

Assessment of Upper Limb Proprioception in Children with Developmental Coordination
Disorder

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Abstract

It has long been suspected that proprioceptive abnormalities underlie the motor problems in children with developmental coordination disorder (DCD). However, current empirical evidence of proprioceptive dysfunction in children with DCD is still inconsistent. To address this issue, this study pursued the following three aims: 1) To obtain objective measures of position sense acuity to verify that children with DCD have proprioceptive deficits. 2) To examine whether the proprioceptive abnormality in children with DCD is joint-specific or a generalized somatosensory deficit that affects distal as well as proximal joints. 3) To investigate the relationship between motor function and position sense acuity in children with and without DCD.

Methods: Twenty children with DCD [(Mean age: 10 years 4 months (SD: 3 months); 9♂, 11♀) and thirty typically developing (TD) children [M age: 10 years 5 months (SD: 3 months); 14 ♂, 16♀] were recruited and screened using Movement Assessment Battery for Children (MABC-2). The DCD group had total MABC-2 score below 5th percentile, and TD group was above 25th percentile. Using a body-scalable wrist and elbow bimanual manipulandum, proprioceptive status was assessed using 1] a wrist and elbow joint position matching task requiring active movement to reproduce a target position with either the same or the opposite hand/forearm, and 2] a psychophysical two-alternate forced choice test for the wrist that relied on passive motion. It required children to discriminate between two joint positions. We measured both aspects of position sense acuity: bias and precision. Bias indicates the proximity of a sensed limb position corresponds to the true physical position of the limb. Precision represents the random

error or the agreement between independent repeated responses and is thus a measure of response consistency.

Results: First, in comparison to TD controls children with DCD exhibited a significantly lower position sense precision on both elbow ($p < 0.05$) and wrist ($p < 0.001$). Position sense bias during active joint position matching at either joint was not significantly higher in children with DCD. Second, the mean wrist position sense discrimination threshold for passive displacement was highly elevated in DCD group (+171%; $p < 0.001$). Third, position sense discrimination threshold correlated significantly with upper limb motor ($r = -0.40$) and balance scores ($r = -0.50$).

Conclusion: This study documents that DCD is associated with a dysfunction of position sense. Furthermore, the proprioceptive dysfunction affected both proximal and distal upper limb joints in children with DCD, which is consistent with a view that proprioceptive dysfunction in DCD is generalized in nature. Given the substantial evidence that proprioceptive deficits degrade motor control, these sensory deficits may partly explain fine motor control impairment in DCD.

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motor function. The JND thresholds explain 16% of the variance of the MABC-2
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1 Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder characterized by poor motor skill learning and uncoordinated movements that significantly interfere with a child's activities of daily living, academic achievement and vocational activities (APA, 2013). The prevalence of DCD is approximately 5-6% of all school-aged children (APA, 2013). Boys are more affected than girls (boy: girl = 2:1 to 5:1). The motor symptoms in DCD may include difficulty on fine and gross motor skills such as tying shoelaces, dressing, handwriting, jumping a rope, and riding a bike. At present, the motor assessment relies on the standardized tests such as the Movement Assessment Battery for Children (MABC-2) or Bruininks-Oseretsky Test of Motor Proficiency (BOT-2). The somatosensory deficits in DCD are not routinely determined.

The etiology of DCD remains unclear. Part of the reason is that children with DCD is a heterogeneous group with wide range of motor difficulties. Some children might demonstrate abnormal performances in gross motor functions such as balance and postural control, while others show difficulties in fine motor functions such as handwriting. Furthermore, children with DCD are frequently comorbid with other developmental disorders. Previous studies have reported that approximately a third of children with DCD overlap with attention deficit hyperactive disorder (ADHD) (Ghanizadeh, 2010; Goulardins et al., 2015; Piek, Pitcher, & Hay, 1999). Children with developmental dyslexia (Fawcett & Nicolson, 1995; Fawcett, Nicolson, & Dean, 1996) and autism spectrum disorder (Matson, Matson, & Beighley, 2011) often exhibit reduced motor competence and poor movement coordination as children with DCD.

Recently, neuroimaging data suggest that neural structures involved in perceptual motor control and sensorimotor function such as motor cortex, basal ganglia, and cerebellum are abnormal in DCD (Biotteau et al., 2016; Brown-Lum & Zwicker, 2015; Peters, Maathuis, & Hadders-Algra, 2013). For example, when performing a visual-motor tracing task, children with DCD showed reduced fractional anisotropy in the left internal capsule related to sensorimotor function. (Debrabant et al., 2016). Other studies showed that children with DCD have been found to have abnormal neural connectivity between middle frontal cortex, anterior cingulate cortex, and to inferior parietal cortex, when performing a simple cognitive motor task (Querne et al., 2008). Moreover, functional connectivity between motor cortex and basal ganglia during the resting state is reduced in children with DCD (McLeod, Langevin, Goodyear, & Dewey, 2014). Indeed, it has been suggested that the brain abnormalities in DCD are not macroscopic, but DCD manifests itself at the molecular level such as the neurotransmitters of the central nervous system (Hadders-Algra, 2003; Smits-Engelsman & Wilson, 2013).

The term proprioception refers to the awareness of limb or body position and motion (Goldscheider, 1898). The mechanism of proprioceptive information depends on the integration of the signals at the peripheral and supraspinal levels. At the peripheral level, proprioceptive signals from muscle spindles, Golgi tendon organs, or mechanoreceptors in ligaments or joint capsules, play a vital role in detecting joint position and motion. Perceptual processes related to proprioception occur at the supraspinal structures such as cerebellum, basal ganglia, and somatosensory cortex (Proske & Gandevia, 2012). Proprioception is integrated with motor processes, and plays

a crucial role in limb and balance control as well as in motor skill learning (Elangovan, Herrmann, & Konczak, 2014; Hillier, Immink, & Thewlis, 2015; Niessen, Veeger, & Janssen, 2009). The loss or dysfunction of proprioception can severely affect motor control producing deficits in movement coordination (Sainburg, Poizner, & Ghez, 1993), and movement control (Konczak et al., 2009).

Previous research proposed that the processing of proprioceptive signals is compromised in children with DCD and that proprioceptive deficits underlie the motor problems in children with DCD. However, at present, the available empirical results supporting the claim of proprioceptive abnormalities in children with DCD are still mixed. For example, some reports demonstrated that children with DCD had poorer proprioceptive function by showing a reduced ability to detect position and motion sense than TD children (Coleman, Piek, & Livesey, 2001; Li, Su, Fu, & Pickett, 2015; Piek & Coleman-Carman, 1995), while other studies could not confirm that DCD have proprioceptive dysfunction (Adams, Ferguson, Lust, Steenbergen, & Smits-Engelsman, 2016; Hoare & Larkin, 1991; Lord & Hulme, 1987; Smyth & Mason, 1997). The lack of solid, unequivocal evidence is likely due to several factors: First, previous studies have relied on the Kinaesthetic Sensitivity Test (KST) (Bairstow & Laszlo, 1981) and the Kinaesthetic Acuity Test (KAT) (Livesey & Parkes, 1995) to measure proprioception. The KST has been criticized for having poor accuracy and sensitivity (Elliott, Connolly, & Doyle, 1986; Visser & Geuze, 2000) and the KAT requires cross-modal transformation (vision and proprioception) to assess proprioceptive acuity. Second, the employed proprioceptive assessment protocols test different aspects of proprioception. They either

passively displace a limb or they require the child to make an active movement. For example, recent reports show that children with DCD required a larger displacement of the forearm before they detect passive motion (Li et al., 2015), but arm position sense errors were normal during active joint position matching (Adams et al., 2016). It should be noted that the difference between assessing proprioceptive function using active or passive motion is not trivial. Sensing the position of a passively displaced limb relies solely on sensory feedback from proprioceptive afferents, while matching a limb position using active motion also involves the processing of internal predicted sensory feedback that is based on the efference copy of the motor command (Konczak et al., 2012; Sciutti et al., 2010; Wolpert, Pearson, & Ghez, 2013). That is, the former minimizes the movement confounding effects and reflects processing of purely internal sensory feedback while the latter reflects the function of somatosensory as well as sensorimotor integration and control processes (Sciutti et al., 2010).

Moreover, proprioceptive signals from proximal and distal segments are processed through different pathways (Clark, Burgess, & Chapin, 1986). It has been reported that proprioceptive afferents from proximal joints project bilaterally, whereas the distal joint afferents project to the contralateral hemisphere (Lu, Barrett, Cibula, Gilmore, & Heilman, 2000). Additional evidence indicates that proprioceptive acuity differs for the different degrees of freedom of the wrist joint (Cappello et al., 2015; Marini, Squeri, Morasso, Konczak, & Masia, 2016), because the mechanoreceptor density of the ligaments stabilizing adduction/abduction movement is higher than for flexion/extension (Hagert, Forsgren, & Ljung, 2005). Moreover, proprioceptive acuity for

wrist and finger joints is lower than for elbow and shoulder joints (Goldscheider, 1898; Putzki et al., 2006). Therefore, position sense acuity at proximal versus distal joints is expected to be different.

In clinical practice, choosing a proper method for assessing proprioception in children with DCD is crucial for several reasons. First, children have relatively short attention spans, the time period of assessment needs to be short and accurate in order to accommodate their demands. Second, the measurements should be objective and quantifiable with precise resolution for having enough sensitivity to detect the proprioceptive deficits. Third, the equipment and experimental methods should be valid and reliable. Therefore, given the above concerns, I employed two available methods and assessed multiple joints of upper limb position sense acuity, mainly the joint position matching method and psychophysical threshold testing method. Two experiments with different methods were conducted in conjunction for better understanding of upper limb position sense function in children with DCD.

