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Comparison of Postural Control During Sit-To-Stand between Typically Developing Children Aged 4 to 12 Years and Young Adults

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Abstract Postural control is a fundamental requirement for performing all functional tasks, including standing up from a chair. Although there is a broad literature on postural control development in typically developing (TD) children, there is a lack of specific information on TD children performing the sit-to-stand (STS). Therefore, the aim of this study was to investigate the development of postural control during STS in TD children of different age groups. Fifty-eight healthy TD children aged 4–12 years and 19 adults participated in this study. They were separated into four groups: 4–6 years, 7–9 years, 10–12 years, and adults. All participants were asked to perform the STS movement with a self-selected pattern. Participants' dynamic stability was quantified according to centre of mass (COM) displacement and velocity in the anterior-posterior, medial-lateral, and vertical directions during the four phases (flexion-momentum, momentum-transfer, extension, and stabilization) of the STS movement. The development of postural control was different in each phase of STS. During the flexion-momentum, extension, and stabilization phases, children aged 4–12 had higher COM displacements and velocities than adults. In the momentum-transfer phases, children aged 4-9 had higher COM displacements and velocities than other groups. In addition, children aged 4¬6 had the highest COM velocity during the extension phase of the STS movement. Children aged 4–12 years and adults used different strategies to control COM during STS movement. Adult-like postural control during STS was not found in children aged 10–12 years.

Keywords Standing Up, Centre of Mass, Balance

1. Introduction

Postural control is the ability to control the body's position in space for purposes of stability and orientation. Postural control is known as a fundamental component of all movements [1]. In children, the development of postural control has been extensively studied in many movements, such as quiet standing [2-3], single-leg standing [4], and walking [5]. These studies have indicated that the developmental process for postural control is related to age [2-5]. There is a wide range of literature on the development of postural control during movement, which shows that the requirements of postural control for each movement are varied [6]. One of the important movements in daily life entails the transition from sitting to standing [7].

Sit-to-stand (STS) is a movement that involves changing the base of support in order to propel the body towards a new position. Achieving STS requires high postural control levels to regulate the shift of the centre of mass (COM) from the seated position, with full support, to a standing position [1]. During the stages that precede leaving the seat, the COM shifts along a horizontal plane towards the feet. After leaving the seat, the COM shifts in a vertical direction towards the standing position [8]. STS in healthy children emerges around 13 months of age [9] and continues to gradually improve with age. A prior study from our laboratory found that children from ages 4–9 years performed the STS movement using more trunk and hip flexion, but less knee flexion and ankle dorsiflexion, than children aged 10–12 and adults [10]. The difference in STS movement patterns between children and adults may come from the absence of fully matured postural control [11]. However, previous studies which included our study [10] have not shown how the ability to control COM during STS develops.

Studying the development of postural control during STS in TD children is important for understanding how children in different age groups control the COM during STS since this information could help clinicians appropriately identify how to treat children with delayed development. Therefore, we did analyse the data of our prior study [9] which aimed to investigate postural control development by reporting COM variables during STS in children aged 4–12 and compare the results with those of young adults. We hypothesised that the ability to control COM in terms of displacement and velocity during STS would be differ among age groups.

2. Materials and Methods

2.1. Participants

Seventy-seven healthy participants (58 children and 19 young adults) participated in this study. They were separated into four groups of the following ages: (1) children aged 4–6 years (n=18); (2) children aged 7–9 years (n=20); (3) children aged 10–12 years (n=20); and (4) young adults aged 18–25 years (n=19). All children showed age-appropriate standard weight and height based on the national growth chart. All adults had normal BMI (18–22.9 kg/m2). Children and adults were excluded if they had known musculoskeletal or neuromuscular diseases that might obstruct STS movements. Characteristics of the participants, including ages, genders, heights, and weights, are described in Table 1. Research related to human use has complied with all relevant national regulations and institutional policies, and has followed the tenets of the Declaration of Helsinki, and has also been approved by the ethical board of the university. Informed consent has been obtained from all individuals included in this study or from their legal guardians.

