Slowed muscle force production and sensory organization deficits contribute to altered postural control strategies in children with developmental coordination disorder

Shirley S.M. Fong[a,b,*], Shamay S.M. Ng[b], Beverley P.H.L. Yiu[c]

[a]Institute of Human Performance, The University of Hong Kong, Hong Kong

[b]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong
[c]Central Kowloon Child Assessment Centre, Department of Health, Hong Kong

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***Corresponding author:**

Shirley S.M. Fong, PT, PhD

Institute of Human Performance,

The University of Hong Kong,

Pokfulam, Hong Kong.

Tel: (852)28315260

Fax: (852)28551712

E-mail address: smfong@hku.hk

Abstract

This study aimed to (1) compare the postural control strategies, sensory organization of balance control, and lower limb muscle performance of children with and without developmental coordination disorder (DCD), and (2) determine the association between postural control strategies, sensory organization parameters and knee muscle performance indices among children with DCD. Fifty-eight DCD-affected children and 46 typically developing children participated in the study. Postural control strategies and sensory organization were evaluated with the Sensory Organization Test (SOT). Knee muscle strength and time to produce maximum muscle torque (at 180°/s) were assessed using an isokinetic machine. Analysis of variance was used to compare the outcome variables between groups, and multiple regression analysis was used to examine the relationships between postural control strategies, sensory organization parameters, and isokinetic indices in children with DCD. The DCD group had significantly lower strategy scores (SOT conditions 5 and 6), lower visual and vestibular ratios, and took a longer time to reach peak torque in the knee flexor muscles than the control group ($p > 0.05$). After accounting for age, sex, and body mass index, the vestibular ratio explained 35.8% of the variance in the strategy score of SOT condition 5 ($p < 0.05$). Moreover, the visual ratio, vestibular ratio, and time to peak torque of the knee flexors were all significant predictors ($p < 0.05$) of the strategy score during SOT condition 6, accounting for 14%, 19.7%, and 19.8% of its variance, respectively. The children with DCD demonstrated deficits in postural control strategy, sensory organization and prolonged duration of muscle force development. Slowed knee muscle force production combined with poor visual and vestibular functioning may result in greater use of hip strategy by children with DCD in sensory challenging environments.

Keywords: Clumsy children; muscle contraction time; motor strategy; sensory inputs; balance

1. Introduction

Developmental coordination disorder (DCD) is one of the most common pediatric sensorimotor disorders, affecting approximately 6% of typically developing children worldwide (American Psychiatric Association, 2000). The prevalence rate of DCD in Hong Kong has not been determined (Child Assessment Service, 2006). Children diagnosed with DCD are characterized by marked impairment in motor coordination that significantly interferes with their academic achievements and daily activities (American Psychiatric Association, 2000). Among the many sensorimotor problems found in children with DCD, poor postural control is the most common, demonstrated in 73-87% of the DCD-affected population (Macnab, Miller, & Polatajko, 2001). The problem requires special attention because suboptimal balance ability may increase the risk of falls, limit activity participation, and affect motor skill development (Fong, Lee, & Pang, 2011; Grove & Lazarus, 2007).

Postural stability requires the optimal reception, processing, and integration of sensory inputs from somatosensory, visual, and vestibular systems along with proper muscle responses and execution of movement strategies such as ankle and hip strategies (Horak & Macpherson, 1996; Nashner, 1997). It has been well documented that children with DCD have widespread impairment in their sensory organization that is associated with greater standing postural sway (Fong et al., 2011; Grove & Lazarus, 2007; Inder & Sullivan, 2005). Yet, how sensory organization deficits influence movement strategies that in turn lead to the greater postural sway is still not known. Moreover, it has been reported that younger children with DCD have lower knee muscle strength (Raynor, 2001) and altered timing of postural muscle contraction (Johnston, Burns, Brauer, & Richardson, 2002). We hypothesize that these neuromuscular deficits may also affect the postural control strategies used by such children. It is important to understand the factors that may affect balance strategies in this pediatric group to design specific remedial interventions to improve their sensorimotor impairments, movement strategies, and balance performance.

