Knee Joint Proprioceptive Acuity and Kinematic Control in Relation to Motor Competency in 13 to 14-Year-Old Adolescents

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Abstract

Motor competence (MC) is a key component reflecting one's ability to execute motor tasks and is an important predictor of physical fitness. For adolescents experiencing rapid growth changes, understanding the factors affecting MC is pertinent to the development of more sophisticated sporting skills. Previous studies considered the influence of poor proprioceptive ability on MC, however, the relationship between lower limb proprioception and MC is unknown, and the relationship between kinematic control and MC is not well understood. Therefore, the aim of this study was to determine to what extent lower limb proprioception (according to knee joint position sense), and kinematic control relate to MC in adolescents. This study was a cross-sectional design. Young people (n = 427, 196 girls and 231 boys) aged 13 to 14 years were recruited. A movement reproduction task was used to assess joint position sense and quality of performance, while the Movement Assessment Battery for Children (mABC-2) was used to assess MC. In addition, this study categorized 80 adolescents who met the criteria according to their mABC-2 scores as the Developmental Coordination Disorder (DCD) group, while 231 adolescents were categorized as Typically Developed (TD), to further compare motor competency. Results showed that kinematic data, specifically normalized jerk, showed a significant correlation with MC. No correlation between knee joint position sense and MC. No group differences between DCD and TD were found. From these results, it may be concluded that rather than proprioception, there is a greater association between MC and kinematic control and sensorimotor integration.

Clinical trial registration number : NCT03150784

Background

Motor competence (MC) is the ability to execute different motor tasks, and reflects the degree of mastery of fine and gross motor skills [1], [2]. MC is a key component in children and adolescents in developing a healthy, active lifestyle and is a predictor of physical fitness [1-3]. Previous literature suggested that MC is expected to improve linearly with physical fitness as children develop, and that higher levels of MC allow for greater participation in physical activities, whereas low MC is associated with less physical activity [1], [2]. Most studies focused on the external factors affecting MC, such as physical education classes and environmental interplay, but little is known about the association between MC and intrinsic factors, such as proprioception.

Proprioception is the conscious awareness of relative body limb position and motion, and plays a crucial role in limb coordination, kinematic control, and motor planning [4, 5].. Afferent proprioceptive signals to the brain originate from muscle spindles, Golgi tendon organs, ligaments, and joint capsules [7, 8]. Typical growth and development demonstrates an age-related pattern of improved proprioception within the elbow joints, where Typically Developed (TD) children show a larger error [9, 10] and variability compared to TD adults [11]. Proprioceptive feedback is important in early skill development, especially when learning a motor sequence [12]. However, little is known about the relationship between proprioception and MC. A better understanding of the influence of MC and proprioception on motor skill development is essential for fostering greater physical activity across the lifespan, especially in those with Developmental Coordination Disorder.

Developmental Coordination Disorder (DCD) is characterized by clumsy movement and poor motor skill learning [13-15]. The exact cause of DCD is unknown, but is often thought to be multifactorial [16]. It has been partially linked with atypical brain development [17], sensorimotor dysfunction in the central nervous system [18], and environmental factors [19]. Therefore, diagnosis of DCD entails a complex developmental and medical history, physical examination, school or workplace report, and motor competence assessment [20]. The Movement Assessment Battery for Children 2nd Edition (mABC-2) assesses motor skill levels in children aged 3 to 16 years.

Children with DCD generally show a lower total standard score on the mABC-2, indicating a lower level of motor skills compared to TD children [21]. In school-aged children and adolescents, the estimated prevalence of DCD is 5-6% [22, 23]. This population showed decreased physical activity, difficulties with activities of daily living, and reduced academic performance and social participation [22, 24, 25]. Decreased MC in the DCD population have significant effects on health and quality of life, as DCD children have been found to be less physically active than their TD peers, and are unable to meet the global physical activity guidelines [26].

