Differential effect of taekwondo training on knee muscle strength and reactive and static balance control in children with developmental coordination disorder: A randomized controlled trial

Shirley S.M. Fong[a,b,*], Joanne W.Y. Chung[a], Lina P.Y. Chow[a], Ada W. W. Ma[a], William W.N. Tsang[b]
[a]Department of Health and Physical Education, The Hong Kong Institute of Education, Hong Kong
[b]Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong

***Correspondence to:**
Shirley S.M. Fong, PT, PhD
~~Department of Health and Physical Education~~
~~The Hong Kong Institute of Education~~
~~Tai Po, N.T., Hong Kong~~
~~Tel: (852) 29486421~~
~~Fax: (852) 29487848~~
~~Email: smfong@ied.edu.hk~~

Abstract

This randomized controlled trial aimed to investigate the effect of short-term intensive TKD training on the isokinetic knee muscle strength and reactive and static balance control of children with developmental coordination disorder (DCD). Among the 44 children with DCD (mean age: 7.6±1.3 years) recruited, 21 were randomly assigned to undergo daily TKD training for one hour over three consecutive months, with the remaining 23 children being assigned to the DCD control group. Eighteen typically developing children (mean age: 7.2±1.0 years) received no training as normal controls. Knee extensor and flexor muscle strength and reactive and static balance control were assessed using an isokinetic machine (with low, moderate and high movement velocities), a motor control test (MCT) and a unilateral stance test (UST), respectively. A repeated measures MANCOVA revealed a significant group through time interaction effect in isokinetic outcomes at 180°/s and in the UST outcome. Post hoc analysis demonstrated that DCD-TKD children's isokinetic knee muscle strength, specifically at 180°/s, was as high as that of the normal control children ($p > 0.0083$) after TKD training. Moreover, UST body sway velocity was slower in the DCD-TKD group than in the DCD control group ($p < 0.001$), and was comparable to that of the normal control group ($p > 0.05$) after TKD training. However, no such improvement in balance was observed in the MCT ($p > 0.025$). The results show that children with DCD who undergo a three-month program of intensive TKD training experience improvements in isokinetic knee muscle strength at 180°/s and static single-leg standing balance control, but do not benefit from improved reactive balance control.

Keywords: sport, balance, isokinetic muscle strength, clumsy children

1. Introduction

Developmental coordination disorder (DCD) is a relatively common sensorimotor disorder affecting approximately six percent of primary school-aged children worldwide. Children with DCD present a number of motor problems including marked delays in achieving motor milestones and poor coordination and body balance (APA, 2000). It has been reported that 73% to 87% of DCD-affected children have postural control deficits (Macnab, Miller, & Polatajko, 2001). Most of the studies conducted to date in this field stress the importance of how sensory deficits in children with DCD affect their static balance control, but de-emphasize the reactive and motor aspects of postural control (Cherng, Hsu, Chen, & Chen, 2007; Fong, Lee, & Pang, 2011; Grove & Lazarus, 2007; Inder & Sullivan, 2005). Only one recent study has examined reflexive postural muscle activation patterns in children with DCD subject to unexpected perturbation (Geuze, 2003). The results show that the onset of muscular response and the amplitude of the response were similar between the DCD and control groups. However, the total time taken to recover from postural disturbance (a more functional outcome measure of reactive postural control) was not reported (Geuze, 2003). Because reactive postural control is essential for many daily activities such as standing in a moving bus, and is the first line of defense against a fall following unexpected external disturbances to balance (NeuroCom, 2008; Shumway-Cook & Woollacott, 2007; Stout, 2006), it is important to investigate functional reactive balance ability in children with DCD.

It is well-known that strengthening the lower limb muscles can improve standing balance control and thus prevent falls in older adults (Moreland, Richardson, Goldsmith, & Clase, 2004; Tsang & Hui-Chan, 2005). Similar to older adults, children with DCD have weaker lower limb muscles (e.g., lower isokinetic peak torque during knee extension and flexion at moderate to fast angular velocities) than their typically developing peers (Raynor, 2001). This may predispose them to instability and falls. We postulated that some kind of exercise training or sports activity aimed at improving muscular strength may enhance the various balance abilities in this particular group of children. Taekwondo (TKD) is a popular sport among young people (Park, Park, & Gerrard, 1989). Due to the fast kicking and spinning it involves, it has been found to be beneficial to DCD-affected children in terms of sensory organization and single-leg standing balance control (Fong, Tsang, & Ng, 2012b). Moreover, a previous study conducted in our laboratory has demonstrated that the duration of TKD training is positively associated with isokinetic knee extensor and flexor muscle strength (body-weight-adjusted peak torque at 240°/s) in typically developing adolescents (Fong & Tsang, 2012). Therefore, we hypothesized that TKD training might also improve lower limb muscle strength, and hence postural stability, in children with DCD.

This randomized controlled trial was aimed at (1) identifying the developmental status of reactive and static balance control and isokinetic knee muscle strength in children with DCD in comparison with children with normal motor development; (2) investigating the effect of short-term intensive TKD training on isokinetic knee muscle strength and reactive and static balance control among children with DCD compared with non-trained DCD-affected children and typically developing children; and (3) determining the association between knee muscle strength and balance performance in children with DCD after short-term TKD training.