To date, only one study has directly examined the postural control strategies used by children with DCD. Fong, Tsang, and Ng (2012a) found that DCD-affected children tended to over-rely on hip strategy (i.e., large and rapid motion at the hip joints with antiphase rotations at the ankle joints) rather than ankle strategy (i.e., body sway centered primarily about the ankle joints) to maintain balance when standing in sensory challenging environments, but they did not offer any explanation for this phenomenon (Horak & Macpherson, 1996; Nashner, 1997). Moreover, the Fong et al. (2012a) study sample was too homogenous (i.e., DCD children with no indications of autistic disorder or attention deficit hyperactivity disorder) and small (DCD group, n = 22; control group, n = 19). Studies with larger sample sizes that use more representative samples (i.e., children with DCD and comorbidities) are needed to accurately detect differences in balance strategies between children with and without DCD and to improve the generalizability of results.

Therefore, this study aimed to (1) compare the postural control strategies, sensory organization of balance control, and lower limb muscle performance of children with and without DCD, and (2) examine the relationship between postural control strategies, sensory organization parameters, and muscle performance indices among children with DCD.

2. Methods

2.1. Participants

This was a cross-sectional, case-control, and exploratory study. All sample size calculations were based on a statistical power of 0.80 and an alpha of 0.05 (two-tailed). Previous studies showed that children with DCD had lower sensory ratios than typically developing children, with effect sizes ranging from 0.3 to 0.8 (Fong et al., 2011; Fong, Tsang, & Ng, 2012b). Moreover, based on a sample of 20 children with DCD and 20 control participants, Raynor (2001) showed that a DCD group had significantly lower isokinetic peak torques, with effect sizes of 1.2 and 1.5 for knee extension and flexion, respectively. For the comparison of sensory organization test (SOT) strategy scores between children with and without DCD, our previous study (Fong et al., 2012a) showed that the minimal effect size was 0.8. In light of the overall available scientific evidence, a medium to large effect size of 0.6 was expected for this study. Therefore, the minimum sample size required to detect a significant between-group difference in outcomes was 45 for each group (objective 1).

Regarding the multiple regression analyses, if up to four variables were to be modeled at an effect size of 0.25 (medium to large), a minimum of 53 children with DCD were needed (objective 2).

Children with DCD were recruited from local child assessment centers and hospitals. They were diagnosed with DCD (with or without comorbid conditions) after a formal multidisciplinary evaluation at the child assessment centres. The inclusion criteria were (1) a formal diagnosis of DCD made by a pediatrician, child psychologist or child psychiatrist, according to the criteria stated in the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2000); (2) demonstrating motor coordination below that expected of the child's chronological age (i.e., Bruininks Oseretsky Test of Motor Proficiency standard score of less than or equal to 42 according to Bruininks (1978); (3) aged between 6 and 11 years; (4) studying in a mainstream school; (5) having no intellectual impairment as determined by a child psychologist at the child assessment center; (6) Chinese ethnicity; and (7) residing in Hong Kong. The exclusion criteria were (1) a diagnosis of neurological or other movement disorder (e.g., cerebral palsy); or (2) significant congenital, musculoskeletal (e.g., fracture) or cardiopulmonary disorder that could affect movement strategies or muscle force production. Age- and sex-matched healthy control children were recruited by convenience sampling from the local community following the inclusion and exclusion criteria stated above except that they did not have any history of DCD. All children in the control group were screened by a pediatric physiotherapist using the Movement Assessment Battery for Children-2 to ensure that they had a total percentile score of greater than the 15th percentile (i.e., had no movement difficulty). Movement ABC-2 has been shown to have good to perfect test-retest (ICC ranging from 0.73 to 0.80), inter-rater (ICC ranging from 0.95 to 1.00) reliability and criterion-related validity (Henderson, Sugden, & Barnett, 2007).