In the first experiment, I assessed position sense acuity at a proximal joint (elbow) and a distal joint (wrist) in children with DCD by employing a joint position matching paradigm. The joint position matching paradigm has a contralateral matching and an ipsilateral matching task. That is, it requires individuals to actively match a position of one limb with the same limb or with opposite limb (Goble, Lewis, Hurvitz, & Brown, 2005). Position sense bias (systematic error) and position sense precision (random error) serve as dependent variables to measure position sense acuity. *Position sense bias* represents how close the matched or remembered position responses of the children are to

the reference position. Zero bias means there is no difference between reference position and the matched or remembered position. *Position sense precision* indicates the random error or agreement across all trials. In general, joint position matching tasks are faster than psychophysical methods, which makes them more viable for clinical use. Active joint position matching has been shown to be suitable for clinical use in children with hemiplegic cerebral palsy (Goble, Hurvitz, & Brown, 2009).

In the second experiment, I utilized a psychophysical threshold testing method that relies only on passive motion to displace a limb or joint. This test removes efference copy of motor command and predicted sensory feedback, to obtain a measure of upper limb position sense acuity. In this assessment, a child performs no movements, but to sense two passively moved hand positions and make verbal judgment about which hand position has greater magnitude (compared to the same starting position). A just-noticeable-difference (JND) position sense threshold can be obtained to measure position sense bias. The psychophysical threshold method has been used in children (Elliott et al., 1986). The test-retest reliability has also been showed to be high ($r = 0.97-0.98$) (Cappello et al., 2015).

The purpose of this study was to provide comprehensive, objective data on the extent of proprioceptive impairment in children with DCD and to relate it to the observable motor deficits. The results of the present study should add to the emerging scientific evidence on somatosensory deficits associated with DCD. More pragmatically, the results would help to develop an effective and sensitive method for examining proprioceptive deficits in children with DCD. The specific aims were as follows:

Aim 1: To test the hypothesis that children with DCD have lower upper limb position sense acuity than typically developing children. Position sense acuity was measured by two independent methods: the joint position matching method and the psychophysical threshold testing method. For the joint position matching method, position error (bias) and position error variability (precision) served as dependent variables of position sense acuity, while for psychophysical threshold testing method, JND threshold served as an indicator of position sense bias. A significant 1) decrease on position sense precision and 2) an increase on JND threshold in children with DCD, will verify Aim 1.

Aim 2: To determine if the proprioceptive deficit is joint-specific or generalized (i.e., involves more than one joint). The position sense acuity (bias and precision) at two joints (elbow and wrist) in DCD and TD children were compared. Based on the previous findings (Holst-Wolf et al., 2016) showing that typical development of position sense is characterized by an age-related change in position sense precision, I expected a difference between DCD and TD would manifest itself in the position sense precision. Therefore, showing a decreased position sense precision at the elbow and wrist joint in children with DCD when compared to TD children will verify Aim 2.

Aim 3: To determine the relationship between motor deficits and proprioceptive abnormalities in children with DCD. Correlation analyses were performed to investigate the association between position sense acuity and motor function in children with DCD. I expected that upper limb position sense acuity would be significantly correlated with upper limb motor function in DCD as measure by M-ABC. Specifically, a significant

correlation between elbow and wrist position sense acuity and the manual dexterity score of MABC-2 will verify aim 3.

2 Method

2.1 Participants

Twenty children with DCD [M age: 10 years 4 months (SD: 3 months); 9 males, 11 females] and thirty TD children [M age: 10 years 5 months (SD: 3 months); 14 males, 16 females] participated in the study. All children were screened using the Movement Assessment Battery for children (MABC-2) by certified physical therapists and trained researchers. The DCD group had total MABC-2 score below 5th percentile, and TD group was above 25th percentile. Parents and teachers were asked to provide the information and medical reports for identifying children with DCD. Children with neurological conditions (e.g., cerebral palsy, autism spectrum disorders), behavioral problems, current upper limb injury, implanted medical devices in the upper limbs, and/or the IQ below 85 were excluded. The study was approved by the Institutional Review Board of National Cheng Kung University Hospital in Taiwan. Parental consent and child assent were obtained prior to data collection. Edinburgh Handedness Inventory was used to determine children's dominant hand (Oldfield, 1971). All children were right-handed.

2.2 Apparatus

2.2.1 Movement Assessment Battery for Children (MABC-2)

MABC-2 is a standardized movement assessment, which is a commonly reported assessment tool to determine the presence of DCD. MABC-2 includes eight subsets covering the domains of fine and gross motor skills including three subsets in manual dexterity, two subsets in aiming and catching skills, and three subsets in balance. The sum of the scores on all subsections provided the children total movement impairment scores (TIS). Children who have TIS ranging at 56 or lower were defined as DCD (below the 5th percentile) and children have TIS above 68 (above 25th percentile) were considered as TD children. The time duration of assessment for each child was about 30-40 minutes. Mean total MABC-2 score for the DCD group was 49.8 (*SD*: 7.0) and 80.9 (*SD*: 8.9) for the TD group. Table 1 shows the MABC-2 subscores for DCD and TD.

Table 1 MABC-2 scores for children with developmental coordination disorder (DCD) and typically developing (TD) children. Data present the mean \pm standard deviation.

	DCD (<i>n</i> =20)	TD (<i>n</i> =30)	Independent t test
MABC-2 manual dexterity scores	18.9 \pm 5.7	29.3 \pm 6.2	<i>p</i> < 0.01
MABC-2 aiming and catching scores	13.3 \pm 3.5	19.7 \pm 4.7	<i>p</i> < 0.01
MABC-2 balance scores	17.6 \pm 5.4	31.9 \pm 4.3	<i>p</i> < 0.01
MABC-2 Total impairment scores	49.8 \pm 7.0	80.9 \pm 8.9	<i>p</i> < 0.01

2.2.2 The wrist bimanual manipulandum

A wrist bimanual manipulandum with one degree of freedom in the horizontal plane was used to perform the wrist joint position matching tasks and psychophysical discrimination threshold testing task (see Figure 1A). The lever arm length, and handle placement are adjustable for each participant (see Figure 1B). Two U.S. Digital H6 optical encoders (2500 quadrature count/revolution; spatial resolution: 0.036°), housed at the rotating point of the manipulandum lever arms, recorded the angular position of the hands, the sampling rate was set at 200 Hz. To allow for the testing of distinct joint positions across the joint range of motion, the device has a pegboard with holes in a semicircular arrangement. By inserting a metal pin, researchers can select a precise standard position from 140 different positions across 0° - 70° range of motion of the wrist in 0.5° increments (see Figure 1C).

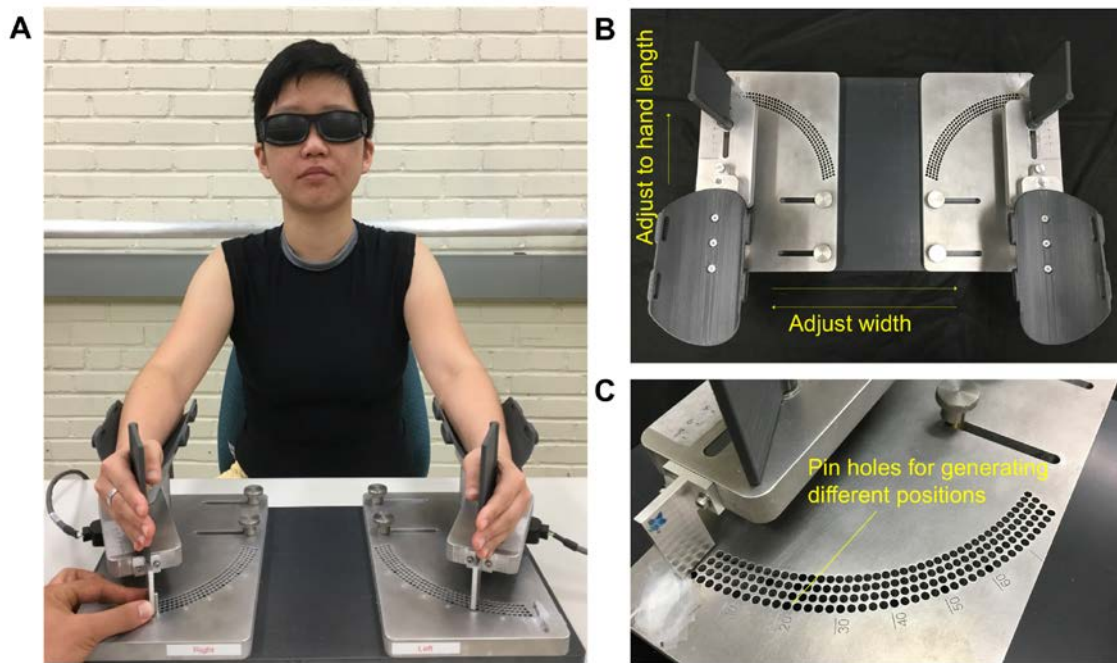


Figure 1. A) Experimental setup during the wrist contralateral matching task. B) The wrist bimanual manipulandum was used for both the active position sense matching and psychophysical discrimination threshold task. C) A pegboard base panel housed under the lever arm allowed to insert a metal pin into a hole to mark a distinct reference position.