The DCD population shows impairments that affect the acquisition and execution of motor-related activities [26]. Previous studies revealed that DCD children performed with poorer kinematic control of the upper limbs compared to TD children [27]. Kinematic control is the ability to initiate and produce purposeful, precise movements. Common kinematic measures include movement trajectory, time, velocity, and normalized jerk [28-30]. Previous studies showed that DCD children performed with slower reaction times, larger endpoint errors, longer movement and/or deceleration times with more curved trajectories, and showed greater variability in movement speed compared to TD children in upper limb tasks [27, 31]. Normalized jerk (NJ), which is often used to measure movement smoothness [30, 32, 33], was found in children with and without DCD to have the same developmental trajectory; however, when controlled for age, children with DCD exhibited greater NJ in upper limb movement [34].

It has been speculated that decreased MC is associated with poor proprioception; however, previous literature on the proprioceptive deficits in the DCD population have been controversial [35-37]. Some studies indicated poorer proprioceptive function in DCD compared to TD adolescents [36, 38-40], whereas other studies showed no differences between the two populations [41-44]. In one research, DCD children were found to require more time in detecting passive elbow joint movement compared to TD children [45], but another study found no differences between the two groups in absolute error [41]. Other evidence indicated low correlation between mABC-2 scores (representing MC) and proprioception of the upper extremities in TD and DCD children [37, 40, 41]. These studies, however, focused mainly on upper extremity proprioception in younger children. Little is known about lower extremity performance in adolescents. For adolescents aged 13 to 14, who are at a critical stage of development where they experience changes in motor abilities and develop new motor skills, lower limb performance is a crucial aspect that affects development of complex skills into their teenage and adult years [46].

Testing of proprioceptive ability, however, remains difficult, as there are very few objective tools to measure proprioception. Previous studies estimated proprioception using a kinesthetic sensitivity test (KST)[35] and kinesthetic acuity test (KAT)[47] in children with[36, 37] and without[35, 37, 48] DCD, but the accuracy of these methods have been criticized [45, 49]. Joint position sense is a simpler method than measuring movement sense [11], and a variety of tools, including goniometers [41] and other customized apparatuses [7, 9, 11, 49], have been used, however, mainly to assess proprioception of the upper extremity. Only one study assessed lower extremity joint position sense using a Biodex isokinetic dynamometer, which is limited to the laboratory setting [50]. To our knowledge, there is currently no valid evidence of an objective assessment for proprioception that can be used for the lower extremities in adolescents.

Thus, our research set out to estimate joint position sense and kinematic control using a single inertial measurement unit (IMU) in a cross-sectional cohort of children, and to explore the extent to which these measures are associated with motor competence in adolescents aged 13 to 14 years.

Materials And Methods

Study design

This study was a cross-sectional design [51]. Baseline data, strength, and power of each participant were collected at the start of the experiment. Participants were then instructed to do a movement reproduction task, and lastly completed a motor competence assessment. After collection of all data, participants were categorized into the DCD group and TD group, and results between the two groups were compared. The study was approved by the University Research Ethics Committee (UREC Registration No: 161033) and conducted in accordance with the Declaration of Helsinki (1964) and later revisions. The study followed the Research Governance Framework for Health and Social Care (DoH 2nd Edition, July 2005) and is registered at ClinicalTrials.gov. (Identifier: NCT03150784).

Participants

This study targeted children aged 13-14 years, a critical age when activity levels reduce and when sporting skills are being built. Data was gathered from screening a whole year group among three mainstream secondary schools in oxfordshire, UK. The exclusion criteria consisted of any contraindications to performing maximal exercise or physical training, as determined by the Physical Activity Health Questionnaire (PARQ); children suffering from muscular/neurological degenerative conditions or with uncontrolled epilepsy/seizures (must be stable epilepsy or on medication for greater than 12 weeks); or surgery in the previous six months. If there were any concerns regarding a child being able to participate safely, we asked parents/guardians to contact the respective GP/paediatrician/physiotherapist.