2. Methods

2.1. Design overview

The study reported in this paper consisted of a randomized, single-blinded, stratified, controlled trial. Children with DCD were randomly assigned to either the three-month TKD intervention group or the control group. Two blinded assessors measured outcomes in all participants both before and after the three-month training period. Because the participants and their parents were not blinded to group allocation, they were requested not to inform the assessors of their group assignments during measurement to avoid potential bias (Fong et al., 2012b).

2.2. Participants and calculation of sample size

To the best of our knowledge, this study was the first to investigate the effect of TKD training on muscle strength and postural control in children with DCD. Therefore, power calculations were based on those of the nearest comparable study (Schoemaker, Hijlkema, & Kalverboer, 1994) as reported by Pless and Carisson (2000). In their meta-analysis, the reported effect size for gross motor training in improving the motor proficiency, including the balance performance, of individuals with DCD was 0.83. Hence a minimum sample size of 14 was necessary to achieve a statistical power of 0.8 in pre- and post-test measurements among the two DCD groups, with alpha set at 0.05. Anticipating a possible dropout rate of 30% (Hiller, McIntyre, & Plummer, 2010), a total of at least 19 children with DCD were needed for the trial.

Participants with DCD were recruited from local hospitals and child assessment centers (CACs). These are the major institutions that provide developmental assessment services for children in Hong Kong. The inclusion criteria were: (1) a formal diagnosis of DCD according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR) (APA, 2000); (2) aged between six and twelve years; and (3) studying within a regular education framework. Individuals with any of the following were excluded from this study: (1) a formal diagnosis of emotional, neurological or other movement disorders; (2) a significant congenital, musculoskeletal or cardiopulmonary condition that might influence postural control; (3) intellectual impairment; (4) receiving physical or occupational therapy; (5) receiving regular or intensive training in sports; (6) demonstrated excessive disruptive behavior during screening; or (7) unable to follow instructions. Children with normal development were recruited from the community through a convenience sampling method adopting the same inclusion and exclusion criteria, although they could not have any history of DCD. They were then screened by an experienced pediatric physiotherapist using the Movement Assessment Battery for Children-2 (MABC-2) before being assigned to the normal control group (Fong et al., 2012b). Children with an MABC-2 total percentile score at or below the 15th percentile (i.e., children at risk of significant movement difficulty) were excluded from the sample (Henderson, Sugden, & Barnett, 2007).

Ethical approval was obtained from the human subjects ethics review committee of the administering institute. The details of this study were explained to each participant and their parent(s). Written informed consent was also obtained. All procedures were conducted in accordance with the Declaration of Helsinki.

2.3. Randomization

To ensure that the DCD-TKD and DCD control groups both contained approximately equal numbers of males and females, all participants with DCD were stratified by sex before being randomly assigned to either group. This randomization procedure was performed by drawing lots, and was carried out by a person independent of the study. The 21 children with DCD who were assigned to the DCD-TKD group received the three-month course of TKD training. Another 23 children with DCD were assigned to the DCD control group. This DCD control group was included to account for the effect of maturation and possible spontaneous improvement over time. In addition, 18 children with normal motor development were allocated to the normal control group (a comparison group, no randomization) to provide a norm for later comparison of outcomes (Fong et al., 2012b).

2.4. Intervention

All of the children in the DCD-TKD training group were required to attend a weekly one-hour TKD training session held at the administering institute for 12 consecutive weeks. Parents were also encouraged to participate in the TKD training classes with their children in order to have a better understanding of the TKD maneuvers and could supervise their children to practise TKD at home. The TKD training protocol that suits the participants' motor abilities was produced by an experienced pediatric physical therapist and a skilled TKD practitioner. It was modified from a typical TKD syllabus for beginners (Park et al., 1989). The details of the protocol were presented in Fong et al. (2012b). The TKD classes were conducted by a World Taekwondo Federation 4th Dan Black Belt qualified instructor and a 2nd Dan Black Belt qualified assistant instructor (Fong et al., 2012b).

Apart from attending the face-to-face TKD training sessions, each participant in the DCD-TKD group was given a prescribed set of TKD home exercises to reinforce what had been learned at each training session and increase the frequency with which they exercised. The home exercises were exactly the same as those practiced during the face-to-face TKD training sessions. The participants were instructed to perform these TKD exercises daily (excluding TKD class days) throughout the three-month study period. The participants' parents were provided with clear written instructions and a log book, and were asked to coach or assist their children in performing the TKD home exercises, which could be completed within an hour. The log books were designed to be completed daily by the parents. The TKD instructors checked the participants' daily log books at each training session to ensure they had all complied with their home exercise requirements. The participants submitted their completed and signed log books to the researchers during the post-intervention assessment. Children in the DCD control and normal control groups received no training within the study period (Fong et al., 2012b).

2.5. Measurement of outcomes

All participants were assessed one month before the start of the TKD intervention (pre-test) and again within two weeks of its completion (post-test). Each participant, regardless of group assignment, underwent the following assessments in sequence.