2.2.3 The elbow bimanual manipulandum

An elbow bimanual manipulandum with one degree of freedom in the horizontal plane was used to perform the elbow joint position matching task (see Figure 2A). Similar to the wrist device, two U.S. Digital H6 optical encoders (2500 quadrature count/revolution; spatial resolution: 0.036°), were housed at the rotating point of the manipulandum lever arms, recorded the angular position of the forearm, the sampling rate was set at 200 Hz (see Figure 2B).

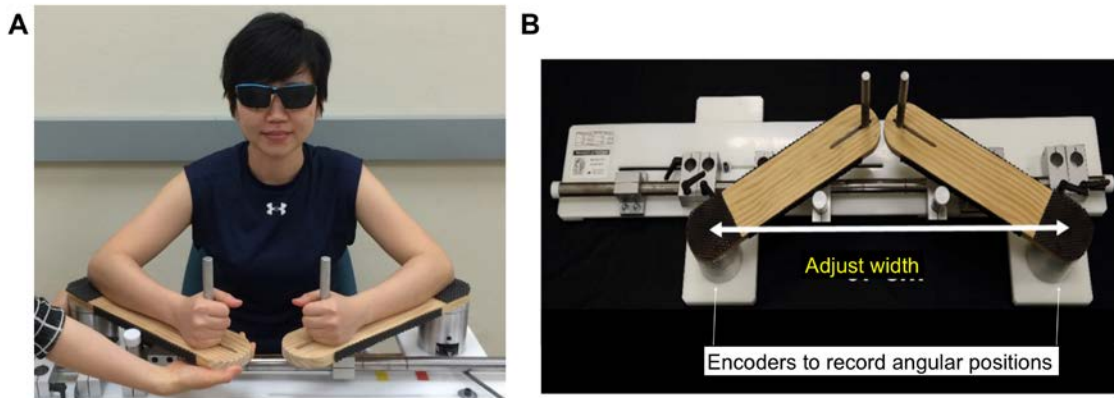


Figure 2. A) Experimental setup during the elbow contralateral matching task. B) The elbow bimanual manipulandum was used to measure position sense acuity at the elbow.

2.3 Procedure

Assessments were conducted in a quiet room for each child to concentrate on the tasks. Children sat comfortably in front of the manipulandum and placed their arms/hands on the levers of manipulandum. Chair height, lever arm length, and handle placement were adjusted to the anthropometrics of each participant in a way that the approximate joint axis of the elbow/wrist aligned directly with rotating axis of the device. Children wore vision occluding goggles to avoid visual disturbances during all tasks (see Figure 1A, Figure 2A, and Figure 3).

All children performed three proprioceptive assessments: 1) joint position matching at the elbow, 2) joint position matching at the wrist, and 3) psychophysical threshold testing at the wrist. The order of the assessments was counterbalanced between children to account for possible order effects. Before the assessment, children performed a few practice trials to become familiar with the procedure and the devices.



Figure 3. Experimental setup for the psychophysical threshold testing task. Here the experimenter displaced the wrist joint with no active movement of the child.

2.3.1 Joint position matching task at the elbow

The joint position matching consisted of a contralateral matching and an ipsilateral matching task. For elbow contralateral matching, the experimenter moved the child's non-dominant hand from the starting position (30° elbow flexion) to the reference position (60° elbow flexion). The movement speed was approximately $20\text{-}25^\circ/\text{s}$. Then, the child matched the reference position with the dominant hand, held the position and then verbally indicated "OK" to inform the experimenter that the target position was

matched. Subsequently, the hand was moved back to the starting position by the experimenter and the next trial began.

For elbow ipsilateral matching, the experimenter moved a child's dominant hand from the same starting position (30° elbow flexion) to the reference position (60° elbow flexion). The movement speed was also approximately 20-25°/s. This reference position was held for 3 seconds and then the hand was moved back to the starting position. Subsequently, the child reproduced the target position by actively moving the dominant hand to a position that she/he felt matched the previously experienced position. The child could adjust the position until satisfied with the match and then verbally indicated that the final matching position was assumed. Each task was repeated five times. The time duration of elbow proprioceptive assessment was approximately 5-10 minutes.

2.3.2 Joint position matching task at the wrist joint

The procedure for the wrist matching tasks were identical to elbow matching with the exception that the starting position of the wrist joint was a natural position (0°), and the reference position was 20° wrist flexion. We only tested the dominant hand to avoid mental fatigue. The time duration of proprioceptive assessment was approximately 5-10 minutes.

2.3.3 Psychophysical threshold task at the wrist

This assessment used the same wrist device as wrist joint position matching task (2.3.2). A child's dominant hand rested on the manipulandum lever and was passively moved to two different positions: a reference position (20° of wrist flexion), and a

comparison position (20.5 – 40 °, in 0.5° increment) (see Figure 3). The two positions were randomly presented. Each position presented for 3 seconds. During each trial, the velocity of the moved hand was maintained in a constant speed of 20°-25°/s. After each trial, using a two-alternative forced choice technique (2AFC), children were asked to verbally judge which position has larger amplitude (i.e., which of the two positions was farther away, the first one or the second one?). Based on the participant's verbal response, an adaptive algorithm (psi-marginal method) generated the subsequent comparison stimulus pair to guarantee fast convergence towards the perceptual threshold within 20 trials. Testing took approximately 15 minutes for each child.

2.4 Measurements

2.4.1 Outcome measures based on joint position matching

For the joint position matching, position error (PE) and position error variability (SDPE) were used. PE, a measure of position sense bias, was calculated as the mean difference between the matching and target angular position. PE indicates systematic error. SDPE, as a measure of position sense precision, was computed as the standard deviation of the PE. SDPE indicates the agreement between repeated responses or random error. PE and SDPE data were normalized by dividing each value over the respective reference position (wrist: 20°; elbow: 30°). PE_{norm} and $SDPE_{norm}$ allow us to compare data across joints.

2.4.2 Outcome measures based on psychophysical threshold testing

For the psychophysical discrimination threshold testing, Position sense discrimination threshold was calculated by fitting children's verbal responses to logistic Weibull function (Kingdom & Prins, 2010; Prins, 2013). Based on the obtained function, the just-noticeable difference (JND) threshold was determined as the angular position at the 75% correct response rate (Elangovan et al., 2014)

2.5 Statistical analysis

Statistical analysis was performed using IBM SPSS version 23.0(IBM Corp, Armonk, NY). Initial statistical analysis using Levine's and Kolmogorov-Smirnov tests determined that all data met homogeneity and normality of variance criteria. PE_{norm} , $SDPE_{norm}$, and JND served as dependent variables.

First, to investigate position sense acuity of different joints between the DCD and TD group, a three-way mixed-design repeated measure ANOVA [2 GROUP * 2 JOINT * 2 TASK] was performed for PE_{norm} and $SDPE_{norm}$. The between-subject factor was GROUP (DCD vs. TD), the within-subject factors were TASK (ipsilateral vs. contralateral) and JOINTS (elbow vs. wrist). Significance level was set as $p < 0.05$, and effect size was reported as η^2 .

Second, to understand if children with DCD is associated with a primary somatosensory deficit, an independent t-test was performed to detect group differences of position sense acuity. Psychophysical discrimination threshold (JND) was the dependent variable, and the two groups served as independent variables. The significant level was set at a value of $p < 0.05$.

Third, to investigate the correlation between upper limb proprioceptive function and motor function, Pearson correlations were conducted. PE_{norm} , $SDPE_{\text{norm}}$, and JND were correlated with three subsets of MABC-2 scores: manual dexterity, ball skill, and balance skill. The significant level was set at a value of $p < 0.05$.

3 Results

3.1 Position sense acuity based on joint position matching

Both groups of children tended to overestimate the true physical position at either joint. Figure 4 shows the respective probability density functions for each group and joint. The mean shift or bias for both groups is similar, but the precision of the DCD children tended to be lower as indicated by the larger spread of the distribution at either joint. This difference in precision was more prominent at the wrist than elbow. Table 2 provides the position sense acuity summary statistics for each group. Table 3 shows the same values of position sense acuity normalized by amplitude for each joint and group. The following analysis focused on the normalized values for PE and SDPE to allow for comparisons between joints.