2.2. Procedures

Ethical approval was obtained from the human subjects ethics review committee of the administering institute. Each participant and his or her guardian gave informed written consent before participating in the study. All experimental procedures were conducted by physiotherapists in accordance with the Declaration of Helsinki. The outcome assessors, except the research assistant who was responsible for interviewing the children and parents, were blinded to the subject groups.

2.2.1. Demographic information

Relevant information (e.g., comorbid conditions) was obtained by medical records and interviewing the participants and their parents. Body height and weight were measured using the Health O Meter (Continental Scale Corp., Bridgeview, IL, USA). Body mass index (BMI) was then calculated by the equation weight/height^2.

2.2.2. Sensory organization and postural control strategy

The sensory organization test of the Smart Equitest computerized dynamic posturography (CDP) machine (NeuroCom International Inc., Clackamas, OR, USA) is a valid and reliable test that provides information on the use of sensory inputs and balance strategies to maintain postural stability in various sensory environments (Di Fabio & Foudriat, 1996; Fong, Fu, & Ng, 2012c; NeuroCom, 2008). During the test, participants stood as steady as possible barefoot on the force platform of the CDP machine. They were instructed to rest their arms by their sides and look forward at a distant visual target. Each participant was then exposed to the following six sensory conditions in sequence. In conditions 1, 2 and 3, participants stood on a fixed platform with eyes open, eyes closed, and eyes open in a sway-referenced visual surround (i.e., the visual surround tilted in response to the child's anteroposterior body sway), respectively. In conditions 4, 5 and 6, participants stood on a sway-referenced platform (i.e., the platform tilted in response to the child's anteroposterior body sway) with eyes open, eyes closed, and eyes open in a sway-referenced visual surround, respectively (Nashner, 1997; NeuroCom, 2008). There were three trials for each testing condition, and each trial lasted for 20 seconds. After a familiarization test, each participant underwent the SOT (total 18 trials) without receiving any feedback from the assessor. To prevent fall-related injuries, all participants wore a security harness throughout the test

(NeuroCom, 2008).

The CDP machine measures postural sway amplitude by capturing the trajectory of the participant's center of pressure (COP) when standing. An equilibrium score (ES), which is defined as the non-dimensional percentage compared to the participant's peak amplitude of AP sway to the theoretical limits of AP stability (8.5° anteriorly and 4.0° posteriorly), was generated (NeuroCom, 2008). An ES of 0 represents a sway that exceeded the limit of stability, whereas an ES of 100 indicates no sway in standing (Nashner, 1997; NeuroCom, 2008). After obtaining the ES of all trials, the mean ES of each SOT condition was computed. These mean equilibrium scores were then used to calculate the somatosensory ratio (i.e., mean ES of condition 2/mean ES of condition 1), visual ratio (i.e., mean ES of condition 4/mean ES of condition 1), and vestibular ratio (i.e., mean ES of condition 5/mean ES of condition 1). These sensory ratios represent the ability of the participant to use a particular sensory input to maintain standing balance. A sensory ratio close to 1 indicates that the participant had superior ability in using that particular sensory input to maintain postural stability (Nashner, 1997; NeuroCom, 2008). The three sensory ratios were used for analysis in this study.

Apart from registering the trajectory of the participant's COP in standing, the force platform of the CDP machine detects horizontal shear forces in the AP direction. Horizontal shear force increases when the participant sways at the hips, rather than at the ankles, to maintain standing balance (NeuroCom, 2008). A strategy score that quantifies the amount of ankle and hip movements used in maintaining standing balance during each trial was derived according to the following formula.