2.5.1. Assessment of static balance control in single-leg standing

Single-leg standing balance was measured in a unilateral stance test (UST) with a computerized dynamic posturography (CDP) machine (Smart Equitest, NeuroCom International Inc., Clackamas OR, USA). Each participant wore a security harness and stood barefoot for ten seconds on the platform of the CDP machine using their dominant leg, which was defined as the one used to kick a ball (Fong, Fu, & Ng, 2012c). The dominant leg was selected in this test to align it with the isokinetic knee muscle strength assessment (in which the dominant leg was also used). Each participant was instructed to stand quietly with both arms resting by the sides of the trunk and their eyes looking forward at a distant visual target, with the hip of the non-supporting leg flexed at 45° to resemble the starting position of a TKD front kick. The sway velocity of the center of pressure (COP) was captured by the CDP machine (NeuroCom, 2008). After a familiarization trial, each participant performed three trials with a ten-second rest in between. The mean COP sway velocity across the three trials was calculated and used for analysis. A previous study had established the good test-retest reliability of the UST in young adolescents, with an intra-class correlation coefficient of 0.77 (Fong et al., 2012c).

2.5.2. Assessment of reactive balance control

Reactive balance control (motor responses to unexpected perturbations) was measured by the motor control test (MCT) with the same CDP machine. Each participant stood quietly with a bare foot on the computer-controlled movable platform of the CDP machine, and wore a security harness to prevent falls. Translatory perturbations were administered unexpectedly to the standing participant by translating the platform in either the anterior or the posterior direction at three different amplitudes (small, medium and large translations scaled to the participant's height). The participant's COP was therefore displaced away from the center in the opposite direction relative to the base of support. Restoring standing balance required a quick movement of the COP back to the central position by activating the leg and trunk muscles (NeuroCom, 2008; Shumway-Cook & Woollacott, 2007). Each translation amplitude measurement test comprised three trials with a very short break (< 10s) in between. Latency times (in ms) between platform translation onset and initiation of postural response (denoted by the force response in the legs registered by the force platform) were calculated. The average latency time for all translation conditions yielded a composite latency score. This composite latency score represents general MCT performance and was used for analysis (Leitner et al., 2009; NeuroCom, 2008).

2.5.3. Isokinetic quadriceps and hamstring muscle strength assessment

The isokinetic concentric strength of the knee extensors (quadriceps) and knee flexors (hamstrings and gastrocnemius) of each participant's dominant leg was tested using a Cybex Norm isokinetic dynamometer (Computer Sports Medicine Inc., Stoughton, MA, USA). Only the dominant leg was tested because there is no significant difference in the isokinetic peak torque of the knee extensors and flexors between the dominant and non-dominant limbs (Holmes & Alderink, 1984). Each participant sat on the chair of the machine with their hips kept at 85° flexion. The knee joint axis of the dominant leg was aligned with the rotational axis of the dynamometer. The participant's trunk and the thigh of the dominant leg were stabilized with straps, such that the starting position was full knee flexion and the endpoint was full knee extension. Three test speeds (60°/s, 180°/s and 240°/s) were adopted. Familiarization trials were performed in the form of three sub-maximal and three maximal concentric knee extensor and flexor contractions (Chan, Maffulli, Korkia, & Li, 1996). After correcting for the effect of gravity on knee torque, five maximal concentric contractions of the knee extensors and flexors were recorded as a test ensemble (CSMI, 2005). The average values of the five bodyweight-adjusted peak torque of each movement velocity were used for analysis.

2.6. Statistical analysis

One-way analysis of variance (ANOVA) and chi-square tests were conducted to compare the three groups in terms of age, body weight, height and sex distribution. To test the overall effect of TKD training and to reduce the probability of type I error due to multiple comparisons, a two-way repeated measures multivariate analysis of covariance (MANCOVA) was conducted, incorporating all (1) isokinetic outcome measures (i.e., isokinetic peak torque of knee extensors and flexors at 60°/s, 180°/s and 240°/s); and (2) postural control outcome measures (i.e., UST COP sway velocity and MCT composite score). The within-subject factor was time and the between-subject factor was group. The intention-to-treat principle (last observation carried forward) was employed. Baseline (pre-test) isokinetic peak torque of knee extensors and flexors at 60°/s, 180°/s and 240°/s, UST COP sway velocity and the MCT composite score were entered as covariates if there was any significant baseline between-group difference in these measures. If the MANCOVA demonstrated a significant interaction effect overall, follow-up analyses were performed using one-way analysis of covariance (ANCOVA) and post hoc pairwise comparisons. Furthermore, pairwise t-tests were used to investigate whether there was any within-group difference between the two assessment intervals.

Pearson's correlation coefficients were then used to examine the bivariate association of isokinetic outcomes (at post-test) with significant balance outcomes (at post-test) in the DCD-TKD children. All of the statistical analyses were performed using SPSS version 20.0 software (SPSS Inc., Chicago, IL, USA). The significance level was set at 0.05 (two-tailed) and was corrected using an appropriate Bonferroni adjustment for the univariate tests to maintain an overall type one error of 5% (i.e., alpha = 0.0083 for comparisons of the isokinetic outcome measures among groups; alpha = 0.025 for comparisons of the UST and MCT outcome measures among groups).