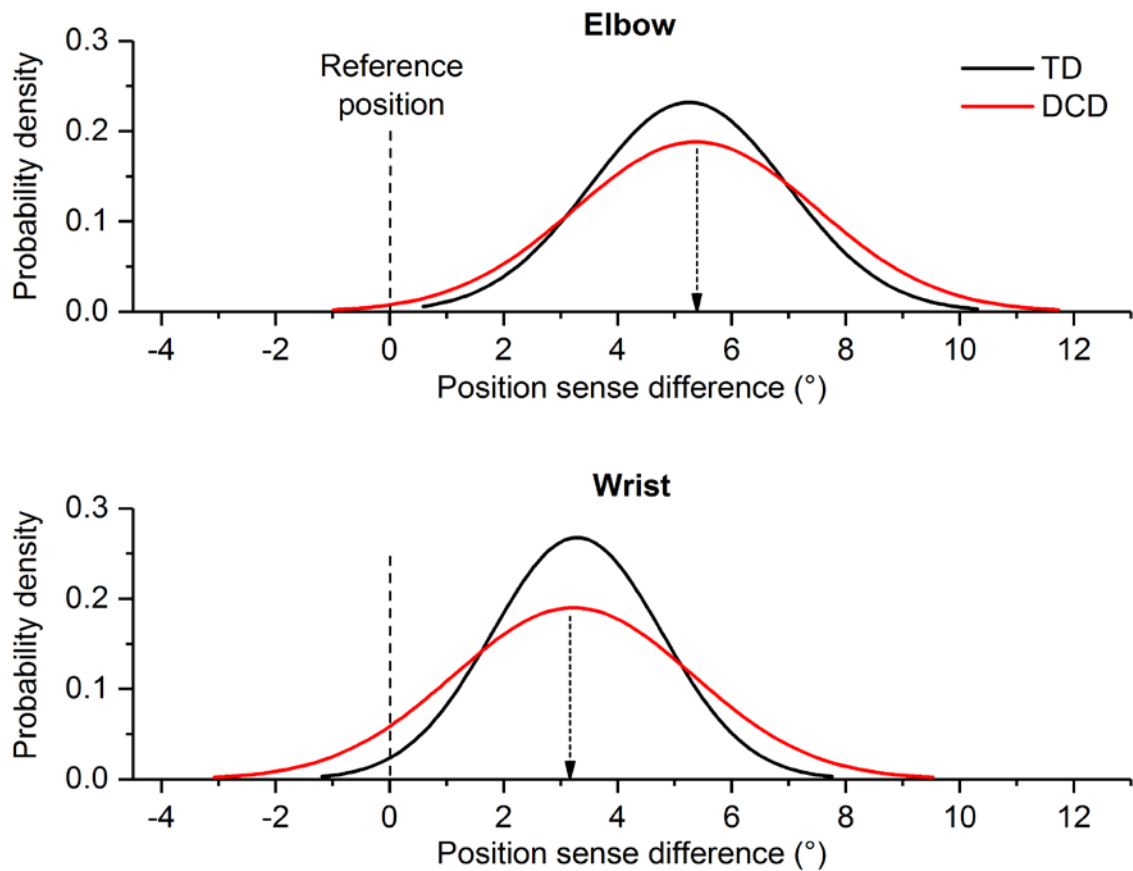


Figure 4. Probability density function of position sense bias at the wrist and the elbow for two groups. Here, the data from the contralateral matching and ipsilateral matching tasks were collapsed for group comparison. Note that children with DCD showed larger spread of the distribution at both the wrist and the elbow, indicating that children had higher random errors between each independent repeated position sense response than TD children did. This group difference of position sense random errors was more prominent for the wrist compared to the elbow.

Table 2 Mean \pm standard deviation of position sense bias (PE) and position sense precision (SDPE) for the DCD and TD groups and each matching task.

		DCD (<i>n</i> =20)		TD (<i>n</i> =30)	
		Contralateral	Ipsilateral	Contralateral	Ipsilateral
Wrist	PE (°)	3.78 \pm 2.73	2.67 \pm 1.56	4.05 \pm 2.79	2.52 \pm 1.40
	SDPE (°)	2.08 \pm 1.03	2.12 \pm 1.03	1.50 \pm 0.69	1.48 \pm 0.74
Elbow	PE (°)	7.92 \pm 3.49	2.82 \pm 1.16	7.40 \pm 3.66	2.88 \pm 1.44
	SDPE (°)	1.80 \pm 1.07	2.45 \pm 1.29	1.44 \pm 0.59	2.00 \pm 0.72

Table 3 Mean \pm standard deviation of PE_{norm} and SDPE_{norm} for the DCD and TD groups and each matching task.

		DCD (<i>n</i> =20)		TD (<i>n</i> =30)	
		Contralateral	Ipsilateral	Contralateral	Ipsilateral
Wrist	PE _{norm} (%)	18.89 \pm 13.67	13.35 \pm 7.78	20.26 \pm 13.96	12.59 \pm 6.99
	SDPE _{norm} (%)	10.39 \pm 5.16	10.61 \pm 5.15	7.51 \pm 3.44	7.39 \pm 3.69
Elbow	PE _{norm} (%)	26.41 \pm 11.63	9.41 \pm 3.87	24.67 \pm 12.21	9.63 \pm 4.79
	SDPE _{norm} (%)	6.00 \pm 3.55	8.15 \pm 4.29	4.79 \pm 1.97	6.69 \pm 2.39

3.1.1 Normalized position sense bias (PE_{norm})

To illustrate how each child with DCD compared to the TD cohort and to understand possible differences between joints, Figure 5A maps the normalized individual position sense bias data at the wrist and elbow of all children with DCD. As can be seen the magnitude of bias was considerably larger for contralateral than for

ipsilateral matching. However, nearly all DCD children fell essentially within the region of the TD cohort. The respective ANOVA analysis showed that mean PE_{norm} of DCD group was not significantly different from the respective mean of the TD cohort for either the wrist or elbow (p 's > 0.05 , see Figure 5B). PE_{norm} was significantly larger for contralateral when compared to ipsilateral matching at each joint (wrist: +6.60%, $F = 9.64$, $p = 0.003$; elbow: +16.02%, $F = 68.79$, $p < 0.001$), indicating that the contralateral matching task resulted in a larger systematic error across both groups.

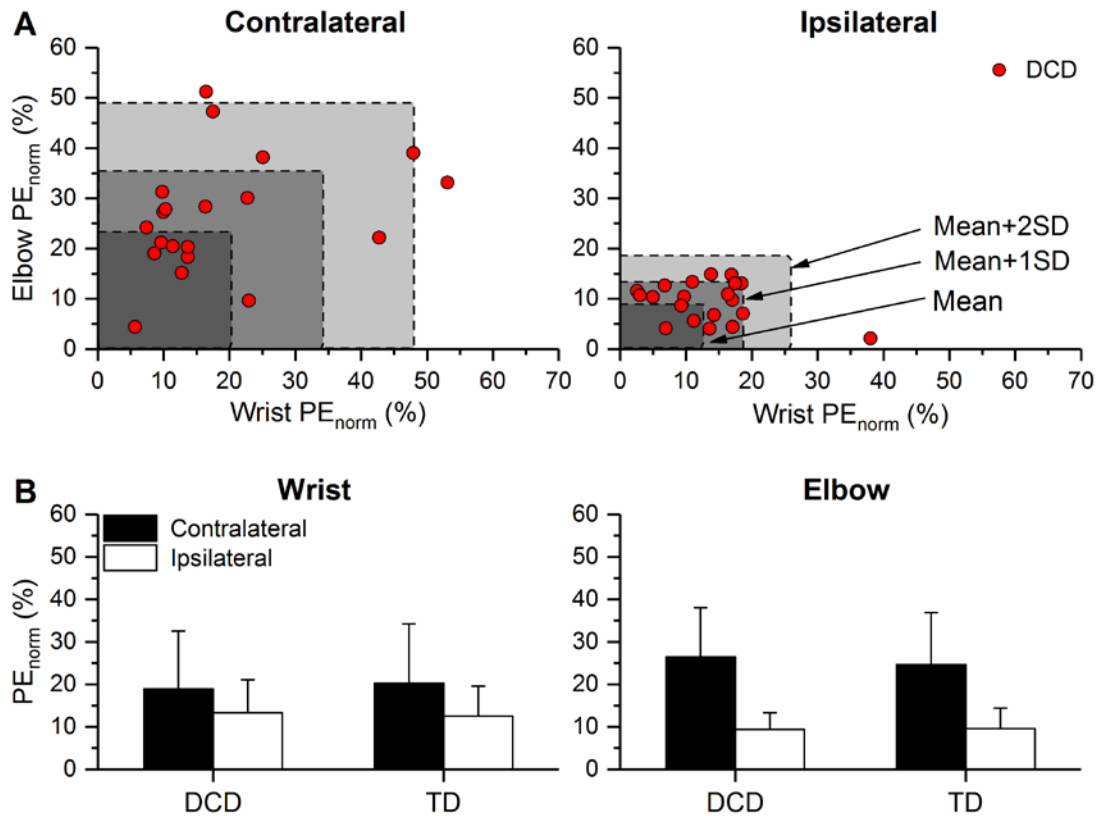


Figure 5. Position error at the wrist and elbow for each matching tasks. A) The wrist PE_{norm} as a function of elbow PE_{norm} for contralateral and ipsilateral matching. All groups showed greater position error at both joints during the contralateral matching. B) Mean

and standard deviation of PE_{norm} at the wrist and the elbow of two conditions for DCD and TD group. No significant group difference was detected at all joints or all matching tasks.

3.1.2 Normalized position sense precision ($SDPE_{norm}$)

Figure 6A maps the individual $SDPE_{norm}$ data of our DCD sample. For the contralateral matching, 13/20 (65%) children with DCD had $SDPE_{norm}$ values that were one standard deviation above the mean of the TD group, and 8/20 (40%) of DCD children had $SDPE_{norm}$ values above 2 standard deviations above those of TD children. For ipsilateral matching, the tendency of children with DCD to exhibit larger response variability was more pronounced. $SDPE_{norm}$ of 10 children (50%) were above two standard deviations of the TD group. The corresponding three-way (2 GROUP * 2 JOINT * 2 TASK) ANOVA revealed a significant main effect of GROUP for $SDPE_{norm}$ indicating that the DCD group had higher random error when judging joint positions compared to the TD group ($F = 16.14, p < 0.001, \eta^2 = 0.25$). It also yielded a significant main effect for JOINT indicating that $SDPE_{norm}$ at the wrist was higher than at the elbow joint (wrist: + 2.57%, $F = 19.78, p < 0.001, \eta^2 = 0.29$). To further examine the group difference for each joint, we performed two separate ANOVAs (GROUP * TASK) for wrist and elbow $SDPE_{norm}$. This analysis yielded a significant main effect for GROUP at the wrist ($F = 11.05, p = 0.002, \eta^2 = 0.19$), and the elbow ($F = 4.24, p = 0.045, \eta^2 = 0.08$) with the DCD group having a higher position sense error variability compared to the TD group (see Figure 6B). Finally, the above ANOVA revealed a significant main effect for TASK. The ipsilateral matching was associated with a higher $SDPE_{norm}$ than the

contralateral matching (+1.04 %, $F = 4.88$, $p = 0.032$, $\eta^2 = 0.09$). All interaction effects were not significant (p 's > 0.05).