Table 1. Characteristics of participants (n=77)

	4–6 yrs. (n=18)	7–9 yrs. (n=20)	10–12 yrs. (n=20)	Adults (n=19)
Age (years)	5.80 (0.90)	8.56 (0.73)	11.66 (0.70)	22.41 (1.98)
Gender (female:male)	9:9	10:10	10:10	10:9
Weight (kg)	20.53 (3.28)	26.50 (4.66)	39.47 (8.57)	56.42 (5.36)
Height (cm)	112.41 (7.10)	126.95 (4.78)	146.01 (9.67)	165.8 (6.78)

2.2. Equipment

STS movements were captured using a motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) with eight Raptor E cameras running at 120 Hz. Twenty-nine markers were placed on each participant's body, as described in the modified Helen Hayes marker set model [12]. These markers were used to calculate COM parameters [13]. To define the phase of STS movement, two force platforms (Bertec Corp., Columbus, OH) with a sample rate of 1200 Hz were used to measure vertical ground reaction force.

2.3. Procedures

Before data collection, each participant was asked to sit on an adjustable bench. The height of the bench was set at 100% of the participant's lower leg length, and the seat depth was set to 25% of the participant's thigh length. Each participant began in the same starting position: arms crossed, feet placed on two force plates set shoulder-width apart, and the lateral malleolus aligned with the centre of the knee joint. Participants were then asked to stand up with their preferred speed and movement pattern. During STS, all participants were allowed to move their feet freely. 2–3 trial runs of STS were allowed in order to familiarise participants with the study protocol. Three successful and complete trials of STS movement were then collected for further analysis [10].

2.4. Data processing

In the present study, the STS movement was separated into four phases, including the flexion-momentum phase (phase I), momentum-transfer phase (phase II), extension phase (phase III), and stabilization phase (phase IV) [10]. The definition and time point of the STS phases are shown in Table 2.

Table 2. Sit-to-stand phase

Phase	Starting	Ending
Phase I: Flexion-momentum	T0: Initiation point of trunk flexion or feet slight backward (time at a horizontal velocity of shoulder marker or ankle marker ≥0.1 m/sec)	T1: Seat-off (the point at the right greater trochanter marker moves up from a reference line formed by two markers placed on the seat)
Phase II: Momentum-transfer	T1: Seat-off	T2: Point of maximum vertical ground reaction force
Phase III: Extension	T2: Point of maximum vertical ground reaction force	T3: The highest point of the shoulder
Phase IV: Stabilization	T3: The highest point of the shoulder	T4: End of movement (time at a vertical and horizontal velocity of right greater trochanter marker ≤0.1 m/sec)

For data processing we used KinTools RT (Version 2.0, Motion Analysis Corporation, Santa Rosa, CA) with the fourth-order Butterworth filter and a cut-off frequency of 6 Hz. Fifteen body segment masses were estimated using Jensen's formula [14] for children 4–12 years of age and Winter's formula [15] for adults 18–25 years of age. These segment masses were used to compute whole-body COM. The COM parameters for each phase (phases I–IV) were calculated by MATLAB as follows: (1) COMap, which corresponds to the COM displacements in the anterior-posterior directions in mm; (2) COMml, as determined by the COM displacements in the medial-lateral directions in mm; (3) COMv, as determined by the COM displacements in the vertical directions in mm; (4) VCOMap, the mean velocity of the COM displacements in the anterior-posterior directions in m/s; (5) VCOMml, the mean velocities of the COM displacements in the medial-lateral directions in m/s; and (6) VCOMv, the mean velocities of the COM displacements in the vertical directions in m/s. These variables were normalized by the body height of each participant.

2.5. Statistical Analysis

Data analysis was performed using the SPSS version 22.0 software. The Shapiro-Wilk test revealed a normal distribution of the data; therefore, all data were presented as mean and standard deviation (SD). A one-way ANOVA with Bonferroni corrections was used to compare the differences of COM parameters between groups (4–6 years, 7–9 years, 10–12 years, and adults). The eta-square was to report the effect size. The significance level was set at less than 0.05.