3. Results

The flow of participants through the study was described in Fong et al. (2012b). To summarize, our sample consisted of 62 children in total (DCD, n = 44; without DCD, n = 18). Five children from the DCD-TKD group (n = 21), ten from the DCD control group (n = 23) and eight from the normal control group (n = 18) dropped out for various reasons (e.g., had no relatives to escort them to the training venue, had school exams, and unable to commit the time) (Fong et al., 2012b). In all, 76.2% of the children assigned to the DCD-TKD group completed the TKD training program, with an average attendance rate of 90.9% for the face-to-face TKD training sessions. The parent-reported TKD home exercise compliance rate was 95.2%. No injuries or adverse events were reported during the entire TKD training course.

3.1. Comparison of baseline characteristics

No significant differences were observed in the demographic characteristics of the three groups ($p > 0.05$) (Table 1). Significant group differences were found in the pre-test measures of isokinetic peak torque of knee extensors at 60°/s ($p = 0.008$), of knee flexors at 60°/s ($p = 0.008$) and in UST COP sway velocity ($p = 0.009$). Group differences in isokinetic peak torque of knee extensors at 180°/s ($p = 0.010$) and of knee flexors at 180°/s ($p = 0.010$) were close to significant (Table 2). Therefore, the baseline values of these five outcomes were treated as covariates in the subsequent multivariate and univariate analyses.

3.2. Changes in isokinetic knee muscle strength at three movement velocities

The repeated measures MANCOVA revealed a significant time by group interaction effect ($p < 0.001$) involving isokinetic peak torque of knee extensors at 180°/s. Children with DCD showed significant improvement (25.4%, $p < 0.001$) in isokinetic peak torque of knee extensors at 180°/s after three months of TKD training. However, no significant improvement was found in either control group over time ($p > 0.05$). Average isokinetic peak torque of knee extensor measures were comparable among the three groups at baseline. However, after TKD training, average isokinetic peak torque of knee extensors at 180°/s among children with DCD was 33.3% higher ($p < 0.001$) than that among the DCD control group, and was comparable to that among the normal control group ($p > 0.0083$). Isokinetic knee extensor peak torque at 180°/s in DCD control children remained significantly lower than that among typically developing children post-test ($p < 0.001$) (Table 2).

A significant time by group interaction effect ($p < 0.001$) was also found in measuring the isokinetic peak torque of knee flexors at 180°/s. Between-group comparisons demonstrated that the differences among the three groups were not statistically significant at baseline ($p > 0.0083$). Paired t-tests revealed that both groups of DCD-affected children made significant improvements over the course of the training program. Isokinetic peak torque of knee flexors at 180°/s improved by 33.6% ($p < 0.001$) in the DCD-TKD group after three months of training. Although a spontaneous increase in isokinetic peak torque of knee flexors at 180°/s (6.1%, $p = 0.035$) was observed in the DCD control group, this improvement was far smaller than that seen in the DCD-TKD group. Interestingly, there was some deterioration in knee flexor peak torque at 180°/s (15.0%, $p = 0.05$) in the normal control group over the study period. Therefore, the average isokinetic peak torque of hamstring (180°/s) measures recorded post-test were similar between the normal control group and the DCD control group ($p > 0.0083$) and between the normal control group and the DCD-TKD group ($p > 0.0083$). However, when comparing knee flexor strength in the DCD-TKD group with that in the DCD control group, DCD-TKD children out-performed DCD control children ($p = 0.003$) post-test, indicating that TKD training could facilitate the development of isokinetic knee flexor muscle strength (at 180°/s) in children with DCD (Table 2).

Measures of isokinetic peak torque of knee extensors at 60°/s ($p = 0.403$) and 240°/s ($p = 0.718$), and of knee flexors at 60°/s ($p = 0.782$) and 240°/s ($p = 0.519$), revealed no significant time by group interaction. There was no significant pre-test or post-test difference ($p > 0.0083$) among the groups in any of the above outcomes, indicating that the three groups were comparable in terms of isokinetic knee extensor and flexor strength at 60°/s and 240°/s regardless of TKD training. Nevertheless, the DCD control group did demonstrate some spontaneous improvement in isokinetic peak torque of knee extensors at 60°/s ($p = 0.020$) and 240°/s ($p = 0.006$) over time (Table 2).

To avoid the possible confounding effect due to developmental differences in the participants, age was treated as a covariate in the secondary analyses and yielded similar results (not shown).

3.3. Changes in UST COP sway velocity and the MCT composite score

There was a significant time by group interaction ($p < 0.001$) in UST COP sway velocity. Paired t-tests revealed that only children with DCD who received TKD training experienced significant improvement (sway velocity decreased by 60.6%, $p < 0.001$) over time. No improvement was found in the two control groups ($p > 0.05$). Between-group comparisons demonstrated that children in the DCD control group swayed at a faster velocity during single-leg standing than did the normal control children both pre-test ($p = 0.012$) and post-test ($p = 0.017$). There was no significant pre-test difference in COP sway velocity between the DCD-TKD group and the DCD control group ($p > 0.025$). However, after three months, DCD-TKD children demonstrated a more significant improvement in COP sway velocity than that observed among DCD control children ($p < 0.001$). The COP stability performance of DCD-TKD children actually surpassed that of typically developing children, though the difference was not statistically significant ($p = 0.685$) (Table 2).

