the sensory ratios (somatosensory, visual and vestibular) and the motor strategy scores (conditions 1 to 6 of the SOT) between the two groups. If significant differences were found in the overall multivariate tests, a follow-up univariate test was conducted for each of the measures. Where the assumptions of MANOVA were not met, independent t-tests were used instead.

Independent t-tests were also performed to compare the composite ESs of the two groups. A significance level of 0.05 was adopted for all the statistical tests (two-tailed).

3. Results

The characteristics of the DCD and control groups are presented in Table 3. The two groups of children were comparable in terms of age, gender, physical activity level and other demographic variables.

3.1 Standing balance in different sensory conditions

The composite equilibrium score which indicates the overall balance ability in all six conditions was 24.2% lower in the DCD group than in the control group ($p < 0.001$). MANOVA revealed an overall difference in equilibrium scores (condition 1 to 6 of the SOT) between the two groups (Wilks' $\lambda = 3.749$, $p = 0.006$). When each individual primary outcome was considered, the between-group difference remained significant for all ESs except in condition 1 of the SOT ($p = 0.143$). The between group ES difference in condition 3 was close to significance ($p = 0.051$) (Table 4). The ESs in the other conditions were lower in the DCD group than in the control group by 11.9% in condition 2 ($p = 0.001$), 29.8% in condition 4 ($p = 0.003$), 47.7% in condition 5 ($p = 0.001$), and 48.6% in condition 6 ($p = 0.012$). The DCD group children had poorer standing balance than those in the control group, particularly when standing in reduced or conflicting sensory conditions.

3.2 Contribution from the three sensory systems to standing balance

MANOVA also revealed an overall difference in the sensory ratios between the two groups (Wilks' $\lambda = 5.454$, $p = 0.003$). The visual and vestibular ratios were lower in the DCD group than the control group by 27.1% ($p = 0.005$) and 46.8% ($p = 0.002$), respectively. However, the somatosensory ratio showed no significant difference between the groups ($p = 0.115$).

3.3 Motor strategies used in different sensory conditions

MANOVA was not used to assess the strategy scores because the covariance matrices of the dependent variables were not equal between the two groups. Independent t-tests revealed no significant differences in the two groups' motor strategy scores in conditions 1 ($p = 0.537$), 2 ($p = 0.149$), 3 ($p = 0.527$) or 4 ($p = 0.094$) of the SOT. The strategy scores were significantly lower in the DCD group than in the control group in conditions 5 ($p = 0.015$) and 6 ($p = 0.018$) only (Table 4). Children with DCD employed the hip strategy more when they had to rely on vestibular inputs to maintain their standing balance.

4. Discussion

Children with DCD (but without autistic disorder or ADHD) have poorer balance than normal children that is evidenced by their lower composite ES scores in the SOT. Their standing balance control was similar to that of the normal control group in less challenging situations (condition 1 of the SOT) when information from all three sensory systems was available and correct. However, they swayed significantly more than their normally developing counterparts in conditions 2 through 6 in which their somatosensory and/or visual inputs were distorted or absent.

4.1 Somatosensory input for postural control among children with DCD

These results demonstrate that without vision, children with DCD swayed on average more than the control group but the between-group difference in ES was relatively small when the somatosensory input was correct. With error in the visual signal (SOT condition 3), there was similar postural sway in both groups. These findings, together with the lack of a group effect in the somatosensory ratio, suggest that children with DCD use somatosensory information for postural control as effectively as children with normal development. Somatosensory function normally matures at three to four years old (Steindl, Kunz, Schrott-Fischer, & Scholtz, 2006) and is not affected by DCD, as these results demonstrate. So children with DCD partially compensate their balance problem by relying on somatosensory input. This is in agreement with Grove and Lazarus (2007) and Przysucha and Taylor (2004) who reported that somatosensory feedback is re-weighted more heavily for postural control in children with DCD.