Strategy score = [1 – (Maximum horizontal AP shear force – minimum horizontal AP shear force)/ 25] x 100

In the equation above, 25lb (11.3kg) is the average difference between the maximum and minimum horizontal shear forces measured with a group of normal participants who used hip strategy alone to balance (NeuroCom, 2008). A high strategy score (close to 100) indicates that the participant predominantly used ankle strategy to maintain standing balance whereas a low strategy score (near 0) indicates that the participant predominantly used hip strategy to maintain postural stability (NeuroCom, 2008). It is worth noting that when normal individuals respond to perturbations of increasing amplitudes and velocities, they gradually shift from an ankle to a hip strategy (i.e., their strategy scores decrease progressively) to restore equilibrium (Horak & Macpherson, 1996; Horak & Nashner, 1986; Nashner, 1997). In this study, the mean strategy score (three trials) of each SOT condition was calculated and the mean strategy scores of SOT conditions 1 to 6 were used for analysis.

2.2.3. Lower limb isokinetic performance

Concentric isokinetic muscle strength and the time taken to reach peak torque of both knee extensors and flexors were evaluated using a Cybex Norm dynamometer (Computer

Sports Medicine Inc., Stoughton, MA, USA) because isokinetic measurements have been found to be valid and reliable in young individuals (Jones & Stratton, 2000; Merlini, Dell'Accio, & Granata, 1995). Only the dominant leg (i.e., the leg that the participant used to kick a ball) was tested, as there is no significant side-to-side difference in knee muscle peak torques (Holmes & Alderink, 1984) and the time taken to achieve peak torque (Barber-Westin, Galloway, Noyes, Corbett, & Walsh, 2005) in children. The whole assessment was conducted while participants were sitting with their hips flexed to 85° and trunk and ipsilateral thigh stabilized by straps. The rotational axis of the dynamometer was aligned with the knee joint axis (i.e., lateral femoral epicondyle), and the shin pad of the adaptor was placed just above the lateral malleolus of the tested leg (CSMI, 2005). Each participant performed a full range of knee flexion and extension at an angular velocity of 180°/s. Before the test, all participants were asked to perform three sub-maximal and three maximal concentric knee extensor and flexor contractions as familiarization trials (Chan, Maffulli, Korkia, & Li, 1996). After correcting the gravitational effect on knee torque, the participants performed five knee flexion and extension movements consecutively at maximal effort throughout the range as a test ensemble (CSMI, 2005). To facilitate the comparison of knee muscle strength between the two groups, the average body-weight-adjusted isokinetic peak torques of the five trials of both knee extensors and flexors were documented and used for analysis. In addition, average 'time to peak torque' (i.e., the duration from the beginning of muscle torque development until the point at which peak torque was first developed) of the five trials of both knee extensors and flexors were analyzed (CSMI, 2005).

2.3. Statistical analysis

Statistical analyses were performed using SPSS 20.0 (SPSS Inc., Chicago, IL, USA), using a significance level of 0.05 (two-tailed). Descriptive statistics are used to report all relevant variables. Kolmogorov-Smirnov tests were used to ascertain the normality of data. Independent *t* tests and the χ^2 test were used to compare the continuous (i.e., age, height, weight, and body mass index) and categorical (i.e., sex) demographic variables, respectively, between the DCD and control groups.

To compare the SOT-derived sensory ratios, SOT-derived strategies scores, and isokinetic outcome parameters between the two groups, three separate multivariate analyses of variance (MANOVA) were performed to avoid the increased probability of committing type I errors associated with multiple comparisons. The Bonferroni-adjusted *p* value and effect size (partial eta-squared) are reported for each outcome variable. By convention, partial eta-squared values of 0.01, 0.06, and 0.14 represent small, medium, and large effect sizes, respectively (Portney & Watkins, 2009).

The Pearson product-moment correlation (*r*) was used to examine the degree of association between SOT-derived scores and isokinetic outcome variables among children with DCD. Next, multiple linear regression analyses were performed to identify the determinants of strategy scores (SOT conditions 5 and 6). Demographics including age, sex, and BMI were first forced into the regression model (enter method) because these factors may influence balance strategies (Greve, Alonso, Bordini, & Camanho, 2007; Steindl, Kunz, Schrott-Fischer, & Scholtz, 2006). Body height and weight were not entered into the regression model because the strategy score is derived from the ratio of sway amplitude (sway angle) to horizontal shear forces and is not affected by the height and weight of the participant (NeuroCom, 2008). Those sensory ratios and isokinetic indices that were significantly associated with any of the aforementioned strategy scores in the bivariate correlational analysis ($p < 0.05$) were then entered into the regression model (enter method). To avoid multicollinearity, the degree of association among the predictor variables was also examined using Pearson's r. Any predictors that had a correlation of > 0.20 were not included in the same regression model.