The MCT composite scores showed no improvement between the pre- and post-test intervals in all three groups ($p > 0.05$). In addition, there was no between-group difference in either pre- or post-test measurements ($p > 0.025$) (Table 2).

3.4. Relationship between isokinetic knee muscle strength (at 60°/s, 180°/s and 240°/s) and balance ability in TKD-trained children with DCD

Children in the DCD-TKD group had significantly higher isokinetic peak torque in both their knee extensors and knee flexors, especially at 180°/s, and had lower UST COP sway velocity than those in the DCD control group post-test (Table 2). Therefore, the isokinetic outcomes and the UST COP sway velocity data were used in the subsequent correlation analysis. The results revealed that only isokinetic peak torque of knee extensors at 180°/s was significantly correlated with UST COP sway velocity in DCD-TKD children post-test ($r = -0.429$, $p = 0.052$) (Portney & Watkins, 2009) (Table 3).

4. Discussion

4.1. Developmental status of knee muscle strength and reactive and static postural control among children with and without DCD

In contrast with our original hypothesis and previous research findings (Raynor, 2001), this study demonstrated that the measures of isokinetic peak torque for both knee extensors and knee flexors at 60°/s, 180°/s and 240°/s were similar among children with and without DCD (age range: 6-12 years), even before the TKD training (Table 2). Raynor (2001) found that children with DCD (age range: 6-10 years) produced significantly lower levels of peak torque during knee extension and flexion than did those in the control group (age range: 6-10 years). When further dividing children by age in the sensitivity analysis, his results showed that older children with DCD (9-10 years old) had similar knee extensor peak torque at a slow velocity (120°/s) to that observed among children in the normal control group. This suggests that the knee muscle strength difference between children with and without DCD may decrease with age (Raynor, 2001). As some children with DCD in the present study were relatively old (up to 12), it is possible that some of them might have already caught up with their typically developing peers in terms of developmental milestones and muscle strength development (Cantell, Smyth, & Ahonen, 1994; Knuckey & Gubbay, 1983; Visser, Geuze, & Kalverboer, 1998). Therefore, we found no significant difference in knee muscle strength between the three groups.

This is the first study to use the motor control test to investigate functional reactive balance control in children with DCD. We found no significant between-group difference in the MCT composite latency score at baseline. Reactive balance ability in children with DCD was as good as that observed in their typically developing peers (Table 2). The question, however, is what conclusion should be drawn from this result. The MCT composite latency score representing the total reaction time between the onset of platform translation and the initiation of force response in the legs (NeuroCom, 2008) can actually be divided into two time periods: premotor reaction time and electromechanical delay (Chung & Ng, 2012). Premotor reaction time represents latency between the start of platform translation and the onset of lower limb muscle reflex contraction (which can be detected by electromyography). It denotes the speed of neural transmission and information processing in the central nervous system. In contrast, electromechanical delay (i.e., the interval between the onset of electomyographic signals and force production in the legs) reflects the neuro-mechanical properties of muscles (Chung & Ng, 2012). It is known that premotor reaction time in children with DCD is as short as that in typically developing children (Geuze, 2003). Therefore, electromechanical delay should also be similar between children with and without DCD, giving them similar total reaction times. In other words, developmental coordination disorder itself may not affect the neuro-mechanical properties of children's muscles.

In line with our previous findings (Fong et al., 2011; Fong et al., 2012b; Fong, Tsang, & Ng, 2012a), this study provides supplemental evidence that static single-leg standing balance control is inferior in children with DCD, regardless of whether they stand on their dominant or non-dominant leg (participants stood on their non-dominant leg in our previous studies, but stood on their dominant leg in this study) (Table 2). This could be attributed to the fact that DCD-affected children are less reliant on visual and vestibular inputs to maintain balance (Fong et al., 2011; Fong et al., 2012b), and may be over-reliant on the hip strategy to achieve balance (Fong et al., 2012a).

4.2. Differential training effect of short-term TKD on knee muscle strength in children with DCD

This study revealed that measures of isokinetic peak torque (at 180°/s) of knee extensors and flexors increased by 25.4% and 33.6%, respectively, in children with DCD following TKD training. At post-test, the peak torque of their knee muscles was comparable to that of typically developing children, and was significantly higher than that of children in the DCD control group. However, knee muscle strength improvements were not observed at other test velocities (i.e. 60°/s and 240°/s) (Table 2). This differential improvement in muscle strength could be explained by the 'specificity' exercise training principle: muscle strength gains are consistently greatest at the training velocity (McArdle, Katch, & Katch, 2010). Because the DCD-TKD novices participating in our study learned and practiced the various kicking techniques at relatively slow joint movement velocities of perhaps 180°/s, the improvement observed in muscle strength was found at this specific movement velocity (180°/s).

This study also confirmed that TKD training for a period as short as three months is sufficient to improve knee muscle strength in children with DCD (Table 2). This finding was expected because of the many resistance training components, such as jumping and kicking and kicking target pads, practiced during TKD training (Park et al., 1989). DCD-TKD children practiced these low-resistance knee flexion-extension movements repeatedly for three consecutive months. This could have induced neural adaptation (from the second week onwards) and subsequent muscular adaptation in the neuromuscular system (McArdle et al., 2010). This study provides further evidence that both neural and muscular adaptations contribute to knee muscle strength improvement in children with DCD.

