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Biomechanical analysis of the timed up-and-go (TUG) test in children with and without Down syndrome

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ABSTRACT

Background: The timed up-and-go (TUG) test consists of multiple functional activities of daily living performed in a sequence, with the goal to complete the test as quickly as possible. Considering children with Down syndrome (DS) have been shown to take longer to complete the TUG test, it is imperative to identify which tasks are problematic for this population in order to individualize physical interventions.
Research question: Is the biomechanical pattern of each functional task during the TUG test different between children with DS and typically developing (TD) children?
Methods: Thirteen children with DS and thirteen TD children aged 5–11 years old completed the TUG test. Kinematic data was captured using a Vicon motion capture system. We visually coded the TUG test into five phases: sit-to-stand, walk-out, turn-around, walk-in, and stand-to-sit. We focused on the center-of-mass (COM) movement in the sit-to-stand phase, spatiotemporal parameters in the walk-out phase, and intersegmental coordination in the turn-around phase.
Results and significance: Children with DS took longer to complete the entire test, as well as each of the five phases. During the sit-to-stand phase, children with DS produced smaller peak vertical COM velocity, medial-lateral COM excursion, and peak knee and hip extension velocity compared to TD peers. Children with DS walked at a slower velocity during the walk-out phase. Both groups demonstrated a similar intersegmental coordination pattern between the head, thorax, and pelvis during the turn-around phase although children with DS had slower average and peak angular velocity at the head, thorax, and pelvis. Our results suggest that children with DS were less able to anticipate transitioning between motor tasks and took longer to initiate motor tasks. Our TUG analysis provides the detailed insights to help evaluate individual motor tasks as well as the transition from one task to another for clinical populations.

1. Introduction

The Timed Up-and-Go (TUG) test is a common test to assess functional mobility and coordination. This test consists of functional activities of daily living, including standing up from a chair, walking, turning around, walking, and sitting down to a chair [1]. During the TUG test, the sit-to-stand and stand-to-sit phases require large lower body muscle forces and a transfer of momentum from the horizontal to vertical direction when raising or lowering the center-of-mass (COM) [2,3]. The walking phases necessitate a fast walking speed to a target three meters away. The turn-around phase requires intersegmental coordination between the head, thorax, and pelvis to redirect the walking path in an opposite direction [4]. Poor performance during the TUG test has been associated with clinical populations with motor dysfunctions including multiple sclerosis [5] and Parkinson's disease [4].

The TUG test has been shown to be valid for the functional mobility assessment of children with Down syndrome (DS), who usually require a longer time to complete the test than typically developing (TD) children [6]. Persons with DS are characterized with lower muscle strength and tone, greater joint flexibility, and slower movement initiation and execution [7,8]. Because of these physical limitations, children with DS often take longer to develop motor skills and demonstrate less coordinated movement patterns [9,10]. Moreover, these motor dysfunctions can inhibit individuals' with DS capacity to accomplish functional activities of daily living and their ability to become independent [11]. While children with DS take longer to complete the entire TUG test, it is unknown whether this results from an ineffective

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biomechanical strategy for a singular functional sub-task or a general ineffectiveness across all of the sub-tasks.

The typical sit-to-stand pattern involves initial forward trunk lean to shift the COM over the feet [12], defined as the momentum-transfer-strategy [13]. However, increased reliance on this strategy, demonstrated by excessive forward movement, has been implicated with slower performance, an underdeveloped motor pattern, and reduced lower body muscle strength in children with cerebral palsy and older adults [12–14]. In addition, the COM trajectory and velocity has not been studied during sit-to-stand in individuals with DS. Moreover, turning is a distinct motor pattern compared to straight-line walking, requiring kinematic sequencing of the lower and upper body [15,16]. For the upper body, a typical intersegmental coordination pattern is defined as the head completes the rotation before the trunk [4]. This strategy not only improves the efficiency of the turn, but indicates head stabilization. However, kinematics of turning has not been studied in children with DS, even though turning occurs daily and can be challenging [16].

The sequence of functional tasks during the TUG test requires motor planning and capacity to anticipate transitioning from one motor task to another [17]. As children with DS may rely on feedback rather than anticipation to complete upper extremity motor tasks, such as tapping and tracking [18,19], it is plausible that the slower performance on the TUG test could result from a reduced capacity to anticipate task transition. Further, previous studies have focused on upper extremity motor tasks and it is imperative to evaluate task transition during locomotion. Therefore, the TUG test is an advantageous protocol to assess because it is more representative of everyday locomotion involving transitions among standing, turning, and walking, compared to typical analysis of straight-line walking.