Movement Reproduction Task

An IMU was attached to the participant's tibial bone (approximately 5cm below the patella) of their dominant leg (Figure 1A). The dominant leg was defined as the leg they would prefer to kick a football. The researcher passively moved the subject's knee to approximately 30° of knee flexion from the 90° starting position and maintained this new position for 3 seconds. The leg was then moved back to the 90^{o} starting position of knee flexion. The subjects were then asked to reproduce the knee movement actively, and match the passive reference angle for 3 seconds with their eyes closed to eliminate external visual cues. The subject repeated this twice, for a total of three trials, keeping their eyes closed during trials (Figure1B).

Measures

Descriptive measures, including age, gender, height, weight, BMI, leg length, grip strength, shoe size, broad jump, and motor competence, were recorded during the baseline assessment. Strength and power were measured by grip strength and broad jump, respectively [52]. mABC-2, which included manual dexterity (MD), aiming & catching (AC), and balance (B), was used to determine motor competence [53]. To detect joint position sense, the absolute angle error (AE, the absolute difference between reference and reproduce angle) and standard deviation between two repeats (SDPE) during the movement reproduction task were recorded. For kinematic performance, movement time (MT), peak angular velocity (PV), and percentage of peak angular velocity (%PV) were also estimated. The smoothness of movement was represented by normalized jerk (NJ) [32, 54-56].

Apparatus

Single IMU (LPMS-B2, LP-RESEARCH Inc. Tokyo, Japan) was used to detect angular movement of the knee joint. Data were recorded at 100Hz and were connected with a PC via Bluetooth 4.1. Movement IMU data were analyzed using a custom programme written in LabVIEW2011 (National Instruments, Ireland).

Three-dimensional orientation was extracted from the sensor, from which angular change in the Euler X plane was derived. Movement time (MT) was derived from the minimum to maximum of angular change [22]. Angular velocity was derived and smoothened using the Savitzky-Golay filter (3rd polynomial, 2nd order), from where peak velocity (PV [deg/s]) and corresponding time, expressed as a percentage of the overall movement, (PTPV) were taken [57].

Movement smoothness was assessed by normalized angular jerk [deg/s^3] which was derived from double differentiation of angular velocity using the same Savitzky-Golay filter at each differentiation. Jerk was normalized according to formula (1), providing normalized jerk (NJ) [58, 59].

$$\mathrm{NJ} = \sqrt{\left(\frac{1}{2} * \int_{T\ start}^{T\ end} Jerk^2(t)dt\right) * Duration^5 \ / \ Length^2} \qquad (1)$$

Data analysis

Descriptive statistics (mean ± standard deviation or frequency) were generated for all variables, and all statistical analysis was done using SPSS 19.0 (IBM Corp, Armonk, NY). We used Pearson correlation to determine the relation between joint position sense (AE, SDPE), motor competence (mABC-2), and kinematic control (MT, PV, %PV). The Levene's and Kolmogorov-Smirnov tests were used to test homogeneity and normality. The Mann-Whitney U test was used to calculate the gender or motor competence group differences (adolescents who scored below the 5th percentile were determined as DCD; those above 25th percentile were determined as TD) of all measures. Significance level was set as $p < 0.05$ for all tests.

Results

There were 427 adolescents (13-14 years old) who participated in this study, including 196 girls and 231 boys. Table 1 shows the descriptive data of all participants. Compared to girls, boys were taller (Cohen's d=0.61; p<0.001), fitter (Cohen's d=0.15; p=0.017) and had stronger performance in both grip strength (Cohen's d=0.47; p<0.001) and broad jump (Cohen's d=0.49; p<0.001). Boys scored higher in motor competence according to the mABC-2 in the manual dexterity (Cohen's d=0.43; p=0.004) and aiming & catching (Cohen's d=0.95; p<0.001) categories, but there were no gender differences in either the balance category or the total score of the mABC-2 (p>0.05).