With respect to the knee muscle strength of the non-TKD trained children with DCD, spontaneous improvements were observed in the isokinetic peak torque of both knee extensors (at 60°/s and 240°/s) and knee flexors (at 180°/s) (Table 2). We believe that growth-related muscle strength improvements also occurred in the DCD-TKD group, but that the growth effect was masked by the TKD training effect. Interestingly, no age-related increase in muscle strength was observed in the normal control group. The typically developing children even showed some deterioration in knee flexor peak torque at 180°/s during the study period. This result could be explained by sampling (self-selection) bias (Portney & Watkins, 2009). Participants in the normal control group were not randomized, and they nominated themselves for the 'physiotherapy assessment'. Their motor ability, though within the normal range (i.e. MABC-2 > 15th percentile), was at the lower end of normal (average MABC-2 percentile rank = 20.18). Children in the normal control group may have led less active lifestyles or their motor and muscle strength development may have been hampered by genetic factors (Armstrong & van Mechelen, 2000).

4.3. Reactive and static postural control in children with DCD after TKD training

The MCT composite latency score measured in this study is an indicator of an individual's reaction time in response to postural disturbances (NeuroCom, 2008). We found that the balance reaction time in children with DCD was as fast as that observed in their typically developing peers, and that TKD training does not improve it further (Table 2). Indeed, a previous study showed no difference in reaction time (i.e., sum of premotor reaction time and electromechanical delay) between martial arts practitioners and controls (O'Donovan, Cheung, Catley, McGregor, & Strutton, 2006), suggesting that reaction time cannot be trained. From the physiological perspective, balance reaction time is a measure of the efficiency of the postural reflex, and of the stretch reflex in particular. For example, when a participant is perturbed forward unexpectedly, muscle spindles in the gastrocnemius, hamstring and paraspinal muscles are stretched (Shumway-Cook & Woollacott, 2007). This stretching force produces a sudden burst of activity in the sensory neurons monitoring these muscle spindles, and the sensory neurons synapse on the spinal motor neurons. As a result, the extrafusal muscle fibers are activated and produce an immediate increase in muscle tone (i.e., postural response is initiated) (Martini, 1995). This closed loop postural response includes a number of reflexive neuro-motor events (Martini, 1995) that are not likely to be hastened by exercise training.

Nor was there an obvious effect of maturation on reactive postural control in children with and without DCD. No spontaneous improvement was observed over time in any of the groups. This may be because our study period was relatively short (three months only). Further study should incorporate a longer training period and follow-up assessments.

Although reactive balance control in children with DCD cannot be improved by a three-month TKD training regime, the present study and our previous study (Fong et al., 2012b) demonstrate that it can improve static single-leg standing balance. Children with DCD who had undergone TKD training attained similar postural sway velocity in single-leg standing to that observed in their normally developing peers. However, no such improvement was observed in the DCD control group over time (i.e., maturation does not help). Their unilateral stance stability remained inferior to that of typically developing children (Table 2). Possible explanations for the improvement in single-leg standing balance following TKD training in children with DCD include: (1) TKD training can improve the vestibular function that provides the most reliable sensory information for postural control (Fong et al., 2012b); (2) similar to karate-trained athletes, TKD-trained children might have more effective cerebral mechanisms for integrating somatosensory, visual and vestibular inputs; therefore, they experience slower body sway while standing (Del Percio et al., 2009); (3) TKD-trained children might have developed better postural adjustment strategies and body alignment while practicing kicking or single-leg standing (Violan, Small, Zetaruk, & Micheli, 1997); and (4) their improved postural stability in a unilateral stance is associated with improved isokinetic knee extensor muscle strength (at 180^{o}/s only, but not at 60^{o}/s or 240^{o}/s due to the specificity of TKD muscle training) as demonstrated in the present study (Table 3). Further study might fruitfully explore other factors that contribute to the improved balance in TKD-trained children with DCD.

4.4. Limitations and future research directions

The major limitation of this study is the relatively high attrition rate among the sample, particularly in the two control groups. We employed the intention-to-treat principle via the last observation carried forward method. This may have contributed to the ‘no change’ observations made for most of the outcome parameters in the two control groups throughout the study period. When analyzing the major reasons for participants dropping out, ‘lost to follow-up’ and ‘unable to commit the time’ accounted for 65.2% of the total attrition rate (Fong et al., 2012b). We consider that because children assigned to the control groups did not receive any intervention, this might have upset both the children and their parents. Further study might improve on our approach by incorporating some sedentary interventions, such as English tutoring, in control groups. A crossover design with an adequate washout period (Portney & Watkins, 2009) might also be feasible. Another limitation of this study is the great within-group variability (large SD value) in the UST COP sway velocity data. Standard error of mean (SEM) is large which means that the average value of the sample might not be representative of the population. Further study should include a larger sample size to minimize the error (Portney & Watkins, 2009). In addition, further study may fruitfully compare the effects of TKD in both DCD-affected and typically developing children by incorporating a non-DCD TKD group. Moreover, the relationship between balance performance and fall risk or activity participation should also be addressed.