4.2 Visual input for postural control among children with DCD

Visual-spatial processing and visual-kinesthetic integration are prerequisites for successful maintenance of stability, but they are usually impaired in children with DCD (Wilson & McKenzie, 1998). SOT visual ratio deficits have previously been reported for children with DCD (Inder & Sullivan, 2005) and confirmed in the present study. We also found that children with DCD (without autistic disorder or ADHD) swayed significantly more when they relied on the visual information to balance (i.e. condition 4 of the SOT). Recent neuro-imaging studies shows that activity in the left posterior parietal cortex is lower in boys with DCD (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009). The parietal cortex integrates multimodal sensory information relevant to motor control, and its dysfunction can cause visual-motor deficits (Kashiwagi et al., 2009). In addition, Marien and his colleagues have pointed out that clumsy children may have disrupted cerebello-cerebral networks that may affect visuo-spatial cognition (Marien, Wackenier, De Surgeloose, De Devn, & Verhoeven, 2010). These neuro-imaging findings may explain why children with DCD have difficulty maintaining balance when forced to rely on visual input.

Interestingly, Grove & Lazarus (2007) did not find any significant deficit in using visual inputs for postural control in children with DCD. This may be due to the fact that they studied a relatively heterogeneous sample and a large age range from six to twelve years old. Normally, visual function matures at seven to ten (Cherng, Lee, & Su, 2003). It is possible that some older children with DCD might have developed a mature visual system for balance, or their visual-motor integration may have improved due to the plasticity of the developing brain (Marien et al., 2010). The participants in our study were relatively homogenous and they had a narrow age range of between six and nine years old. It is reasonable to speculate that children with DCD who are younger than ten years old may have delayed development of their visual function for postural control.

4.3 Vestibular input for postural control among children with DCD

The vestibular system is the most important and reliable sensor for postural control because it measures any acceleration of the head in relation to gravity during stance (Nashner, 1997). This system also transmits information that triggers the vestibulo-ocular reflex that stabilizes visual images on the retina during head and body movements (Tanguy, Quarck, Etard, Gauthier, & Denise, 2008). A normally functioning vestibular system is thus critical in balance control, particularly in challenging conditions.

In this study, we found that children with DCD swayed significantly more when they had to rely on vestibular information alone to maintain their balance, as reflected by their significantly lower vestibular ratios and ES scores in SOT conditions 5 and 6. This partially concurs with the findings of Grove and Lazarus (2007) who reported that seven out of 16 children with DCD (no information about co-morbidity) demonstrated impaired postural stability under SOT conditions 5 and 6 in which vestibular feedback was the sole accurate source of orienting feedback for postural control. However, since the SOT is not a direct measure of how the complex vestibular system contributes to active postural control, further research is needed to confirm and localize the vestibular dysfunction in this group of children using vestibular function tests and neurological examination (Grove & Lazarus, 2007; Black, 2001).

4.4 Postural control strategies among children with DCD

This has been the first study to investigate the motor strategies used by children with DCD to control their standing posture. It is well known that the ankle strategy is the first pattern for controlling upright body sway and that individual tend to shift to the hip strategy in more unstable conditions (Nashner, 1997). Analysis of the strategy scores generated in this study reveals that children with DCD shifted from ankle to hip strategies in a similar manner to normally developing children when the challenge to balance increased across the six conditions of the SOT. When standing under less challenging conditions (conditions 2 to 4), the movement strategies adopted by the DCD group to maintain balance did not differ from those of the control group even though the children with DCD swayed more (attained lower composite scores) than the normal controls. However, children with DCD had difficulty adjusting their postural strategy in conditions in which they needed to rely more on vestibular input for balance control (SOT conditions 5 and 6). The DCD group responded by using comparatively more of the hip strategy rather than the ankle strategy. These findings reflect the fact that children with DCD do not fully adapt to their poor postural control, particularly in environments where they must depend on vestibular signals. They are unable to account for the restricted and/or distorted visual and somatosensory inputs and maintain postural stability. Over-reliance on the hip strategy by these children might not be effective when balancing on unstable surfaces, and it would increase their energy consumption for postural control and increase the risk of falling (Ray, Horvat, Croce, Mason, & Wolf, 2008).