Table 1. Descriptive data of 13- to 14-year-old participants (n = 427) of the study, including gender, age, height, weight, body mass index, leg length, power as measured by grip strength and broad jump, and motor competency as measured by the Movement Assessment Battery for Children 2nd Edition (mABC-2).

	Total (n=427)	Boys (n=231)	Girls (n=196)	p value
Gender (male/female)	231/196			
Height(cm)	162.13 (8.71)	166.41 (8.56)	161.44 (7.74) *	<0.001
Weight (kg)	54.73 (12.15)	55.67 (13.20)	53.63 (10.71)	0.206
BMI	20.31 (4.49)	20.00 (4.05)	20.67 (4.94) *	0.017
Leg length (cm)	88.22 (5.94)	89.27 (6.04)	86.98 (5.57) *	<0.001
Grip Strength (kg)	24.28 (6.89)	25.73 (7.91)	22.58 (4.96) *	<0.001
Broad Jump (m)	1.60 (0.27)	1.66 (0.26)	1.53 (0.27) *	<0.001
mABC-2				
Manual dexterity	21.04 (6.82)	24.70 (5.35)	22.11±6.63 *	0.004
Aiming & catching	17.67 (4.92)	19.52 (4.53)	15.20±4.34 *	<0.001
Balance	29.22 (6.23)	28.98 (5.89)	29.47±6.65	0.079
Total score	67.93 (11.94)	73.20 (10.96)	66.79±12.12	0.082

Data is presented as mean (SD), and * indicates significant difference between genders.

Results of knee joint position sense and kinematic performance are shown in Table 2. The mean value of AE is 5.52±3.80° and SDPE is 1.46±1.67. There were no gender differences in the joint position sense and kinematic data except for the movement time (Cohen's d=0.16; p=0.022), which showed boys taking less time to reach the target angle.

Table 2. Analysis of knee joint position sense (proprioceptive acuity) and kinematic control between participants of different genders (n = 427).

Variables	Total	Boys (n=231)	Girls (n=196)	p-value
Proprioception				
Absolute error (°)	5.52 (3.80)	5.60 (3.92)	5.44 (3.66)	0.842
Position sense error variability (SDPE)	1.46 (1.67)	1.38 (1.08)	1.55 (2.17)	0.772
Kinematic analysis				
Movement time (s)	1.46 (0.39)	1.43 (0.40)	1.49 (0.37)*	0.022
Peak velocity (°/s)	69.45 (19.72)	70.90 (120.67)	67.74 (18.45)	0.175
% of peak velocity (%)	39.82 (9.52)	39.33 (9.96)	40.40 (8.96)	0.126
Normalized Jerk (m/s^3)	9390814.86 (17560673.16)	16732067.91 (238728000)	738623.77 (3006903.63)	0.970

Data is shown as mean (SD), with * indicating significant difference between genders

Table 3 shows the correlation between joint position sense, MC, and kinematic control. AE was positively correlated with SDPE (r=0.155, p=0.001) but there was no correlation between knee joint position sense (AE & SDPE) and MC (mABC-2 categories score and total score) (p>0.05). The kinematic data showed significant correlation with MC. MT was negatively correlated with manual dexterity (r=-0.102, p=0.035) and total score of mABC-2 (r=-0.108, p=0.025). PV was negatively correlated with the balance category in mABC-2 (r=-0.098, P=0.044) and NJ was negatively correlated with manual dexterity (r=-0.101, p=0.037), balance (r=-0.159, p=0.001), and the total score of mABC-2 (r=-0.176, p<0.001) (Table 2).

Table 3. The correlation between knee joint position sense, kinematic control, and motor competency in the participants.