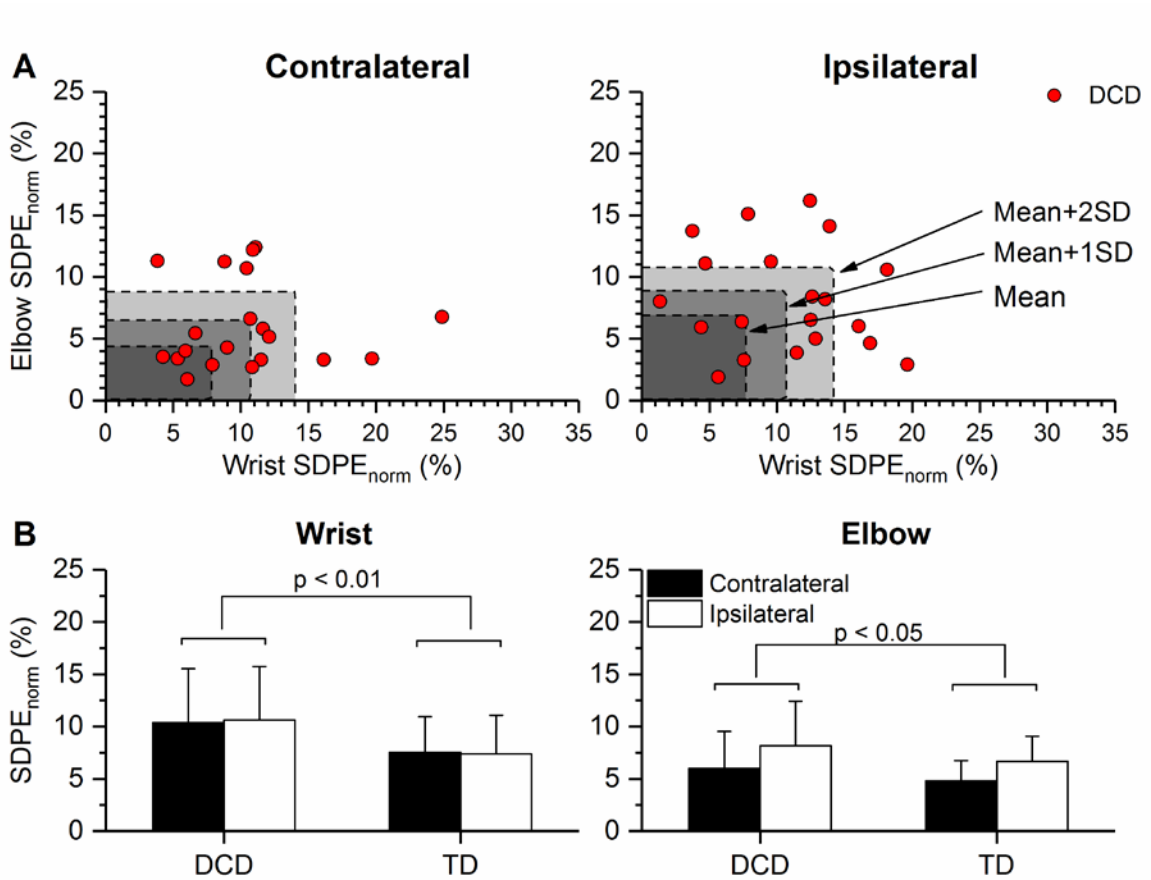


Figure 6. Normalized position error variability at the wrist and elbow for matching task.

A) The wrist $SDPE_{norm}$ as a function of elbow $SDPE_{norm}$ for contralateral and ipsilateral matching. Thirteen children with DCD had $SDPE_{norm}$ values one standard deviation above the mean of the TD group in the contralateral matching, and eight children with DCD had $SDPE_{norm}$ values above two standard deviations above those of TD children. B) Mean and standard deviation of $SDPE_{norm}$ at the wrist and the elbow of two matching tasks for DCD and TD group. The DCD group had higher position error variability at both joints compared to the TD group.

3.2 Position sense acuity based on psychophysical threshold testing

3.2.1 Position sense discrimination threshold (JND)

Sensing wrist joint position based on passive joint rotation without muscle activation was assessed. This psychophysical threshold testing allows us to determine if children with DCD have an underlying primary somatosensory deficit. Thirteen out of twenty (65%) children with DCD exhibited thresholds above the maximum of the TD group (see Figure 7A). Figure 7B shows the respective sensitivity functions for both groups indicating a higher threshold for the DCD group. DCD children as a group had significantly elevated position sense JND thresholds (M: 3.96°, SD: 1.74°) when compared to the TD group (M: 2.32° SD: 1.0°) ($t = 4.23, p < 0.001$, see Figure 7C). The computed effect size was large to very large (Cohen's $d = 1.16$). The mean JND threshold of the DCD group was 171% greater than that of the TD group.

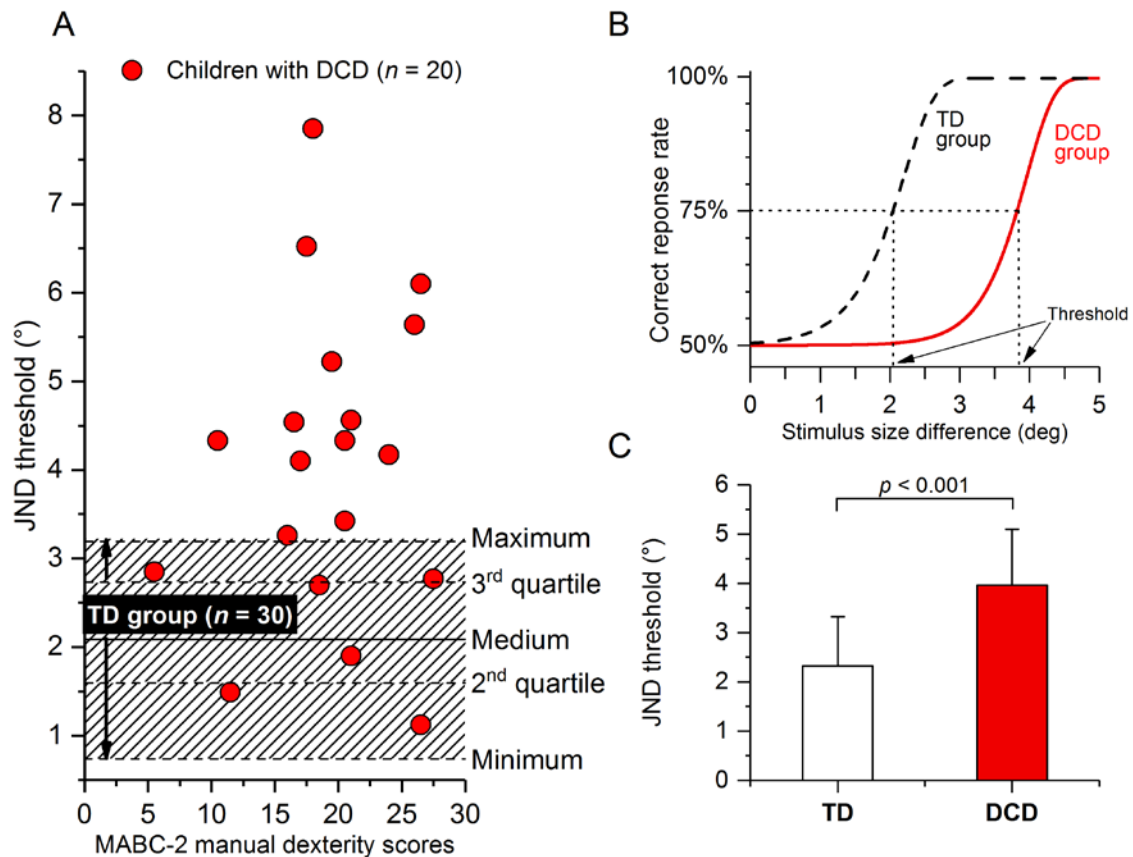


Figure 7. The comparison of position sense JND thresholds in children with DCD and TD children. A) Individual data of position sense JND thresholds and MABC-2 manual dexterity scores in 20 children with DCD. The shaded area presents the data of TD group. Notice that majority of children with DCD is above the maximum of TD children. B) The position sense psychophysical sensitivity function for DCD and TD group. Children with DCD have elevated JND thresholds than TD children. C) The respective mean and standard deviation of the individual subject JND thresholds for each group. Children with DCD had significantly higher JND discrimination threshold when comparing to TD children.