The neuro-physiological explanations of the poor balance strategies in children with DCD have become clearer in recent years. A number of neuro-imaging studies have suggested that poor cerebellar and basal ganglia functioning could be the major causes of motor dysfunction in this group of children (Ivry, 2003; Marien et al., 2010; Groenewegen, 2003; Zwicker, Missiuna, & Boyd, 2009). The function of the cerebellum in postural control is to modulate the amplitude of postural muscle contractions in response to changing environmental conditions, while the basal ganglia control the swift adjustment of muscle tension. If these structures are compromised, children have problems generating and applying forces in a coordinated way to control the body’s position in space (Shumway-Cook & Woollacott, 2007).

Previous studies have also suggested that neuromuscular deficits in children with DCD may contribute to their altered balance strategies (Huh et al., 1998; Johnston et al., 2002; Raynor, 2001; Smits-Engelsman, Westenberg, & Duysens, 2008). Their motor impairments typically include lower maximal knee muscle strength and power, increased knee flexor and extensor co-activation (Raynor, 2001); less steady force production (Smits-Engelsman et al., 2008); inconsistent and less efficient motor-control strategies to execute movements (Huh et al., 1998); inconsistent timing of postural muscle activation (Johnston et al., 2002; Williams, 2002); proximal to distal muscle activation patterns; and increased and prolonged activation or co-contraction of the ankle muscles in standing (Geuze, 2003; Williams & Castro, 1997). These may partly explain the ineffective motor strategies demonstrated by our DCD group in more challenging environments.

Another interesting finding of this study is that although the children with DCD had lower composite scores (they swayed more) in condition 4 of the SOT where somatosensory information was distorted, they used a good mix of hip and ankle strategies to balance that was similar to that of their normal peers. This is different from the observations of Horak and his colleagues (1990), who found that somatosensory loss could result in increased reliance on the hip strategy in standing, even in conditions in which a pure ankle strategy should have been more effective. In their study, somatosensory loss was induced by ischemic disruption of somatosensory inputs from the feet, while in our study the children stood on a sway-referenced support surface that provided inaccurate somatosensory information only. The tactile and proprioceptive receptors in the soles and feet were intact, and nerve conduction was not affected in our children with DCD. This may explain the discrepancy between our observations and those of Horak's group (1990). Moreover, Horak's subjects were healthy normal adults who received anaesthesia of both feet and both ankles during the study. The participants might not have been able to adapt to this somatosensory loss condition immediately during the test. Our participants were children born with DCD who might have learned to compensate for their motor disabilities.

4.5 Clinical implications

Balance dysfunction has an important impact on activity, particularly in situations that demand good balance such as walking on uneven terrain (Grove & Lazarus, 2007). Sensory deficits coupled with the ineffective motor control strategies used in certain sensory deprived conditions by children with DCD may predispose them to falls and injuries in their daily activities. Therefore, physical rehabilitation programs for children with DCD (Pless & Carlsson, 2000) should include individualized postural control training emphasizing the use of visual and vestibular inputs as well as appropriate use of ankle and hip strategies.

4.6 Limitations and consideration for future studies

The results of this study raise the question as to whether the greater use of hip strategy in conditions 5 and 6 of the SOT is a cause (i.e. over-reliance on hip strategy to balance) or a consequence (i.e. respond with the hip strategy when unstable) of postural instability among children with DCD. It was beyond the scope of this study to examine this issue, so further research is needed. Greater reliance on the hip strategy should in any case lead to more falls, particularly when standing on unstable surfaces, a cause for concern (Ray et al., 2008). Further study might fruitfully examine more directly the relationship between fall risk and postural control strategies in children with DCD.

This study has definitely confirmed that children with DCD sway significantly more under reduced or conflicting sensory conditions. However the underlying mechanism of these balance deficits is not yet confirmed, because postural control involves complex sensory-motor systems (Nashner, 1997). Children with DCD may have many other motor deficits which cause their increased postural sway, particularly under challenging conditions. More studies of their motor abilities and postural control are warranted. Future studies might attempt to differentiate the motor and balance deficits of children with different DCD subtypes or with different co-morbid psychiatric conditions (Macnab et al., 2001). Although we tried to select a 'pure' DCD group for this study, it cannot be ruled out that other co-morbid conditions such as dyslexia could have contaminated our results. Care is therefore called for in generalizing the study's findings.

Finally, more studies under dynamic conditions are called for to determine if this would further expose children with DCD to falls. How balance deficits affect activity and participation in daily living has also not yet been examined, and this important area awaits further research.