	AE	SDPE	MT	PV	%PV	NJ	mABC-2 MD	mABC-2 AC	mABC-2 B	mABC-2 total
Joint position sense										
AE		0.155**	-0.043	-0.179**	-0.027	0.190**	-0.015	-0.027	-0.024	-0.032
SDPE			0.191**	-0.086	0.046	0.096*	-0.058	-0.048	-0.061	-0.085
Kinematic control										
MT				-0.618 **	-0.288**	0.325**	-0.102*	-0.082	-0.031	-0.108*
PV					0.202**	-0.142*	0.003	0.015	-0.098*	-0.043
%PV						-0.054	0.046	-0.074	0.006	-0.001
NJ							-0.101*	-0.085	-0.159**	-0.176**

*, p<0.05; **, P<0.001

Abbreviations: AE, Absolute error; SDPE, Position sense error variability; MT, movement time; PV, Peak velocity; %PV, percentage time to peak velocity; NJ, Normalized jerk; MD, manual dexterity; AC, aiming & catching; B, balance

Eighty children met the specific criteria according to the mABC-2 and were assigned into the DCD group while 231 children were categorized as TD. Table 4 shows adolescents with DCD had higher BMI (Cohen's d=0.40; p=0.003), shorter leg length (Cohen's d=0.49; p<0.001), lower grip strength (Cohen's d=0.23; p=0.038), and lower lower-limb power (Cohen's d=0.69; p<0.001) compared to their TD counterparts. However, there were no significant group differences in joint position sense and kinematic movement performance (Table 5).

Table 4. Descriptive data of the participants that were categorized in the Developmental Coordination Disorder (DCD) group and the Typically Developed (TD) group, according to their total score as obtained from the Movement Assessment Battery for Children 2nd edition (mABC-2).

Variance	DCD group (n=80)	TD group (n=231)	p value
Height (cm)	162.86 (8.61)	164.20 (7.71)	0.074
Weight (kg)	56.38 (12.67)	53.32 (11.57)	0.071
BMI (kg/m^2)	21.18 (4.03)	19.70 (3.63)	0.003
Leg length (cm)	86.04 (6.20)	88.76 (5.24)	<0.001
Shoe size (UK)	6.32 (2.09)	6.67 (1.93)	0.088
Grip strength (kg)	22.75 (7.43)	24.33 (6.64)	0.038
Broad jump (m)	1.46 (0.26)	1.64 (0.26)	<0.001

Data are presented as mean (SD).

DCD, Developmental coordination disorder; TD, typical development

Table 5. Analysis of knee joint position sense and kinematic control between adolescents that were categorized as either with Developmental Coordination Disorder (DCD) or as Typically Developed (TD) according to their Movement Assessment Battery for Children 2nd edition (mABC-2) total score.

Variance	DCD group (n=80)	TD group (n=231)	p-value
Proprioception			
Absolute error (°)	5.84 (3.36)	5.56 (3.69)	0.904
Position sense error variability (SDPE)	1.73 (1.89)	1.35 (1.14)	0.093
Kinematic analysis			
Movement time (s)	1.53 (0.50)	1.42 (0.35)	0.183
Peak velocity (°/s)	71.91 (24.22)	69.24 (19.35)	0.331
% of peak velocity (%)	39.92 (9.39)	39.81 (9.25)	0.879
Normalized Jerk (m/s^3)	47231111.41 (405557000)	732468.17 (2778288.30)	0.746

Data are presented as mean (SD)

DCD, Developmental coordination disorder; TD, typical development

Discussion

This is the first study to estimate lower limb proprioceptive acuity and kinematic control of 13 to 14-year-old adolescents in a large cross-sectional sample with quantitative measures. There was a significant correlation found between MC and kinematic control, but no correlation was found between MC and knee joint position sense. A significant negative correlation was found between normalized jerk (NJ) and MC in the categories of manual dexterity, balance function, and total score of the mABC-2. Furthermore, the 80 adolescents categorized in the DCD group were found to have similar knee joint position sense and kinematic control of the lower limbs with those who are typically developed, with variability in measures observed in both groups.