3. Results

Figure 1 shows the overall COM displacement and velocity as well as the COM displacement and velocity in every direction (Figures 2-4). Patterns of COM displacements during STS were similar across all groups. For the patterns of COM velocities during the flexion-momentum and momentum-transfer phases of STS movement, children aged 4–9 years could not continually increase their COM velocity like the children aged 10–12 and the adult groups could, as shown by the undulating line on the graph. The peak velocity of total COM and COM in the medial-lateral and vertical directions for all age groups occurred in phase III (extension phase). Additionally, peak velocity of COM in the anterior-posterior direction in children aged 4–12 occurred in phase I (the flexion-momentum phase), whereas, for adults, peak velocity occurred in phase II (the momentum-transfer phase). The mean and standard deviation of the COM parameters in each phase are shown in Table 3.

In phase I (the flexion-momentum phase), the COMap ($F_{3,76} = 42.27$, $P < 0.001$, $\eta^2 = 0.64$), COMml ($F_{3,76} = 4.98$, $P = 0.003$, $\eta^2 = 0.17$), COMv ($F_{3,76} = 13.21$, $P < 0.001$, $\eta^2 = 0.35$), VCOMap ($F_{3,76} = 68.99$, $P < 0.001$, $\eta^2 = 0.74$), VCOMml ($F_{3,76} = 9.98$, $P < 0.001$, $\eta^2 = 0.29$), and VCOMv ($F_{3,76} = 19.59$, $P < 0.001$, $\eta^2 = 0.45$) parameters showed significant differences between the groups. Post hoc analysis revealed that children aged 4–12 showed significantly greater COM displacements and velocities in the anterior-posterior, medial-lateral, and vertical directions during this phase than adults. In addition, children aged 4–9 had a significantly higher displacement and velocity of COM in the anterior-posterior and vertical directions than children aged 10–12.

In phase II (momentum-transfer phase), the results showed a significant difference between groups for the COMap ($F_{3,76} = 8.01$, $P < 0.001$, $\eta^2 = 0.25$), VCOMap ($F_{3,76} = 47.58$, $P < 0.001$, $\eta^2 = 0.66$), and VCOMml ($F_{3,76} = 4.52$, $P = 0.006$, $\eta^2 = 0.16$). Children aged 4–9 had significantly greater COM displacements and velocity in the anterior-posterior direction than both children aged 10–12 years and adults. In addition, children aged 4–12 demonstrated significantly higher COM velocities in the medial-lateral direction during this phase than adults.

In phase III (the extension phase), the VCOMap ($F_{3,76} = 21.63$, $P < 0.001$, $\eta^2 = 0.47$), VCOMml ($F_{3,76} = 6.71$, $P < 0.001$, $\eta^2 = 0.22$), and VCOMv ($F_{3,76} = 14.51$, $P < 0.001$,

$\eta 2 = 0.37$) parameters showed significant differences between the groups. Post hoc analysis revealed that during this phase, children aged 4–12 showed significantly greater COM velocity in the anterior-posterior, medial-lateral and vertical directions than adults. In addition, children aged 4–6 had the highest COM velocity in the anterior-posterior and vertical directions during this phase.

In phase IV (the stabilisation phase), the results showed significant differences between the groups for the COMap ($F_{3,76} = 4.99$, $P = 0.003$, $\eta 2 = 0.17$), COMml ($F_{3,76} = 8.29$, $P < 0.001$, $\eta 2 = 0.25$), and COMv ($F_{3,76} = 5.49$, $P = 0.002$, $\eta 2 = 0.18$) parameters. Children aged 4–12 showed greater COM displacement in the anterior-posterior, medial-lateral, and vertical directions than adults.

4. Discussion

To our knowledge, our study is the first to evaluate age-related changes in body sway during STS movement in TD children aged 4–12 years compared with adults. Our main finding was that all COM parameters during STS are age-related. Additionally, patterns of COM velocity were shown to be different between age groups. In the early phases of STS, the pattern of total COM velocity in children aged 4–9 was not smooth, unlike in children aged 10–12 and in young adults. This result might suggest that the maturity of overall postural control during STS is still not fully developed in children aged 4–9. However, when considering the timing of the peak velocity in each direction, our results showed that children aged 4–12 years had different timings of this value when compared with adults, particularly in the anterior-posterior direction. Therefore, the maturity of postural control in children aged 10–12 may not still be fully developed during STS movements. In general, the biomechanical demands required in each phase of STS are different, so the development process of postural control in each phase of STS may also differ between age groups, which is why we divided the STS task into four phases.