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Declaration of conflicting interests

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References

American Psychiatric Association APA. (2000). *Diagnostic and statistical manual of mental disorders.* Washington, DC: American Psychiatric Association.

Armstrong, N., & van Mechelen, W. (2000). *Paediatric exercise science and medicine.* Oxford: Oxford University Press.

Cantell, M.H., Smyth, M.M., & Ahonen, T.P. (1994). Clumsiness in adolescence: educational, motor, and social outcomes of motor delay detected at 5 years. *Adapted Physical Activity Quarterly,* 11, 115-129.

Chan, K.M., Maffulli, N., Korkia, P., & Li, R.C.T. (1996). *Principles and practice of isokinetics in sports medicine and rehabilitation.* Hong Kong: Williams and Wilkins.

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.

Chung, P., & Ng, G. (2012). Taekwondo training improves the neuromotor excitability and reaction of large and small muscles. *Physical Therapy in Sport,* 13, 163-169.

CSMI. (2005). *HUMAC/NORM testing and rehabilitation system user's guide: Model 770.* MA: Computer Sports Medicine, Inc.

Del Percio, C., Babiloni, C., Marzano, N., Lacoboni, M., Infarinato, F., Vecchio, E., et al. (2009). Neural efficiency of athletes' brain for upright standing: A high-resolution EEG study. *Brain Research Bulletin,* 79, 193-200.

Fong, S.S.M., Lee, V.Y.L., & Pang, M.Y.C. (2011). Sensory organization of balance control in children with developmental coordination disorder. *Research in Developmental Disabilities,* 32, 2376-2382.

Fong, S.S.M., & Tsang, W.W.N. (2012). Relationship between the duration of taekwondo training and lower limb muscle strength in adolescents. *Hong Kong Physiotherapy Journal,* 30, 25-28.

Fong, S.S.M., Tsang, W.W.N., & Ng, G.Y.F. (2012a). Altered postural control strategies and sensory organization in children with developmental coordination disorder. *Human Movement Science* doi: 10.1016/j.humov.2011.11.003.

Fong, S.S.M., Tsang, W.W.N., & Ng, G.Y.F. (2012b). Taekwondo training improves sensory organization and balance control in children with developmental coordination disorder: A randomized controlled trial. *Research in Developmental Disabilities*, 33, 85-95.

Fong, S.S.M., Fu, S.N., & Ng, G.Y.F. (2012c). Taekwondo training speeds up the development of balance and sensory functions in young adolescents. *Journal of Science and Medicine in Sport,* 15, 64-68.

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

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.

Henderson, S.E., Sugden, D.A., & Barnett, A.L. (2007). *Movement Assessment Battery for Children-2 (MABC-2)* (2nd ed.). London: Pearson Assessment.

Hiller, S., McIntyre, A., & Plummer, L. (2010). Aquatic physical therapy for children with developmental coordination disorder: A pilot randomized controlled trial. *Physical & Occupational Therapy in Pediatrics*, 30, 111-124.

Holmes, J.R., & Alderink, G.J. (1984). Isokinetic strength characteristics of the quadriceps femoris and hamstring muscles in high school students. *Physical Therapy*, 64, 914–918.

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.

Knuckey, N.W., & Gubbay, S.S. (1983). Clumsy children: a prognostic study. *Australian Paediatric Journal*, 19, 9-13.

Leitner, C., Mair, P., Paul, B., Wick, F., Mittermaier, C., Sycha, T., et al. (2009). Reliability of posturographic measurements in the assessment of impaired sensorimotor function in chronic low back pain. *Journal of Electromyography and Kinesiology*, 19, 380-390.

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

Martini, F.H. (1995). *Fundamentals of Anatomy and Physiology* (3rd ed.). New Jersey: Prentice-Hall International, Inc.

McArdle, W.D., Katch, F.I., & Katch, V.L. (2010). *Exercise physiology – Nutrition, energy, and human performance.* (7th ed.). Philadelphia: Lippincott Williams & Wilkins.

Moreland, J.D., Richardson, J.A., Goldsmith, C.H., & Clase, C.M. (2004). Muscle weakness and falls in older adults: A systematic review and meta-analysis. *Journal of the American Geriatrics Society*, 52, 1121-1129.

NeuroCom. (2008). *Balance Manager Systems – Instructions for Use.* Oregon: NeuroCom International, Inc.

O’Donovan, O., Cheung, J., Catley, M., McGregor, A.H., & Strutton, P.H. (2006). An investigation of leg and trunk strength and reaction times of hard-style martial arts practitioners. *Journal of Sports Science and Medicine*, Combat Sports Special Issue, 5-12.

Park, Y.H., Park, Y. H., & Gerrard, J. (1989). *Tae Kwon Do: the ultimate reference guide to the world’s most popular martial art.* London: Ward Lock.

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

Portney, L.G., & Watkins, M.P. (2009). *Foundations of clinical research – Applications to practice* (3rd ed.). New Jersey: Pearson Education, Inc.

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

Schoemaker, M., Hijlkema, M., & Kalverboer, A. (1994). Physiotherapy for clumsy children: An evaluation study. *Developmental Medicine and Child Neurology*, 36, 143-155.