In regards to proprioceptive acuity and MC, Goble et al. found that children (8-10 years) demonstrated larger position error (PE) with shorter duration and more velocity peaks compared to older adolescents (16-18 years) during an active elbow position matching task, indicating that age-related improvements in proprioceptive acuity continue throughout childhood and adolescence [9, 60, 61]. Another article stated that standard variation of position error (SDPE) of the wrist was significantly associated with the aiming & catching and balance portions of the mABC-2 score, but not with position error (PE) [7]. A large sample size study (n=354) also demonstrated improvement in developmental elbow joint acuity in children aged 5-18 years for SDPE but not for PE [11].One of the main objectives of the present study was to determine the extent to which joint position sense is associated with MC, and our results showed that neither PE nor SDPE of the knee joint correlated with any category or the total score of mABC-2. A possible reason for the inconsistent results might be that the mABC-2 does not specifically target knee joint performance, but rather, overall upper and lower limb movement. The manual dexterity and aiming & catching tasks of the mABC-2 mainly assess upper limb fine movement acuity, accuracy, speed, and coordination, whereas the balance tasks mainly focus on lower limb speed and coordination, and postural control and adjustment. Test of proprioceptive ability, however, is not reflected in any of the components of the mABC-2 directly, and thus may not a representative picture of MC in adolescents. In addition, proprioception reflects somatosensory input whereas MC represents sensorimotor output. A previous anatomical study found that although these neural networks overlap, they are not identical, perhaps indicating little association between proprioceptive function and MC, as reflected in the results of our study [50].

The present study also assessed the relationship between kinematic control and MC. Age has been found to be a factor in kinematic control, with better scores seen in older children, however, very little developmental studies have looked at adolescent performance [9, 60, 61]. Normalized jerk, which is the kinematic measurement of movement smoothness, was recorded during in our study. Results showed weak but significant negative correlation between NJ and MC in the categories of manual dexterity, balance function, and total mABC-2 score, indicating that a better overall MC is associated with better kinematic control in movement tasks.

Furthermore, the present study analyzed the differences in proprioceptive ability and kinematic control between adolescents with and without DCD, and found no significant group differences in either category. Variability was seen within groups, with DCD adolescents exhibiting greater variability compared to TD. Tseng et al. found that in children between 9 to 11 years of age, those categorized in the DCD group performed significantly poorer in SDPE than the TD group for wrist and elbow joint proprioception, but there was no group difference in PE [7, 49]. Chen et al. found significant negative correlations between proprioceptive acuity of the knee and ankle joint and balance function in children with DCD compared to TD; however, participants were spread across two age bands (7-10 years and 11-16 years) of the mABC-2 [50]. In the present study, we proved that 13 to 14-year old adolescents with and without DCD showed similar performance for PE and SDPE of the knee joint in a movement reproduction task. Although no significant differences were found between groups in the present study, variability was higher for the DCD population (Table 5). This may indicate that the knee joint proprioceptive task may not be challenging enough to elicit differences between TD and DCD adolescents. A previous imaging study found that cortical processes seen in children with DCD are markedly different from those in TD children [34], which indicates the possible use of compensatory strategies during motor performance to mask for movement insufficiencies, especially in older children with DCD. In regards to kinematic control, our results are consistent with a previous upper limb study that showed that DCD and TD children exhibited similarities in motor performance, with group differences demonstrated only for movement smoothness (NJ). Although the present study did not conduct statistical analysis between DCD and TD groups for NJ, the coefficient of variation (CV) based on our data indicated that the DCD group showed larger CV on NJ than the TD group (CV= 8.59 and 3.79, respectively), representing that DCD adolescents performed with larger variation in movement smoothness [34]. Though overall performances of active movement between children with and without DCD were similar, results from previous studies indicated the possibility that children with DCD require greater engagement of motor cortical areas to control movement after initiation [34]. Differences in performance between groups may be more apparent in activities that require more complex and technical skills, such as in sports, which may have further implications on social participation, especially at a turning point in adolescent growth.