The first phase (flexion-momentum phase) involved the movement of COM in a horizontal direction, which requires sufficient horizontal upper-body momentum generated by the coordination between the trunk and the lower extremity muscles [16, 17]. Our study found that children aged 4–12 generated more COM velocity and COM displacement in all directions than adults. Additionally, children aged 4–9 had a greater displacement and velocity of COM in the anterior-posterior and vertical directions than children aged 10–12 years. This might be because of the differences in the ability to control COM between children and adults. Previous studies showed that during the first phase of STS movement, older adults who had reduced levels of postural control had a greater COM velocity than younger adults [18,19]. This may indicate that the ability to control COM in this phase is still not fully developed in children aged 4–12. Therefore, children aged 4–12 tend to develop a large forward momentum with a high velocity before standing up; such momentum is then used to drive the upper body into the base of support.

Consequently, a large amount of forward momentum with a high velocity of COM in phase I also influenced the movement of COM in phase II. Phase II, which is the momentum-transfer phase, involves the transition of upper-body momentum to the lower extremities [16]. Our study found that children aged 4–9 had greater COM displacement and velocity in the anterior-posterior direction than children aged 10–12 and adults.

As a consequence of the movement, the main goal of the extension phase (phase III) is to move the COM vertically to a standing position [16, 17]. Our results found that children aged 4–12 demonstrated a higher COM velocity in all directions than adults. In addition, children aged 4–6 had the highest COM velocity in the anterior-posterior and vertical directions during this phase. This higher velocity of COM in children may be due to the inefficiency of lower extremity segmental motion [19]. A previous study showed that children had a slightly delayed onset of thigh extension when standing up, and also initiated trunk and shank extension slightly sooner. These time delays meant that the exploitation of momentum-transfer was limited and the requirement for active force production in generating vertical momentum was increased [20]. From this evidence, it could be assumed that children generate a large amount of vertical momentum with a high velocity in order to extend the body into a standing position.

The stabilisation phase (phase IV) involves the stabilisation of COM, which requires both feedback and feedforward processes [21]. Our study found that children aged 4–12 had higher COM displacement than adults in all directions. This may be because of immature processes of the internal models of action as determined by motor and postural strategies in children aged 7–10 [22-23], from sensory integration while standing [24], and from the immaturity of anticipatory postural adjustment [25] in children under 12 years old. This study enhances our understanding of the ability to control COM during STS movement in different age groups. The difference between adults and children is minimally valued, which may not be considered important in practical terms. However, this information provides crucial biomechanical knowledge which can be used to reference further studies of children with developmental disorders.

Our study was limited by the three-year division of each group of children, as they were grouped based on the physical education classes that they took. However, the group of children aged 4–6 included children who were in the intensive stage of balance control development [26], which may have been the reason for the larger intra-individual variability in this group. Future studies should investigate the variability of the posture control parameters in this group and confirm that they can create such a group.