3. Results

3.1. Participant characteristics

Fifty-eight children with DCD and 46 control children participated in the study. There was no significant difference in demographic characteristics between the two groups (Table 1).

3.2. Comparison of outcome variables

The DCD-affected children had significantly lower visual ($p < 0.001$) and vestibular ($p = 0.003$) ratios than the control participants, but the somatosensory ratio was comparable between the two groups ($p > 0.05$). In addition, the strategy scores of SOT condition 5 ($p = 0.005$) and 6 ($p = 0.005$) were significantly lower among children in the DCD group. No significant difference ($p > 0.05$) was observed between groups in the strategy scores for SOT conditions 1 to 4 (Table 2).

For the isokinetic outcome variables, no significant difference was identified between groups in the body-weight-adjusted peak torques of knee extensors and flexors ($p > 0.05$). However, the DCD group participants generated peak torque in knee flexion that was substantially slower than the control group ($p = 0.001$). Delayed muscle force production was not observed ($p > 0.05$) in the knee extensor muscles of children with DCD when compared to their typically developing peers (Table 2).

3.3. Associations with SOT-derived strategy scores

Moderate correlations ($p < 0.05$) were found between SOT-derived strategy score (condition 6), the visual ratio, vestibular ratio and time to peak torque of the knee flexors among children with DCD. The SOT-derived vestibular ratio was also moderately correlated with ($p < 0.05$) the strategy score obtained during SOT condition 5 (Table 3). Moreover, moderate to high correlations ($p < 0.05$) existed among the predictor variables (i.e., SOT visual ratio, vestibular ratio and time to peak torque of the knee flexors) (Table 3). Therefore, separate regression models were used in the subsequent analyses to avoid possible multicollinearity.

In the first set of regression models (model 1), the vestibular ratio was used to predict strategy score of SOT condition 5. After accounting for age, sex, and BMI, the vestibular ratio explained 35.8% of the variance ($p < 0.001$) in the strategy score of the condition 5 (Table 4). In the second set of regression models, the visual ratio, vestibular ratio and time to peak torque of the knee flexors were used to predict the strategy score of SOT condition 6. As in the previous model, we first accounted for demographics including age, sex, and BMI. The results showed that the visual ratio (model 2), vestibular ratio (model 3), and time to peak torque of the knee flexors (model 4) were all significant predictors of strategy score (SOT condition 6), accounting for 14% ($p = 0.004$), 19.7% ($p < 0.001$), and 19.8% ($p < 0.001$) of its variance, respectively (Table 4).

4. Discussion

4.1. Differential sensorimotor performance and balance strategies of children with and without DCD

This appears to be the first study that has examined the time course of the development of peak torque in children with DCD. Our results revealed that the DCD-affected children took a longer time (0.1s) to produce maximum muscle force during knee flexion at moderate movement velocity (180°/s). However, delayed maximal muscle force production was not observed in the knee extensor muscles (Table 2). The physiological reasons for this phenomenon are unclear but it has been suggested that the contractile speed of muscle or shortening speed of sarcomeres (Asai & Aoki, 1996; De Ste Croix, Deighan, & Armstrong, 2004), degree of motor unit activation and synchronization (Asai & Aoki, 1996; Kannus & Beynnon, 1993), amount and rate of neural activation (Komi, 1986), degree of co-activation in the antagonist muscle (De Ste Croix et al., 2004), muscle fiber type and composition (Hosking, Young, Dubowitz, & Edwards, 1978), and stiffness of muscle and tendons (Mayhew & Bemben, 1994) may account for the rate of muscle torque development. Further studies could explore the physiological mechanisms that contribute to the slower maximum torque production of specific postural muscles in children with DCD.