Lastly, this was a large sample size study which crossed 3 local schools in UK. According to mABC-2 norm, 80 out of 427 adolescents identified as being in the 5^{th} percentile, and are indicated as having significant movement difficulty. Although a large number of adolescent participants were categorized as DCD with significant movement difficulty, they did not show significant group difference in either joint position sense or kinematic performance when compared with TD adolescents during the movement reproduction task (Table 5). Although studies have confirmed the validity and reliability of the mABC-2 for the younger age bands and found significant motor differences between DCD and TD children, the subjects in these studies are typically spread across a wide age band, and mainly focus on upper extremity movement [21, 62]. There is insufficient evidence on the validity of the mABC-2 for the adolescent age band. Furthermore, the similarities in motor competence between DCD and TD children may be less apparent because adolescents are at a critical stage when internal motor processes mature rapidly and when external factors play a key role in complex motor skill development. This may also indicate that mABC-2 norms do not reflect the full picture of motor competency in adolescents. Further studies assessing the mABC-2 for adolescents are needed to expand on our findings.

The present study estimated the proprioception and motor control of the lower limb in adolescents with and without DCD. However, there were some limitations. First, joint position sense could be affected by an internally predicted sensory feedback, afferent sensory feedback, or the integration of both [63]. An active, rather than passive, reproducing task was used to estimate proprioceptive acuity. Active movement contains motor cues that are made available to the nervous system to predict movement outcome [11]. Also, the active reproducing task might be combined with the effects of short-term memory, and may not provide a “pure” measure of proprioceptive acuity. Though this task is considered a practical and functional method from a clinical perspective, further studies are needed to explore its assessment of lower extremity proprioception [11]. Furthermore, a focus on more complex and technical motor performance in children with and without DCD and the subsequent effects on social participation may be helpful for design of future proprioceptive and functional interventions that may be applicable to the school setting.

Conclusion

Motor competence may be associated with sensorimotor control and integration as a whole. Adolescents with DCD performed identical knee joint position sense and kinematic control of lower limb with TD peers, with no significant correlation between knee joint position sense and MC, although there was a weak correlation between kinematic control and MC. Our observations suggest that young people with DCD do not have issues with proprioception, but rather with sensorimotor control and integration, and indicate directions for future research in better understanding kinematic control.

Abbreviations

AC
aiming & catching
AE
absolute angle error
B
balance
DCD
Developmental Coordination Disorder
IMU
inertial measurement unit
KST
kinesthetic sensitivity test
KAT
kinesthetic acuity test
MC
motor competence
MD
manual dexterity
MT
movement time
mABC-2
Movement Assessment Battery for Children 2nd Edition
NJ
normalized jerk
PARQ
Physical Activity Health Questionnaire
PE
position error
PTPV
percentage of overall movement
PV
peak angular velocity
%PV
percentage of peak angular velocity
SDPE
standard deviation between two repeats
TD
Typically Developed

Declarations

IMPLICATIONS AND CONTRIBUTION

Clinical motor competence training should be implemented to target kinematic control and sensorimotor integration in adolescents.

Conflicts of Interest.

Authors declare no Conflict of Interest.

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Authors' Contributions

Yan-Ci Liu, Patrick Esser and Helen Dawes have given substantial contributions to the conception or the design of the manuscript, Yan-Ci Liu, Benjamin David Weedon, Daniella Springet and Shawn Joshi contributed to acquisition, analysis and interpretation of the data. All authors have participated to drafting the manuscript. All authors read and approved the final version of the manuscript.