Shumway-Cook, A., & Woollacott, M.H. (2007). *Motor control: Translating research into clinical practice* (3rd ed.). Philadelphia: Lippincott Williams and Wilkins.

Stout, J.L. (2006). Gait: Development and analysis. In S.K. Campbell, D.W. Vander Linden, & R.J. Palisano (Eds.), *Physical Therapy for Children* (3rd ed., pp. 161-190).

Tsang, W.W.N., & Hui-Chan, C.W.Y. (2005). Comparison of muscle torque, balance, and confidence in older tai chi and healthy adults. *Medicine & Science in Sports & Exercise*, 37, 280-289.

Violan, M.A., Small, E.W., Zetaruk, M.N., & Micheli, L.J. (1997). The effect of karate training on flexibility, muscle strength, and balance in 8- to 13-year-old boys. *Pediatric Exercise Science*, 9, 55-64.

Visser, J., Geuze, R.H., & Kalverboer, A.F. (1998). The relationship between physical growth, the level of activity and the development of motor skills in adolescence: differences between children with DCD and controls. *Human Movement Science*, 17, 573-608.

Tables

Table 1. Participant characteristics at baseline

	DCD-TKD group (n = 21)	**DCD control group (n = 23)**	**Normal control group (n = 18)**	**p value**
Age, years	7.7±1.3	7.4±1.2	7.2±1.0	0.411
Sex (Male/female), n	17/4	18/5	14/4	0.965
Height, cm	127.4±9.9	123.2±11.2	122.7±10.1	0.294
Body weight, kg	28.1±9.2	26.7±10.1	26.8±8.4	0.872
BMI, kg/m^2	16.8±3.2	17.0±3.2	17.3±2.7	0.873
Co-morbidity				
Attention deficit hyperactivity disorder	3	4	0	
Attention deficit disorder	3	4	0	
Dyslexia	4	2	0	
Asperger syndrome	2	3	0	
Autism spectrum disorders	1	0	0	

Note: Values are mean ± SD.

Table 2. Comparison of outcome measurements among the three groups (pre- and post-TKD training) and within individual groups

	DCD-TKD group (n = 21)		**DCD control group (n = 23)**		**Normal control group (n = 18)**		**p value**		
Measurements	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**	**Pre-test (Group effect)**	**Post-test (Group effect)**	**Group x time effect**
Body-weight-adjusted isokinetic peak torque of knee extensors at									
60°/s (Nm)	95.46± 16.19	99.77± 21.74	91.26± 26.07	106.30± 37.12[e]	115.17± 29.67	119.54± 41.47	0.008[a]	0.403	0.403
180°/s (Nm)	80.29± 21.60	100.67± 11.09[c,e]	81.49± 16.74	75.53± 18.01	98.22± 20.29	98.67± 20.37[c]	0.010	<0.001[a]	<0.001[a]
240°/s (Nm)	69.78± 20.90	72.92± 18.61	64.00± 17.73	70.83± 21.97[e]	78.12± 19.53	80.17± 23.62	0.077	0.983	0.718
Body-weight-adjusted isokinetic peak torque of knee flexors at									
60°/s (Nm)	55.14± 21.08	59.14± 22.62	52.35± 21.78	54.13± 24.86	71.17± 13.98	75.61± 19.92	0.008[a]	0.782	0.782
180°/s (Nm)	44.90± 15.06	60.00± 8.89[c,e]	43.26± 13.98	45.91± 15.36[e]	56.39± 13.19	47.94± 14.96[e]	0.010	<0.001[a]	<0.001[a]
240°/s (Nm)	40.58±	41.20±	39.33±	42.46±	48.71±	44.71±	0.065	0.811	0.519

	14.98	16.13	12.66	16.32	11.71	14.81			
Unilateral stance test									
COP sway velocity (°/s)	3.71± 2.03	1.46± 0.46^{d,e}	3.94± 2.27	3.60± 2.38	2.15± 1.05	2.11± 1.35^{d}	0.009^{b}	<0.001^{b}	<0.001^{b}
Motor control test									
Composite score (ms)	128.16± 44.00	128.54± 44.76	138.10± 33.96	137.67± 33.02	108.00± 51.14	107.50 ±50.89	0.089	0.066	0.657

Note: Values are mean ± SD or p values.

Group by time interaction and among the three groups:

[a] Denotes a difference significant at $p < 0.0083$;

[b] Denotes a difference significant at $p < 0.025$.

Among groups:

[c] Denotes a difference significant at $p < 0.0083$ when compared with the DCD control group;

[d] Denotes a difference significant at $p < 0.025$ when compared with the DCD control group.

Within group (time effect):

[e] Denotes a difference significant at $p < 0.05$ when compared with pre-test values.

Table 3. Correlations between isokinetic peak torque of knee muscles and UST COP sway velocity in DCD-TKD group post-test

Body-weight-adjusted isokinetic peak torque	**Unilateral stance test COP sway velocity (°/s)**
Knee extensors	
60°/s	-0.265
180°/s	-0.429*
240°/s	-0.048
Knee flexors	
60°/s	-0.244
180°/s	-0.326
240°/s	-0.044

* Denotes a significant difference at $p < 0.05$.