Despite the slowness of muscle force generation in the children with DCD, their maximal level of force production (i.e., body-weight-adjusted peak torque) was as high as the typically developing children. This finding is in exact agreement with that of our previous study (Fong, Chung, Chow, Ma, & Tsang, 2013). Although one earlier study suggested that younger children aged 6 to 8 years with DCD had lower levels of peak torque during knee extension and flexion than typically developing children (Raynor, 2001), these findings do not contradict our results. Because the DCD-affected children in our study were aged 6 to 11 years, they might have grown out of the muscle weakness problem during the maturation process (Fong et al., 2013).

Concurring with several previous reports (Fong et al., 2011; Fong et al., 2012a; Fong et al., 2012b; Grove & Lazarus, 2007; Inder & Sullivan, 2005), this study confirmed that the children with DCD were less able to rely on visual and vestibular inputs to maintain standing balance than their typically developing counterparts. Dysfunction of the parietal cortex may explain the visual-motor (e.g., visual-postural control) deficits (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009), and inadequate vestibular stimulation during development may explain the lower vestibular function (Fong et al., 2012b). Moreover, our finding suggests that the DCD-affected children used somatosensory information for maintaining balance as effectively as the children with normal motor development. This could be the case because somatosensory feedback is re-weighted more heavily for postural control in children with DCD due to their visual and vestibular deficits (Fong et al., 2012a; Grove & Lazarus, 2007; Przysucha & Taylor, 2004).

This study also demonstrated a trend for strategy scores to decrease progressively from SOT condition 1 to 6 in both groups. The DCD group attained significantly lower strategy scores in SOT conditions 5 and 6 than the control group (Table 2). These findings were anticipated, and in agreement with those of our previous study (Fong et al., 2012a). Under simple sensory conditions (e.g., SOT conditions 1 to 4), both groups of children predominantly fine-tuned their standing posture by swaying on their ankles. A shift towards hip strategy, especially in children with DCD, occurred in SOT conditions 5 and 6 when the participants experienced greater postural instability. Previous studies have proposed several neurophysiological mechanisms such as cerebellar and basal ganglia dysfunctions (Fong et al., 2012a; Groenewegen, 2003; Zwicker, Missiuna, & Boyd, 2009) and neuromuscular deficits (Fong et al., 2012a; Raynor, 2001; Smits-Engelsman, Westenberg, & Duysens, 2008) to explain the motor dysfunctions among children with DCD. However, these explanations are yet to be confirmed in the context of postural control.

4.2. Determinants of altered postural control strategies in children with DCD

This study sought to explain the exaggerated hip movements used by children with DCD to maintain standing balance under sensory depriving (SOT condition 5) and conflicting (SOT condition 6) environments. We found that the vestibular ratio was independently associated with the strategy score obtained during SOT condition 5 (Table 4). As that condition only provided accurate vestibular information to the participants (Nashner, 1997; NeuroCom, 2008), the children with DCD who had poor reliance on vestibular input to control their posture may have been challenged. When they became unstable, those children might have responded by increasing the sway of their hips to maintain equilibrium (Horak & Macpherson, 1996; Nashner, 1997).