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Figures

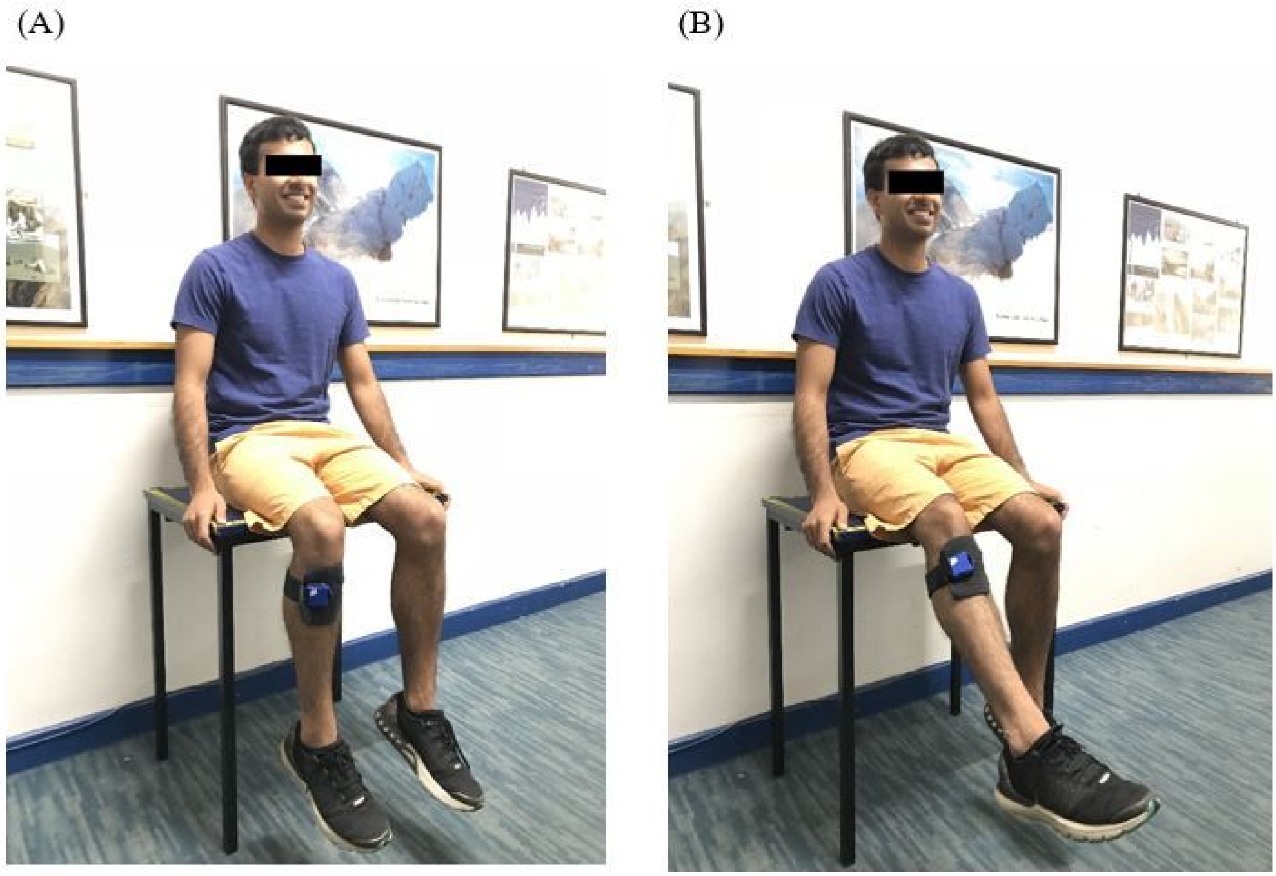

Figure 1

The starting and end positions of the movement reproduction task.

(A) Participants were instructed to sit on a table with their leg relaxed and both hands holding the table for stability. (B) Participants actively moved their leg to the target angle and were instructed to hold the new angle for 3 seconds, repeating this twice for a total of three trials.