The purpose of this study was to investigate the biomechanical strategies between children with and without DS during the performance of the sit-to-stand, walk-out, and turn-around phases of the TUG test and their influence on the time to complete the TUG test. We did not evaluate the stand-to-sit phase of the TUG test because of the heterogeneity of the strategies utilized. Our hypothesis was that children with DS will take longer to complete each phase of the TUG test, resulting in a longer time for the entire TUG test. During the sit-to-stand phase, children with DS will demonstrate greater anterior/posterior (AP) COM movement, slower COM vertical velocity and slower ankle, knee, and hip extension velocity. During the walk-out phase, children with DS will walk slower, and display shorter and wider steps. During the turn-around phase, both groups will demonstrate a similar intersegmental pattern such that the head turns before the thorax and pelvis. However, children with DS will take longer to initiate and complete the turn of each segment, and demonstrate reduced turning velocity.

2. Methods

2.1. Participants

We recruited 22 children with DS and 17 TD children aged 5–11 years. Children with DS were recruited through local DS parent support groups and TD children through our personal contacts. Exclusion criteria included additional motor or cognitive disorders and uncorrected vision and hearing problems. This study was approved by the institutional review board at the hosting university. Prior to data collection, informed consents were obtained from the parents and verbal assent was obtained from the children. Nine children with DS had missing marker data as they moved out of camera view during the TUG test, or they refused to wear the full-body marker set due to skin sensitivity. We therefore removed these subjects from data analysis and age-matched 13 TD children (Table 1). The DS group had similar age, body-mass, and height, but had shorter leg lengths than the TD group ($p = 0.024$).

2.2. Protocol

We collected anthropometric measurements, including height, body mass, and leg length, defined as the distance from the anterior superior iliac spine to the medial epicondyle of the femur to the medial malleolus of the ankle. A 35-marker Vicon PSIS full-body marker set was attached to the subjects [20]. An 8-camera Vicon motion capture system (Oxford, UK) collected kinematic data at a sampling rate of 100 Hz. The kinematic data were filtered using a fourth-order zero-lag Butterworth filter with a 6 Hz cutoff frequency.

Subjects sat on a chair without side arms, with arms at their sides, feet in contact with the floor, hip and knee flexed at about 90° with a neutral ankle. Upon the verbal “Go” command, the subjects stood up from the chair, walked towards a target three meters away, touched the target, turned around, and walked back to the chair and sat down as quickly as possible. After adequate practice, we collected five successful trials, defined as (a) completion of the entire task, (b) not running, and (c) not becoming distracted.

2.3. Data analysis

We visually separated each trial into five phases: (1) sit-to-stand, (2) walk-out, (3) turn-around, (4) walk-in, and (5) stand-to-sit. Sit-to-stand started with initiation of forward trunk lean and ended with the end of vertical movement of the upper body. Turn-around started at the mid-stance of the final step of the walk-out phase and ended at the mid-stance of the first step of the walk-in phase. Stand-to-sit started at the beginning of pelvis rotation before lowering to the chair and ended with the end of vertical movement of the upper body. The walk-out and walk-in phases were coded as the time between sit-to-stand and turn-around, and between turn-around and stand-to-sit, respectively.

To assess the ability to quickly raise the COM during the sit-to-stand phase, we assessed AP, medial/lateral (ML), and vertical COM excursion and peak velocity, as well as, peak ankle, knee, and hip joint extension angle and velocity. We estimated COM position using a segmental analysis from the full-body marker set [20]. Joint angles were determined using the Vicon Plug-In Gait model where a positive angle denotes flexion. To evaluate the proficiency during the walk-out phase, we calculated step length, step width, and velocity. We normalized step length and width by leg length and velocity by the square root of gravitational acceleration ($9.81\ m/s^2$) multiplied by leg length [21].

During the turn-around phase we evaluated the coordination across the head, thorax, and pelvis, as well as the duration to complete the turn and the average and peak angular velocity for each segment. The coordination of the segments was assessed by comparison of the timing of the turn onset for each body segment. Angles in the transverse plane for the head, thorax, and pelvis were obtained from the Vicon Plug-In Gait model. A 10-frame window incrementally moved one frame across the turn phase was used to determine the standard deviation of the segment angle. Timing onset was determined when the standard deviation of the 10 frames was greater than that of the walk-out phase [22]. This was completed for each segment and normalized as a percentage of turn phase. The offset was defined as the time frame when the segment angle reached the average walk-out angle minus 170°, indicating orientation in the opposite direction. Turn-duration for each segment was defined as the difference between the onset and offset. The angular velocity of each segment was determined using the central difference method, from which the average and peak velocity were obtained.

2.4. Statistical analysis

We conducted independent t-tests on the time for each phase and the entire TUG test between the two groups. For the sit-to-stand and walk-out phases, we conducted independent t-tests for the COM and peak joint angle variables. For the turn-around phase, we conducted

Table 1
Mean (SD) of subject characteristics.