3.3 Correlation of proprioceptive measures with motor function scores

To understand the relationship between position sense and motor function, we performed a correlation analysis between the proprioceptive acuity measures (PE, SDPE, and JND) and the MABC-2 subscores. For PE, the analysis showed that no significant correlation between PE and either of the MABC-2 sub-measures (p 's > 0.05). For SDPE, the MABC-2 manual dexterity score significantly correlated with contralateral SDPE at the wrist ($r = -0.37, p = 0.008$, see Figure 8, left panel). The manual dexterity scores were not correlated significantly with ipsilateral SDPE at the wrist ($p > 0.05$, see Figure 8, right panel), and SDPE at the elbow (p 's > 0.05). Data also showed that the MABC-2 balance score significantly correlated with SDPE at the wrist (contralateral: $r = -0.31, p = 0.028$; ipsilateral: $r = -0.29, p = 0.037$, see Figure 9) and the elbow (contralateral: $r = -0.30, p = 0.038$; ipsilateral: $r = -0.30, p = 0.036$, see Figure 10). For JND threshold, the MABC-2 manual dexterity score correlated significantly with JND ($r = -0.40, p = 0.005$, see left panel of Figure 11). There is also a significant negative correlation between MABC-2 balance scores and JND ($r = -0.50, p < 0.001$; see right panel of Figure 11). No significant correlations were found between the proprioceptive measure and MABC-2 aiming and catching scores (p 's > 0.05). These data indicate that 1) a higher random or variable error, and 2) a higher position sense discrimination threshold, are associated with lower fine motor and balance function in DCD. Nevertheless, all proprioceptive measures predict about 8 - 25% of the variance of the MABC-2 motor measures.

To further examine the within-group correlation between proprioception and motor function, we conducted the same correlation analysis within our DCD and TD groups. The results yielded no significant correlation between proprioceptive measures and motor scores for our sample of DCD and TD cohort (p 's > 0.05).

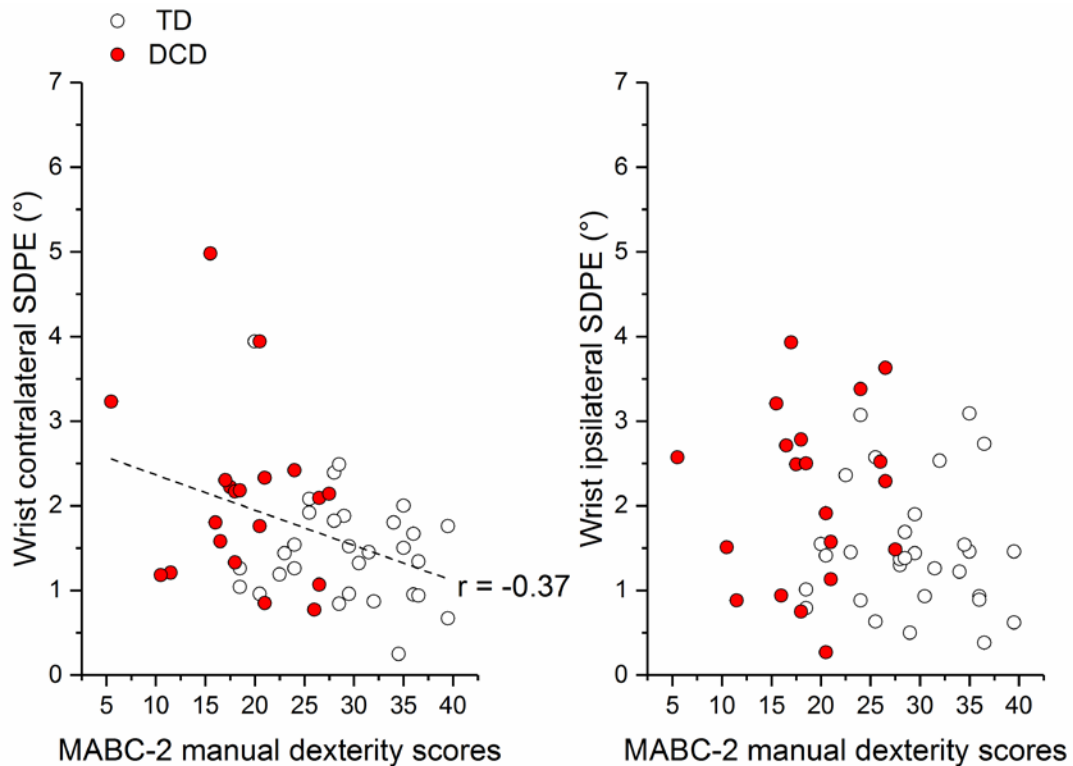


Figure 8. The relationship between wrist SDPE and MABC-2 manual dexterity scores. Each data point represents the individual SDPE and the respective MABC-2 manual dexterity score. The MABC-2 manual dexterity score indicates fine motor function. A significant negative correlation was found between wrist contralateral SDPE and fine motor function (left panel). No significant correlation was detected between wrist ipsilateral SDPE and MABC-2 fine motor function scores (right panel). The contralateral

wrist SDPE explain approximately 13% of the variance of the MABC-2 fine motor function measure.

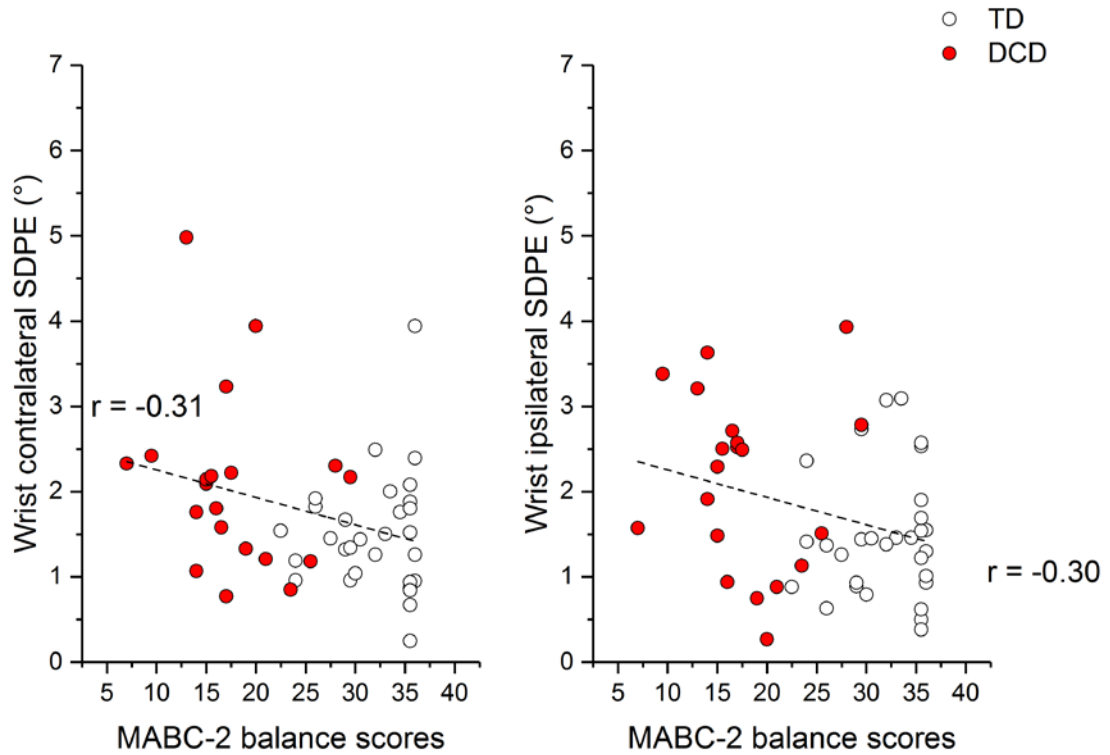


Figure 9. The relationship between wrist SDPE and MABC-2 balance scores. Each data point represents the individual wrist SDPE and the respective MABC-2 balance score in each child. Lower limb motor function is indicated by the MABC-2 balance scores. Significant negative correlations were found between wrist SDPE and fine motor function. The wrist SDPE explain about ~9% of the variance of the MABC-2 balance measures.