5. Conclusions

Children with DCD swayed more when they were compelled to rely on visual and/or vestibular inputs to maintain standing posture. They tended to use hip strategy excessively when vestibular signals were impaired. Training programs should therefore target on sensori-motor deficits in order to improve postural control in this patient population.

Acknowledgements

The authors would like to acknowledge the helpful statistical advice of Dr. Raymond Chung.

Declaration of interest

No funding was provided for the preparation of this paper. The authors have no conflicts of interest that are directly relevant to the content of this article.

References

American Psychiatric Association, APA. (2000). *Diagnostic and Statistical Manual of Mental Disorders*. Washington, DC: American Psychiatric Association.

Black, F.O. (2001). What can posturography tell us about vestibular function? *Annals of the New York Academy of Sciences*, 942, 446–464.

Black, F.O., Shupert, C.L., Horak, F.B., & Nashner, L.M. (1988). Abnormal postural control associated with peripheral vestibular disorders. *Progress in Brain Research*, 76, 263–275.

Bruininks, R.H. (1978). *Bruininks-Oseretsky Test of Motor Proficiency: Examiner's Manual*. Circle Pines, MN: American Guidance Service.

Cermak, S.A., & Larkin, D. (2002). *Developmental Coordination Disorder*. Albany, New York: Delmar Thomson Learning.

Cherng, R.J., Hsu, Y.W., Chen, Y.J., & Chen, J.Y. (2007). Standing balance of children with developmental coordination disorder under altered sensory conditions. *Human Movement Science,* 26, 913–926.

Cherng, R.J., Lee, H.Y., & Su, F.C. (2003). Frequency spectral characteristics of standing balance in children and young adults. *Medical Engineering & Physics,* 25, 509–515.

Di Fabio, R., & Foudriat, B.A. (1996). Responsiveness and reliability of a pediatric strategy score for balance. *Physiotherapy Research International*, 1, 180–194.

Fong, S.S.M., Fu, S.N., & Ng, G.Y.F. (2011b). Taekwondo training improves the development of balance and sensory functions in young adolescents. *Journal of Science and Medicine in Sport*, doi: 10.1016/j.jsams.2011.06.001

Fong, S.S.M., Lee, V.Y.L., & Pang, M.Y.C. (2011a). Sensory organization of balance control in children with developmental coordination disorder. *Research in Developmental Disabilities*, doi:10.1016/j.ridd.2011.07.025

Geuze, R.H. (2003). Static balance and developmental coordination disorder. *Human Movement Science,* 22, 527–548.

Groenewegen, H.J. (2003). The basal ganglia and motor control. *Neural plasticity*, 10, 107–120.

Grove, C.R., & Lazarus, J.A.C. (2007). Impaired re-weighting of sensory feedback for maintenance of postural control in children with developmental coordination disorder. *Human Movement Science*, 26, 457–476.

Horak, F.B., Nashner, L.M., & Diener, H.C. (1990). Postural strategies associated with somatosensory and vestibular loss. *Experimental Brain Research*, 82, 167–177.

Horak, F.B., & Macpherson, J.M. (1996). Postural orientation and equilibrium. In J.T. Shepard, L.G. Rowell, & J.A. Dempsey, et al., *Handbook of Physiology, Section 7, Exercise: Regulation and Integration of Multiple Systems* (pp. 255-292). New York: Oxford University Press.

Huh, J., Williams, H.G., & Burke, J.R. (1998). Development of bilateral motor control in children with developmental coordination disorders. *Developmental Medicine & Child Neurology,* 40, 474–484.

Hung, W.W.Y., & Pang, M.Y.C. (2010). Effects of group-based versus individual-based exercise training on motor performance in children with developmental coordination disorder: A randomized controlled pilot study. *Journal of Rehabilitation Medicine,* 42, 122–128.

Inder, J.M., & Sullivan, S.J. (2005). Motor and postural response profiles of four children with developmental coordination disorder. *Pediatric Physical Therapy*, 17, 18–29.

Ivry, R.B. (2003). Cerebellar involvement in clumsiness and other developmental disorders. *Neural Plasticity*, 10, 141–453.