Another important finding of this study is that time to peak torque of the knee flexors was the major determinant of the strategy score obtained during SOT condition 6, and that the vestibular and visual ratios were also significant, but less strong, predictors (Table 4). Our results point to the powerful influence of the knee flexors' force production time on postural control strategy. The major knee flexor muscles, hamstrings, are also important hip extensors because they cross both hip and knee joints (Standring, 2008). The hamstring muscle group is thus particularly important in controlling the forward sway of the body (i.e., hip flexion) in balance strategies (Horak & Nashner, 1986). Horak and Nashner (1986) showed that hamstring muscle reflex contraction latency can be as short as 100-150ms in response to a forward postural disturbance. This hints that when the hamstring muscles cannot produce enough torque within a short period to control forward sway, the result might be excessive hip flexion (hip sway) as observed in the children with DCD. Moreover, although SOT condition 6 provided visual and vestibular inputs to the participants, the children with DCD had difficulties in relying on these senses to balance. They might have swayed their hips more as a compensatory strategy (Horak & Macpherson, 1996; Nashner, 1997). When they swayed their hips, the hamstring muscles would have worked slowly, thereby exaggerating the postural sway and further compromising their body balance. In summary, excessive sway of the hips when balancing in a sensory conflicting environment may be a manifestation of slowed hamstring muscle contraction and poor vestibular and visual functions in children with DCD.

4.3. Clinical implication

The overuse of hip strategy to balance increases energy consumption and may increase the risk of falling, especially when standing on an unstable surface (Ray, Horvat, Croce, Mason, & Wolf, 2008). We found that the significant determinants of excessive hip sway were prolonged time to peak torque in the knee flexors and a decreased ability to rely on visual and vestibular inputs to balance. Our findings shed light on the causes of poor postural control in children with DCD. Results also imply that balance training programs should be designed to improve postural muscle contraction speed, sensory organization, and postural control strategies, thereby improving the balance performance and reducing the susceptibility to falls within DCD-affected children.

4.4. Limitations and future research directions

One of the limitations of this study is that we could not assess the temporal changes of balance strategies and other neuromuscular parameters within the subjects due to the cross-sectional study design. Individual variation in growth and maturation may have confounded the results. Another possible confounding factor is the comorbid conditions. For example, 14% of our DCD group participants had attention deficit hyperactivity disorder (ADHD). This disorder may also affect sensory organization and balance functions in children (Shum & Pang, 2009). Nevertheless, given the high prevalence of comorbidities in children with DCD (e.g., 43% of children with DCD have ADHD) (Child Assessment Service, 2006), we included a relatively heterogeneous sample to improve the generalizability of the findings. Finally, the determinant of postural control strategies is undoubtedly multifaceted, and potential contributing factors such as postural muscle recruitment timing, pattern, and sequence during balance movements were not measured. Further studies could record the postural muscles' temporal and spatial activities directly by electromyography and in a more functional context (e.g., during balance movements).

5. Conclusions

The children with DCD demonstrated deficits in postural control strategy, speed of muscle force production, and sensory organization. It seems that the greater use of hip strategy in sensory challenging environments was a manifestation of slowness to generate knee flexor muscle torque and poor visual and vestibular functions in this type of child.

Declaration of interest

No funding was provided for the study. The authors have no conflicts of interest that are

directly relevant to the content of this paper.

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Tables

Table 1

Characteristics of participants.

	DCD group (n = 58)	Control group (n = 46)	*P* value
Age, years	7.6 ± 1.2	8.0 ± 1.8	0.235
Sex (boys/girls), n	49/9	34/12	0.182
Height, cm	126.6 ± 10.2	128.4 ± 14.7	0.482
Weight, kg	27.8 ± 8.5	30.0 ± 7.7	0.169
BMI, kg/m^2	16.9 ± 2.7	18.1 ± 3.6	0.058
Comorbidity			
Attention deficit disorder, n	7	0	
Attention deficit hyperactivity disorder, n	8	0	
Dyslexia, n	6	0	
Asperger syndrome, n	6	0	
Autism spectrum disorders, n	6	0	

Values are mean ± SD.

Table 2

Comparison of outcome variables.