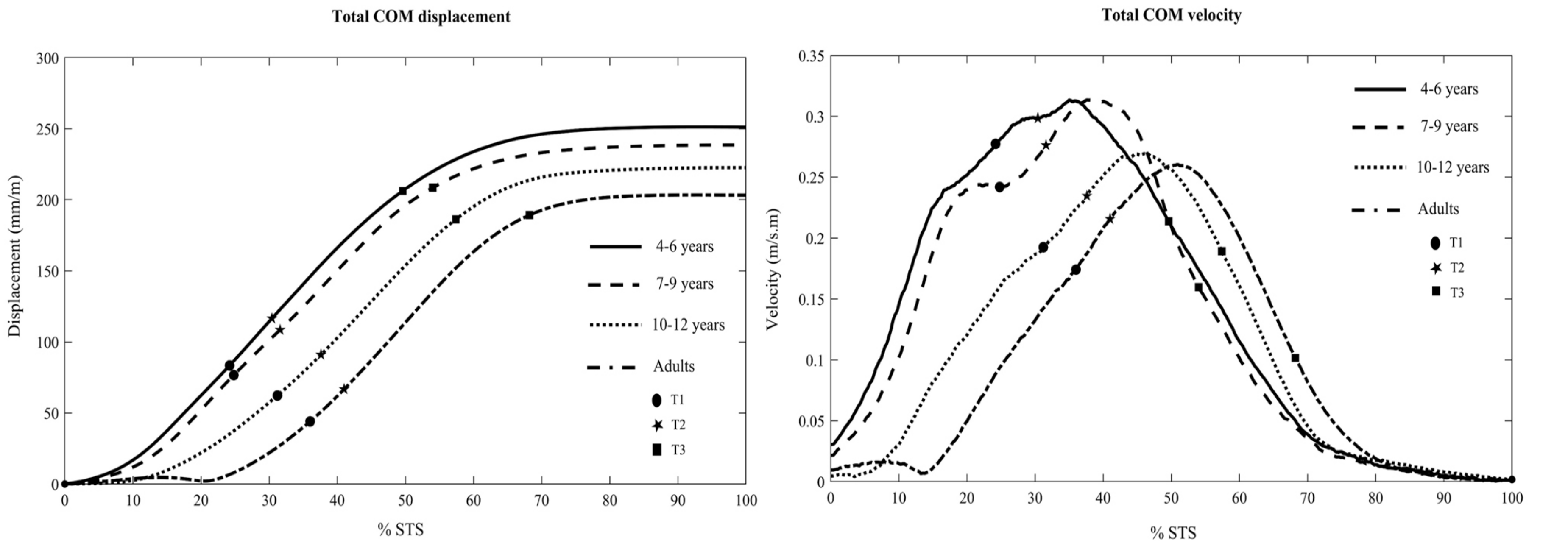

Figure 1. The total COM displacement and velocity during sit-to-stand. T1 is the point at which the right greater trochanter marker moves up, T2 is the point at which the maximum vertical ground reaction force is reached, and T3 is the highest point of the shoulder.