Johnston, L.M., Burns, Y.R., Brauer, S.G., & Richardson, C.A. (2002). Differences in postural control and movement performance during goal directed reaching in children with developmental coordination disorder. *Human Movement Science*, 21, 583–601.

Kashiwagi, M., Iwaki, S., Narumi, Y., Tamai, H., & Suzuki, S. (2009). Parietal dysfunction in developmental coordination disorder: A functional MRI study. *NeuroReport*, 20, 1319–1324.

Macnab, J.J., Miller, L.T., & Polatajko, H.J. (2001). The search of subtypes of DCD: Is cluster analysis the answer? *Human Movement Science,* 20, 49–72.

Marien, P., Wackenier, P., De Surgeloose, D., De Devn, P.P., & Verhoeven, J. (2010). Developmental coordination disorder: Disruption of the cerebello-cerebral network evidenced by SPECT. *Cerebellum*, 9, 405–410.

Nashner, L.M. (1997). Computerized dynamic posturography. In G.P. Jacobson, C.W. Newman, & J.M. Kartush., *Handbook of Balance Function and Testing* (pp. 261-307). St. Louis: Mosby Yearbook Inc.

NeuroCom. (2008). *Balance Manager Systems: Instructions for Use*. Clackamas, OR: NeuroCom International.

Pitcher, T.M., Piek, J.P., & Barrett, N.C. (2002). Timing and force control in boys with attention deficit hyperactivity disorder: Subtype differences and the effect of comorbid developmental coordination disorder. *Human Movement Science*, 21, 919–945.

Pless, M., & Carlsson, M. (2000). Effects of motor skill intervention on developmental coordination disorder: A meta-analysis. *Adapted Physical Activity Quarterly,* 17, 381–401.

Przysucha, E., & Taylor, M.J. (2004). Control of stance and developmental coordination disorder: The role of visual information. *Adapted Physical Activity Quarterly*, 21, 19–33.

Ray, C.T., Horvat, M., Croce, R., Mason, R.C., & Wolf, S.L. (2008). The impact of vision loss on postural stability and balance strategies in individuals with profound vision loss. *Gait & Posture*, 28, 58–61.

Raynor, A.J. (2001). Strength, power, and coactivation in children with developmental coordination disorder. *Developmental Medicine & Child Neurology,* 43, 676–684.

Ridley, K., Ainsworth, B.E., & Olds, T.S. (2008). Development of a compendium of energy expenditures for youth. *International Journal of Behavioral Nutrition and Physical Activity,* 5, 45–52.

Shum, S.B.M., & Pang, M.Y.C. (2009). Children with attention deficit hyperactivity disorder have impaired balance function: Involvement of somatosensory, visual, and vestibular systems. *Journal of Pediatrics*, 155, 245–249.

Shumway-Cook, A., & Woollacott, M.H. (2007). *Motor control: Translating Research into Clinical Practice*. (3rd ed.). Philadelphia: Lippincott Williams & Wilkins.

Smits-Engelsman, B.C.M., Westenberg, Y., & Duysens, J. (2008). Children with developmental coordination disorder are equally able to generate force but show more variability than typically developing children. *Human Movement Science*, 27, 296–309.

Steindl, R., Kunz, K., Schrott-Fischer, A., & Scholtz, A.W. (2006). Effect of age and sex on maturation of sensory systems and balance control. *Developmental Medicine & Child Neurology,* 48, 477–482.

Tanguy, S., Quarck, G., Etard, O., Gauthier, A., & Denise, P. (2008). Vestibulo-ocular reflex and motion sickness in figure skaters. *European Journal of Applied Physiology,* 104, 1031–1037.

Williams, H.G. (2002). Motor control in children with developmental coordination disorder. In S.A. Cermak, & D. Larkin, *Developmental Coordination Disorder*. Albany, New York: Delmar Thomson Learning.

Williams, H., & Castro, A. (1997). Timing and force characteristics of muscle activity: Postural control in children with and without developmental coordination disorders. *Australian Educational and Developmental Psychologist*, 14, 43–54.

Wilson, P.H., McKenzie, B.E. (1998). Information processing deficits associated with developmental coordination disorder: A meta-analysis of research findings. *The Journal of Child Psychology and Psychiatry*, 39, 829–840.