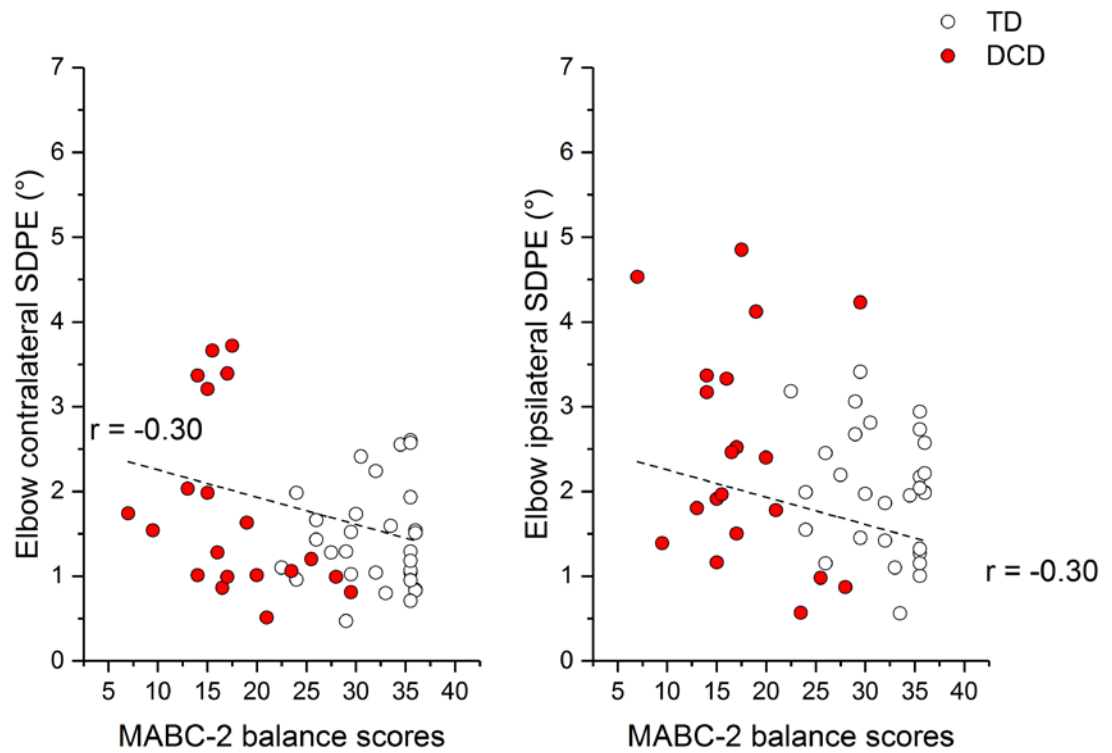


Figure 10. The relationship between elbow SDPE and MABC-2 balance scores. Each data point represents the individual elbow SDPE and the respective MABC-2 balance score. Significant negative correlations were found between both elbow contralateral and ipsilateral SDPE, and MABC-2 balance scores. This elbow SDPE explains 9% of the variance of the MABC-2 motor balance measures.

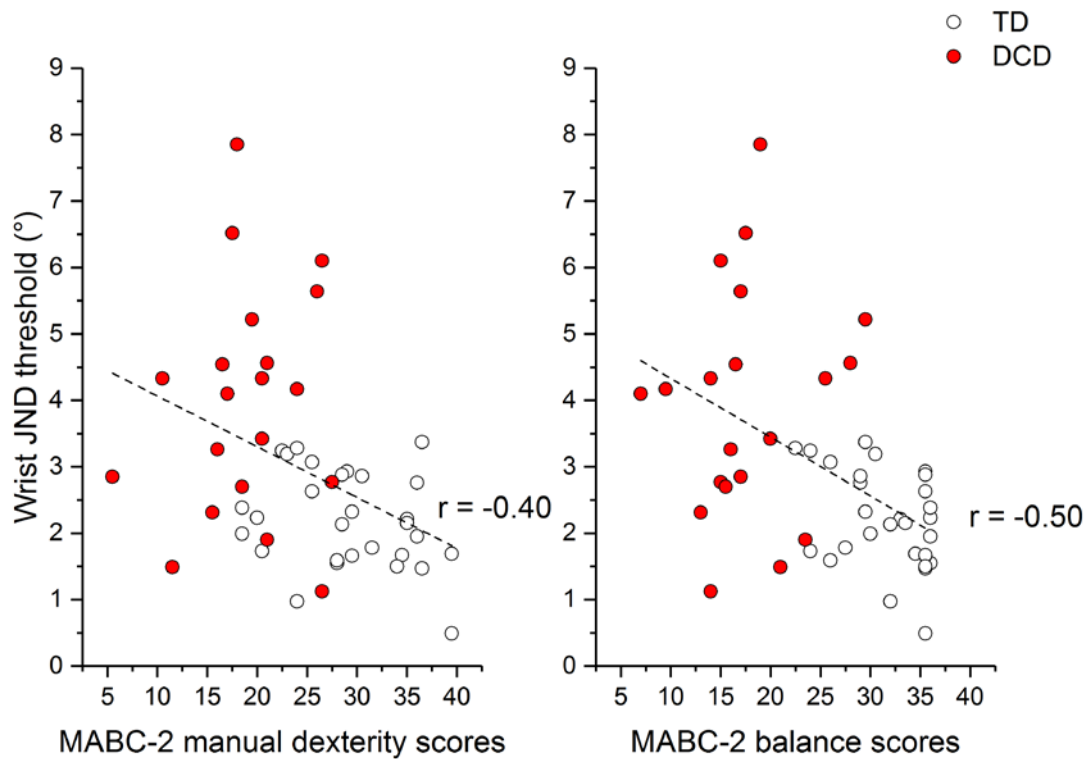


Figure 11. The relationship between wrist JND thresholds and MABC-2 manual dexterity score and balance score. Each data point represents a child's JND threshold and the respective MABC-2 manual dexterity and balance score. Fine motor function is indicated by the MABC-2 manual dexterity score, and lower limb motor function is presented by the MABC-2 balance score. A significant negative correlation was found between wrist JND threshold, and both MABC-2 fine motor and lower limb motor function. The JND thresholds explain 16% of the variance of the MABC-2 fine motor function, and 25% for MABC-2 lower limb motor function.

4 Discussion

The present study investigated position sense acuity at two upper limb joints in children with DCD. I utilized a newly designed wrist and elbow manipulandum device, and adopted two well-established protocols, a joint position matching paradigm and a psychophysical threshold testing method to assess position sense acuity at the elbow and the wrist in children with DCD. One protocol tested proprioceptive-motor function, which required a child to actively match a previously assumed joint position. The other examined “pure” proprioceptive limb position sense, in which the wrist joint was passively moved and no volitional movement of the child was required. Given that upper limb function like manual dexterity is often poor in children with DCD, I sought to understand, if upper limb position sense acuity is systematically affected and how well proprioceptive status may predict motor function in children with and without DCD.

The main results can be summarized as follows: First, children with DCD had significantly lower position sense precision at both the wrist and elbow compared to the TD group ([aim 1](#) and [aim 2](#)). Second, a difference of position sense bias was elucidated during passive motion, but not during active joint position matching. That is, the position sense discrimination thresholds were significantly elevated in the DCD group with 65% of the children having thresholds above the control group maximum ([aim 1](#)). Third, upper limb position sense acuity, especially the elevated position sense discrimination thresholds, tended to be associated with upper and lower motor function measures ([aim 3](#)). A last, minor finding was that ipsilateral joint matching yields somewhat lower acuity

values compared to contralateral matching. These results will be discussed in the following paragraph.

4.1 Children with DCD demonstrate upper limb proprioceptive deficits

This study provides objective evidence that upper limb position sense is affected in children with DCD. At present, no simple, standardized protocol for proprioceptive assessment exists, and consequently proprioceptive status is not routinely determined in children with DCD. This stands in contrast to the long-established notion that proprioceptive dysfunction may underlie the overt motor deficits in DCD (Bairstow & Laszlo, 1981; Coleman et al., 2001; Smyth & Mason, 1998). The present results show that, first, position sense precision was diminished at both the elbow and wrist in children with DCD. Similarly, previous studies reported that children with DCD had reduced motor precision by showing an increased within-trial variability during motor tasks such as a limb coordination (Mackenzie et al., 2008) or force generating task (Smits-Engelsman, Westenberg, & Duysens, 2008). Second, the JND threshold of the DCD group was increased by 171% when compared to TD controls. This complements recent work on passive limb motion sense reporting that the time to detect forearm motion in 10-year-olds with DCD was increased by 178% (Li et al., 2015). Extrapolating from our sample of 20 children with DCD indicates that at the age of 10 years approximately 2/3 of the DCD population presents with reduced proprioceptive acuity.

The underlying pathomechanism behind this proprioceptive dysfunction in DCD is poorly understood. At present, no distinct neural signature of DCD has been identified

(Biotteau et al., 2016; Brown-Lum & Zwicker, 2015). No firm evidence exists to indicate that mechanoreceptor or peripheral nervous impairment are potential causes for the observed proprioceptive dysfunction in children with DCD. Moreover, abnormal processes of sensorimotor integration or motor control in DCD cannot account for the observed reduced proprioceptive acuity given that the proprioceptive impairment was measurable in the absence of volitional movement. That is, the proprioceptive deficit is not explainable as a confounder of motor planning or motor execution problems. It is also not explained by assuming that children with DCD were systematically hypertonic or that involuntary muscle contractions consistently accompanied the passive displacement of the wrist/hand. While children with DCD may reveal abnormal muscle tone, hypotonia is more common (Hadders-Algra, 2003). Moreover, concentric muscle contractions during passive movement shorten intrafusal spindle fibers, which would increase muscle spindle sensitivity. However, heightened stretch sensitivity also improves perceptual acuity, which was not observed in our cohort of children with DCD. Thus, the observed perceptual deficit rather points to abnormal sensory processing of proprioceptive signals. Similar proprioceptive acuity deficits are observed in diseases affecting the cortico-basal ganglia-thalamo-cortical circuitry such as dystonia and Parkinson's disease [for reviews see Konczak and Abbruzzese (2013); Konczak et al. (2009)]. Impaired position sense judgments are not consistent with cerebellar damage. Although the cerebellum receives massive proprioceptive input via the spinocerebellar tract, position sense judgments of patients with cerebellar ataxia are normal (Maschke, Gomez, Tuite, & Konczak, 2003). This conclusion warrants a caveat. Abnormal perceptual thresholds do not imply that

processes of sensorimotor integration and motor control are unaffected or the cerebellum is not implicated in DCD. In fact, recent imaging evidence suggests that cerebellar dysplasia can underlie DCD (Mariën, Wackenier, De Surgeloose, De Deyn, & Verhoeven, 2010)

4.2 Proprioceptive deficits are not restricted to a single joint in children with DCD

Position sense deficits in children with DCD can be present in both proximal and distal arm joints, which corroborates the notion that DCD is associated with generalized proprioceptive dysfunction. Indeed, proprioceptive deficits demonstrate a generalized attribute in other movement disorders. For example, patients with Parkinson's disease have impaired proprioception at different joints such as fingers (Norman Putzki et al., 2006), wrist, (Schneider, Diamond, & Markham, 1987), forearm (Konczak, Krawczewski, Tuite, & Maschke, 2007), and shoulder (Schneider et al., 1987). Other movement disorders such as dystonia have also been found to have proprioceptive impairments on segments other than the dystonic body parts (Konczak, Aman, Chen, Li, & Watson, 2015; Norman Putzki et al., 2006). The current report adds evidence on somatosensory function in children with DCD and support the hypothesis of generalized nature of proprioceptive deficits of DCD.