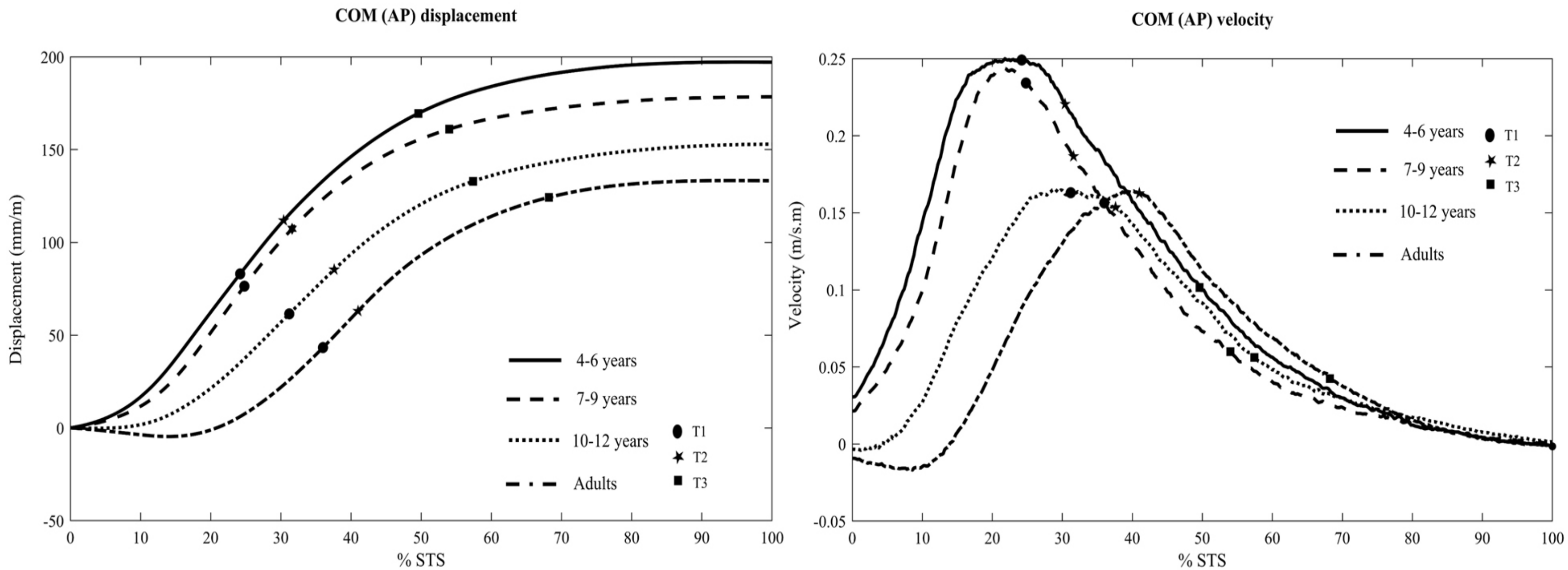

Figure 2. The COM displacement and velocity in antero-posterior (AP) direction during sit-to-stand. T1 is the point at which the right greater trochanter marker moves up, T2 is the point at which the maximum vertical ground reaction force is reached, and T3 is the highest point of the shoulder.