	DCD group (n = 58)	Control group (n = 46)	*P* value	Effect size
SOT – Sensory ratio				
Somatosensory ratio	0.9 ± 0.1	1.0 ± 0.0	0.084	0.030
Visual ratio	0.6 ± 0.2	0.7 ± 0.2	< 0.001[c]	0.130
Vestibular ratio	0.4 ± 0.2	0.5 ± 0.2	0.003[b]	0.084
SOT – Strategy score				
Condition 1	97.7 ± 8.0	99.2 ± 2.7	0.247	0.013
Condition 2	97.5 ± 6.4	99.2 ± 1.7	0.079	0.031
Condition 3	96.3 ± 7.6	97.7 ± 5.8	0.284	0.011
Condition 4	83.4 ± 5.7	85.1 ± 6.7	0.166	0.019
Condition 5	64.7 ± 15.6	73.5 ± 15.3	0.005[b]	0.076
Condition 6	49.7 ± 26.5	64.1 ± 23.2	0.005[b]	0.076
Body-weight-adjusted isokinetic peak torque at 180°/s, Nm/body weight				
Knee extensors	73.1 ± 21.4	73.9 ± 27.3	0.889	< 0.001
Knee flexors	43.5 ± 17.8	49.4 ± 17.8	0.151	0.027
Time to peak torque at 180°/s, s				

Knee extensors	0.3 ± 0.2	0.3 ± 0.1	0.131	0.030
Knee flexors	0.3 ± 0.1	0.2 ± 0.1	0.001[c]	0.127

Values are mean±SD.

[a]$p < 0.05$.

[b]$p < 0.01$.

[c]$p < 0.001$.

Table 3

Correlations among SOT-derived and isokinetic outcome variables in the children with DCD.

	Strategy score of SOT condition 5	Strategy score of SOT condition 6	SOT visual ratio	SOT vestibular ratio
Strategy score of SOT condition 5	---	---	---	---
Strategy score of SOT condition 6	0.466[c]	---	---	---
SOT visual ratio	0.260	0.374[b]	---	---
SOT vestibular ratio	0.582[c]	0.446[c]	0.613[c]	---
Time to peak torque of the knee flexors	-0.089	-0.399[b]	-0.368[b]	-0.201

[a]$p < 0.05$.

[b]$p < 0.01$.

[c]$p < 0.001$.

Table 4

Multiple regression analysis for determining the SOT strategy scores in the children with DCD.

Model	Predictors	F	R^2 change	Unstandardized regression coefficient (B)	95% Confidence interval (CI)	Standardized regression coefficient (β)	P value
Dependent variable 1: Strategy score of SOT condition 5							
Model 1	Age	9.790	0.009	0.138	-3.029, 3.306	0.011	0.930
	Sex (boy = 1, girl = 2)			6.610	-2.541, 15.760	0.156	0.153
	BMI			-1.443	-2.892, 0.005	-0.251	0.051
	SOT vestibular ratio		**0.358**	**46.665**	**30.268, 63.062**	**0.639**	**<0.001**[c]
Dependent variable 2: Strategy score of SOT condition 6							
Model 2	Age	3.282	0.002	0.005	-6.437, 6.446	<0.001	0.999

	Sex (boy = 1, girl = 2)			14.451	-3.916, 32.817	0.200	0.120
	BMI			-1.255	-4.154, 1.644	-0.128	0.389
	SOT visual ratio		**0.140**	**46.736**	**15.692, 77.780**	**0.401**	**0.004[b]**
Model 3	Age	4.541	0.002	0.219	-5.931, 6.369	0.010	0.943
	Sex (boy = 1, girl = 2)			12.483	-5.281, 30.248	0.173	0.164
	BMI			-1.579	-4.391, 1.233	-0.161	0.265
	SOT vestibular ratio		**0.197**	**59.043**	**27.212, 90.874**	**0.475**	**<0.001[c]**
Model 4	Age	4.552	0.002	1.483	-4.597, 7.562	0.069	0.627
	Sex (boy = 1, girl = 2)			16.632	-1.040, 34.305	0.231	0.065
	BMI			-2.182	-5.074, 0.710	-0.223	0.136
	Time to peak torque of the knee flexors		**0.198**	**-210.140**	**-323.261, -97.019**	**-0.480**	**<0.001[c]**

[a]$p < 0.05$.

[b]$p < 0.01$.

[c]$p < 0.001$.