Zwicker, J.G., Missiuna, C., & Boyd, L.A. (2009). Neural correlates of developmental coordination disorder: A review of hypotheses. *Journal of Child Neurology*, 24, 1273–1281.

Tables

Table 1. Testing conditions of the sensory organization test

Condition	**Description**	**Accurate sensory signals available**
1	Eyes open, fixed support	Somatosensory, visual, vestibular
2	Eyes closed, fixed support	Somatosensory, vestibular
3	Sway-referenced[a] vision, fixed support	Somatosensory, vestibular
4	Eyes open, sway-referenced[a] support	Visual, vestibular
5	Eyes closed, sway-referenced[a] support	Vestibular
6	Sway-referenced[a] vision and sway-referenced[a] support	Vestibular

[a] Sway-referenced – tilting of the support surface and/or the visual surround about an axis co-linear with the ankle joints to directly follow the anterior-posterior sway of the subject’s centre of gravity (NeuroCom, 2008).

Table 2. Sensory ratio analysis

Sensory ratio[a]	Description	Computation
Somatosensory	The ability of the child to use somatosensory information for maintaining balance.	ES of Condition 2 / ES of Condition 1
Visual	The ability of the child to use visual information for maintaining balance.	ES of Condition 4 / ES of Condition 1
Vestibular	The ability of the child to use vestibular information for maintaining balance.	ES of Condition 5 / ES of Condition 1

[a] The sensory ratios were generated by the Smart Equitest ® system; computational formulas are shown in the text (NeuroCom, 2008).

Table 3. Subject characteristics

	DCD group (n=22)	**Control group (n=19)**	***p* value**
Mean age (years and months) (SD)	7 years 6 months (1 year 5 months)	6 years 11 months (1 year 1 month)	0.137
Gender (male/female), n	16M/6F	13M/6F	0.763
Mean height, cm (SD)	124.8 (10.4)	121.3 (11.9)	0.309
Mean weight, kg (SD)	27.4 (8.4)	29.3 (12.6)	0.600
Type of physical activity			
Swimming, n	6	6	---
Basketball, n	2	0	---
Soccer, n	1	1	---
Roller skating, n	0	3	---
Table tennis, n	1	1	---
Riding a bicycle, n	1	0	---
Badminton, n	1	1	---
Athletics (track & field), n	0	1	---
Golf, n	0	1	---
Running, n	0	1	---
Gymnastics, n	0	1	---
None	12	7	---
Physical activity level (MET hours per week) (SD)	2.3 (3.1)	3.7 (3.7)	0.193

Table 4. Results from the sensory organization test

	DCD group (n=22)	**Control group (n=19)**	***p* value**
Equilibrium score (SD)			
Condition 1	82.4 (12.9)	87.2 (5.4)	0.143
Condition 2	73.6 (11.5)	83.5 (5.5)	0.001*
Condition 3	71.3 (16.1)	79.4 (7.6)	0.051
Condition 4	43.0 (20.2)	61.2 (16.6)	0.003*
Condition 5	21.2 (17.0)	40.6 (19.2)	0.001*
Condition 6	14.6 (15.8)	28.4 (17.6)	0.012*
Composite ES (SD)	43.3 (12.8)	57.1 (9.6)	<0.001*
Sensory ratio analysis (SD)			
Somatosensory ratio	0.91 (0.14)	0.96 (0.56)	0.115
Visual ratio	0.51 (0.22)	0.70 (0.18)	0.005*
Vestibular ratio	0.25 (0.18)	0.47 (0.22)	0.002*
Strategy score (SD)			
Condition 1	96.6 (12.4)	98.4 (4.1)	0.537
Condition 2	97.1 (5.3)	99.0 (2.1)	0.149
Condition 3	95.9 (10.2)	97.5 (4.5)	0.527
Condition 4	77.4 (13.3)	83.5 (8.2)	0.094
Condition 5	58.3 (14.3)	71.8 (19.3)	0.015*
Condition 6	47.4 (30.6)	66.9 (16.7)	0.018*

*Indicates a between-group difference significant at the p<0.05 level.