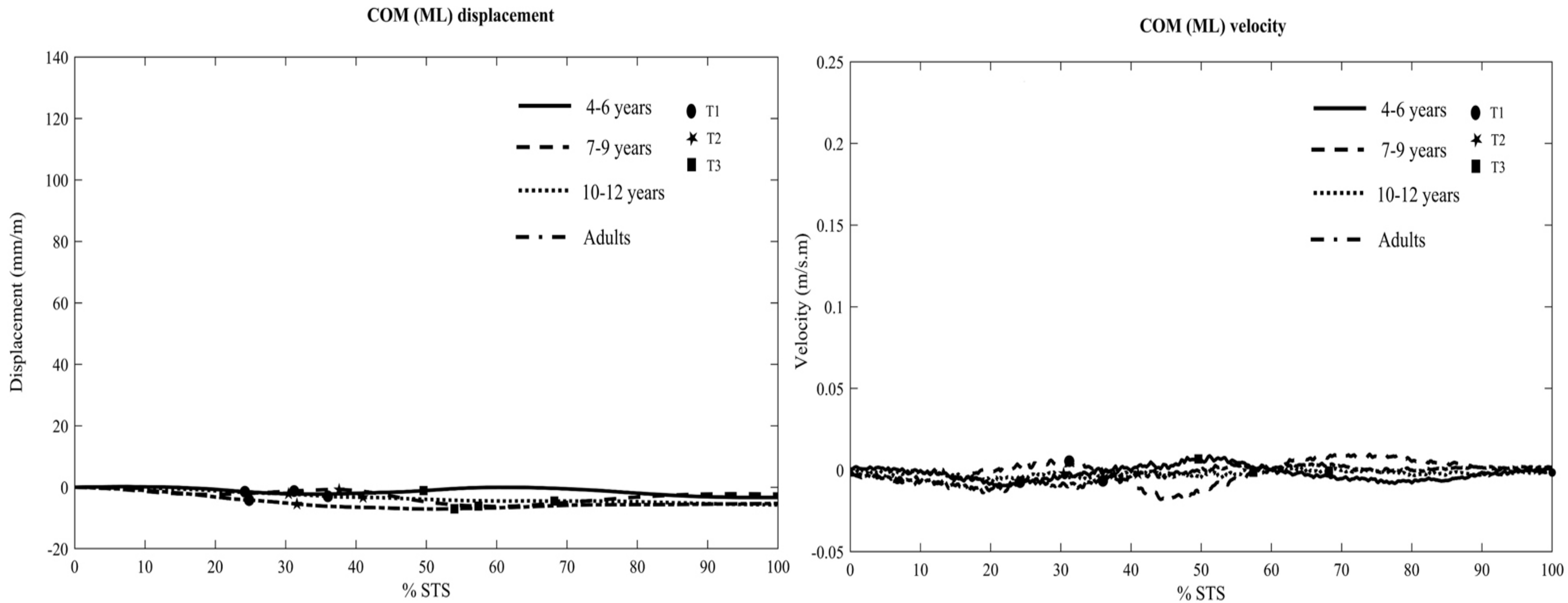

Figure 3. The COM displacement and velocity in medio-lateral (ML) direction during sit-to-stand. T1 is the point at which the right greater trochanter marker moves up, T2 is the point at which the maximum vertical ground reaction force is reached, and T3 is the highest point of the shoulder.

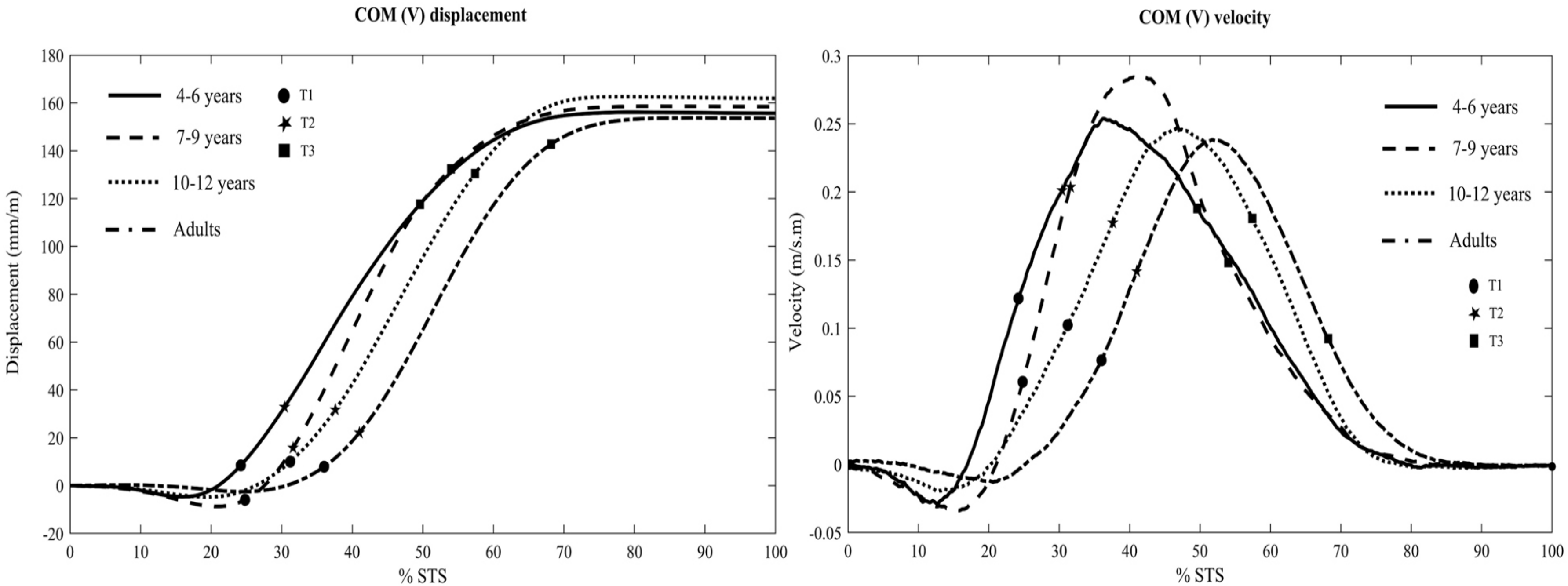

Figure 4. The COM displacement and velocity in vertical (V) direction during sit-to-stand. T1 is the point at which the right greater trochanter marker moves up, T2 is the point at which the maximum vertical ground reaction force is reached, and T3 is the highest point of the shoulder.