Notably, even though the children with DCD showed position sense deficits at both proximal and distal joints, the magnitude of wrist proprioceptive deficits is higher than the elbow in children with DCD. In the current study, the proprioceptive deficits at the wrist showed a larger effect size ($p < 0.001$, eta square = 0.19, medium to large effect

size) than the elbow ($p < 0.05$, eta square = 0.08, small to medium effect size), meaning that the position sense deficits were more marked in the distal than proximal joints of the upper limbs. Studies have proposed that, although the proprioceptive mechanisms are similar in location and function, the proprioceptive ability might be different for the two joints (Clark, Burgess, Chapin, & Lipscomb, 1985). Even though there is no apparent neurophysiological reason why children with DCD had more prominent proprioceptive random error at the wrist, it is possible that the cortical sensorimotor processing differs between children with and without DCD, and this difference was more prominent in the cortical representation of the distal joints (e.g., wrist or hand) compared to proximal portion (e.g. elbow) (Gardner & Johnson, 2013).

Children with DCD are a heterogeneous group in exhibiting marked impairment of motor coordination, perceptual and movement performances (Schoemaker et al., 2001; Wright & Sugden, 1996). Thus, it was not surprising to observe a range of perceptual responses in our sample of children during proprioceptive assessment. Note that some children had normal wrist position sense but had abnormal position sense acuity at the elbow, while others showed the opposite pattern. As few empirical studies confirm within-group variability of upper limb position sense acuity at different joints in children with DCD, we offer objective data to support the heterogeneity of DCD in proprioceptive function.

4.3 Abnormal precision, but not bias during active joint position matching in DCD

Children with DCD show lower position sense precision position, that is, the error variability was significantly higher in the DCD cohort. This implies that perceptual precision or response repeatability is affected in children with DCD. On a first glance, it seems surprising that proprioceptive bias is abnormal for threshold testing, but not for position matching testing. However, the results are consistent with a recent study on the typical development of forearm position sense that also employed a joint position matching paradigm and showed that position sense development during childhood is characterized by an age-related increase in precision (i.e. reduced random error), not a decrease in bias (Holst-Wolf, Yeh, & Konczak, 2016). That is, the proprioceptive development of children with DCD follows a similar trajectory, but with respect to their TD cohort, children with DCD are proprioceptively less precise or delayed (Li et al., 2015). Moreover, this result also informs us that the passive psychophysical method seems to be more sensitive to detect somatosensory deficit in children with DCD.

4.4 Children with DCD demonstrate higher position sense bias during passive motion based assessment, but not for active movement proprioceptive assessment

Children with DCD did not show an abnormal position sense bias during the active joint position matching task – a finding consistent with Adams et al. (2016). However, the altered position sense bias was showed during the psychophysical threshold

testing in DCD. That is, the JND threshold was significantly elevated in DCD group. Notice that the natures of the two assessments are not identical. The passive psychophysical threshold testing requires an individual to experience different angular positions, while the active joint position matching involves the process of sensing the position followed by response by matching movement. Clinicians and researchers need to recognize that an active joint matching method does not test “pure” sensory function, but sensorimotor function. It does require an action and consequently involves voluntary motor control networks. We already know that motor commands interfere with haptic judgments in typically developing children and involve cortico-cerebellar efference copy mechanisms (Gori et al., 2012). It is therefore not implausible that motor interference plays a role in the perceptual deficits in children with and without DCD, although we currently lack solid empirical evidence to substantiate this claim.

4.5 Why did the contralateral condition have a greater proprioceptive bias and the ipsilateral condition a lower precision?

In joint position matching paradigm, the nature of contralateral and ipsilateral position sense matching is different. First, the involvement of brain hemispheres differs between the two conditions of position sense matching. Ipsilateral matching is uni-manual and mostly reflects the activation of the contralateral brain hemisphere, whereas contralateral matching requires bimanual movements and is involved inter-hemisphere transfer of somatosensory signals between the two hemispheres. Therefore, the

contralateral matching condition would result in a greater position sense bias than ipsilateral matching (Elangovan et al., 2014; Holst-Wolf et al., 2016) due to the inter-hemisphere transfer of the proprioceptive-motor information. Our results supported the view of inter-hemisphere transformation of sensory information by demonstrating that all groups of children had greater position sense bias during contralateral matching than ipsilateral matching. Second, the cognitive demands of the two conditions are also different. The ipsilateral matching includes a working memory component, in which children are asked to reproduce the previously given position. The contralateral matching does not require working memory because the target position was always available, or so-called “online”, for children to perform matching movements on the contralateral limb. However, the working memory issue was not seen in the current study because all groups, not just the DCD group, had significantly smaller position sense bias on the ipsilateral matching compared to the contralateral matching. During the task, children had 3 seconds to sense the position and were asked to reproduce the sensed position with no delay. Indeed, a previous study has shown that the effect of working memory load on ipsilateral matching task is minimum (Goble, Mousigian, & Brown, 2012)

4.6 Relationship between proprioception and motor function

Children with DCD are known to have difficulties with fine motor skills such as hand writing or drawing, and may exhibit balance problems. Given that a link between proprioceptive and motor dysfunction in children with DCD has long been proposed (Bairstow & Laszlo, 1981; Johnston, Ali, Hill, & Bremner, 2017, Piek & Coleman-Carman, 1995; Sigmundsson, 2005), I examined the extent to which wrist proprioceptive

acuity correlates with upper and lower limb motor measures. The results show that the MABC-2 manual dexterity score negatively correlates with position sense precision and JND thresholds meaning that children with higher proprioceptive thresholds, or lower precisions tend to have poorer fine motor control. Position sense precision and JND thresholds also correlated significantly with the MABC-2 balance score, implying that upper limb proprioceptive status can serve as a predictor of lower limb balance function. While both findings confirm a link between the motor and sensory signs in children with and without DCD, one needs to recognize that wrist position sense acuity predicts only about 8-25% of the variance of the MABC-2 motor measures. Furthermore, when investigating the within group correlation, the relationship between proprioceptive measures and MABC-2 motor scores was not significant. Possible explanations for this lack of a strong relationship are threefold: First, the MABC-2 motor measures are relatively coarse. The majority of TD children in this study reached highest balance scores of MABC-2. Second, the MABC-2 instrument does not target wrist movement specifically. Thus, one may argue, it is surprising to find a significant correlation, at all. In other words, to expect a higher correlation than found here, one likely needs to couple measures of wrist proprioceptive acuity with distinct measures of wrist motor performance. Third, the neural networks involved in somatosensory processing overlap with sensorimotor networks, but they are not identical. That is, one should not and cannot expect to see a very tight relationship between proprioceptive and motor measures in DCD.

4.7 Limitations of the study

There are limitations in this study. First, this study only included children aged 10-11 years. Further research is required to confirm the findings for children beyond this age range. Second, I only measured position sense of upper limb joints in the transverse plane. Understanding whether lower limb position sense function would generate similar results needs further exploration.

5 Summary and Conclusion

This is the first report to systematically examine upper limb position sense dysfunction in children with DCD, and to relate such deficits to the observable motor abnormalities. Thus, this study adds an important information to the body of knowledge on somatosensory function in children with DCD. Its main findings are summarized as follows:

First, upper limb position sense is affected in children with DCD. The results of this study showed that position sense precision was reduced, and the position discrimination threshold was elevated by 171% in DCD group as compared to the TD. This result implied that children with DCD are associated an underlying primary somatosensory deficit, which likely contributes to the fine motor problems in DCD.

Second, this study documented an impairment of position sense precision at proximal and distal joints of upper limb in children with DCD. This finding indicates that the proprioceptive dysfunction in children with DCD is not restricted to a single joint, but is likely generalized in nature. Even though the present study did not assess position

sense acuity at all upper limb joints, one can expect that children with DCD would also have abnormal position sense acuity at other upper limb joints (i.e., shoulder and fingers). Therefore, when assessing upper limb proprioception, clinicians could potentially test one joint to determine if a child has a proprioceptive dysfunction.

Third, a significant negative correlation between upper limb position sense bias and MABC-2 motor subscores was found. This finding confirms a link between motor and sensory function. While fine motor function measures of MABC-2 provide a coarse measurement of wrist movement functions along with other gross motor functions, finding a significant negative correlation means that wrist proprioceptive measures can be a valuable predictor of motor impairment in DCD. To further evaluate this relationship between proprioceptive and motor function in DCD, a more distinct, joint-specific motor assessment is necessary.

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