Table 3. Centre of mass (COM) parameters in each phase during sit-to-stand in each group

	4–6 yrs. (n=18)	7–9 yrs. (n=20)	10–12 yrs. (n=20)	Adults (n=19)
Phase I				
COMap (mm/m)	78.97 (13.74)	70.65 (15.20)	53.16 (9.82) [a,b]	39.01 (7.31) [a,b,c]
COMml (mm/m)	4.98 (2.19)	5.33 (4.24)	4.04 (2.94)	2.04 (1.10) [a,b,c]
COMv (mm/m)	11.89 (5.21)	12.22 (5.56)	7.56 (5.34) [a,b]	3.78 (2.32) [a,b,c]
VCOMap (m/s.m)	0.169 (0.033)	0.141 (0.036)	0.081 (0.027) [a,b]	0.046 (0.016) [a,b,c]
VCOMml (m/s.m)	0.011 (0.004)	0.010 (0.007)	0.006 (0.005)	0.002 (0.001) [a,b,c]
VCOMv (m/s.m)	0.026 (0.012)	0.025 (0.013)	0.011 (0.009) [a,b]	0.004 (0.003) [a,b,c]
Phase II				
COMap (mm/m)	44.10 (17.62)	34.04 (19.34)	23.54 (11.04) [a,b]	24.84 (6.61) [a,b]
COMml (mm/m)	2.02 (1.36)	1.75 (1.14)	2.07 (3.77)	0.83 (0.40)
COMv (mm/m)	14.14 (10.31)	10.01 (5.61)	15.77 (9.11)	15.35 (3.02)
VCOMap (m/s.m)	0.339 (0.046)	0.271 (0.057) [a]	0.188 (0.036) [a,b]	0.195 (0.035) [a,b]
VCOMml (m/s.m)	0.015 (0.010)	0.014 (0.006)	0.012 (0.011)	0.004 (0.003) [a,b,c]
VCOMv (m/s.m)	0.111 (0.068)	0.094 (0.058)	0.119 (0.076)	0.121 (0.029)
Phase III				
COMap (mm/m)	53.39 (16.26)	54.55 (17.91)	52.55 (17.96)	55.64 (8.56)
COMml (mm/m)	5.92 (2.59)	6.08 (3.49)	5.55 (5.79)	3.01 (1.28)
COMv (mm/m)	127.74 (28.12)	140.07 (21.76)	130.39 (24.67)	130.88 (12.49)
VCOMap (m/s.m)	0.164 (0.034)	0.124 (0.029) [a]	0.096 (0.029) [a,b]	0.096 (0.027) [a,b]
VCOMml (m/s.m)	0.019 (0.010)	0.014 (0.005)	0.013 (0.015)	0.005 (0.002) [a,b,c]
VCOMv (m/s.m)	0.398 (0.073)	0.324 (0.081) [a]	0.301 (0.104) [a]	0.223 (0.059) [a,b,c]
Phase IV				
COMap (mm/m)	25.17 (11.98)	24.34 (12.22)	23.73 (7.05)	14.26 (8.04) [a,b,c]
COMml (mm/m)	11.44 (8.13)	7.86 (4.03)	6.88 (2.89)	3.80 (2.35) [a,b,c]
COMv (mm/m)	23.99 (14.02)	22.79 (14.15)	26.83 (19.11)	8.81 (9.22) [a,b,c]
VCOMap (m/s.m)	0.026 (0.0169)	0.025 (0.012)	0.026 (0.009)	0.018 (0.009)
VCOMml (m/s.m)	0.011 (0.008)	0.009 (0.005)	0.007 (0.003)	0.005 (0.002)
VCOMv (m/s.m)	0.026 (0.018)	0.024 (0.015)	0.021 (0.022)	0.011 (0.011)

a. Significant difference from group 4–6 year ($p < 0.05$); b. Significant difference from group 7–9 year ($p < 0.05$); c. Significant difference from group 10–12 year ($p < 0.05$).

5. Conclusions

This study revealed a relationship between age and the quality of posture control during STS movement. In addition, this study showed differences in the ability to control the COM among children aged 4–12, as well as between children and adults. The development of postural control in each phase of STS is different for each age group, and some levels of postural control maturation may occur before the age of 12. However, in general, fully mature postural control is still not present during STS movements in children aged 10–12 years.

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