Group	Gender	Age (yrs)	Height (m)	BMI (kg/m^2)	Body mass (kg)	Leg length (m)
TD	6F/7M	8.27 (1.74)	1.33 (0.10)	17.08 (2.25)	30.72 (7.24)	0.72 (0.08)
DS	10 F/3M	9.00 (1.85)	1.25 (0.12)	19.61 (4.43)	31.25 (11.05)	0.64 (0.08)*

TD: typically developing children; DS: children with Down syndrome. Symbol * denotes that the DS group had a shorter leg length than the TD group (student t-test, p = 0.024).

two-way (2 group x 3 segment) ANOVAs with repeated measures on segment to compare the timing, duration, average velocity, and peak velocity of the head, thorax, and pelvis. Normality was assessed using the Shapiro-Wilk test and variables were log transformed if normality was violated. Post-hoc analysis was conducted using pairwise comparisons with Bonferroni adjustments when necessary. Statistical analysis was conducted using SAS software (Cary, NC). A significance level was set at alpha = 0.05.

3. Results

3.1. Duration of TUG phases

The DS group not only took longer to complete the TUG test, but also required more time to complete each phase (Fig. 1). On average, the DS group completed the TUG test in 7.74 s compared to 4.67 s for the TD group. Statistical analysis demonstrated that the DS group took a longer time for the entire TUG task ($t(24) = 4.82$, $p < 0.001$) as well as for the sit-to-stand phase ($t(24) = 2.11$, $p = 0.045$), the walk-out phase ($t(24) = 4.30$, $p < 0.001$), the turn-around phase ($t(24) = 7.69$, $p < 0.001$), the walk-in phase ($t(24) = 3.75$, $p = 0.001$), and the stand-to-sit phase ($t(24) = 4.76$, $p < 0.001$).

3.2. Sit-to-stand phase

Both groups demonstrated similar AP and vertical COM excursions and timing of peak COM velocities, but the TD group had greater ML excursion than the DS group (Table 2). ML COM excursion was, on average, 1.28 cm smaller in the DS group than in the TD group ($t(23) = 2.36$, $p = 0.027$). The DS group had a slower peak vertical COM velocity than the TD group ($t(23) = -2.33$, $p = 0.029$). Further, the DS group displayed lower peak ankle extension angles ($t(23) = 2.26$, $p = 0.033$), slower peak knee extension velocities ($t(23) = 2.38$, $p = 0.026$), and slower peak hip extension velocities ($t(23) = 2.62$, $p = 0.015$) than the TD group. Both groups reached peak joint angular velocities around the same percentage of the sit-to-stand phase.

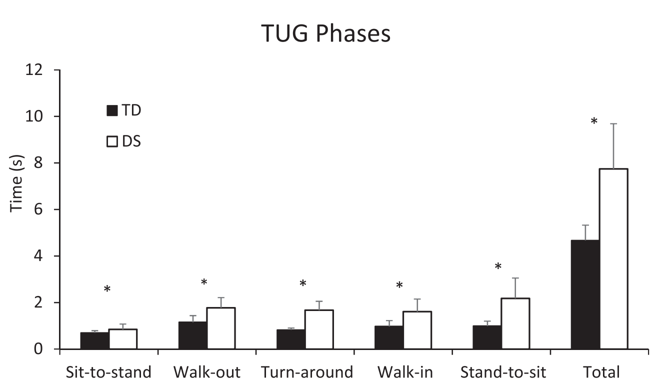

Fig. 1. Mean and standard deviation of the duration for each phase and the total duration to complete the TUG test. Symbol * indicates a group difference between the TD and DS groups at $p < 0.05$.

3.3. Walk-out phase

The DS group walked with similar normalized step length and width, but at a slower normalized velocity than the TD group (Table 3). Statistical analysis demonstrated that the DS group displayed an average (SD) slower normalized speed of 0.14 (0.11) compared to the TD group ($t(24) = 3.36$, $p = 0.003$).

3.4. Turn-around phase

While the DS group coordinated the turning of the head, thorax, and pelvis segments similarly to the TD group, they took longer to initiate and complete their turn, as well as moved at slower angular velocities (Fig. 2). Statistical analysis demonstrated a group main effect for the timing of onset ($F(1,24) = 50.84$, $p < 0.001$), where the DS group took longer to initiate the turn of all three segments (Fig. 2a). There was also a segment main effect ($F(2,44) = 5.28$, $p = 0.009$) where the pelvis turn onset occurred before the head in both groups. Similarly, a group main effect ($F(1,24) = 28.60$, $p < 0.001$) and segment main effect ($F(2,48) = 4.76$, $p = 0.013$) was found for the turn duration, where the DS group took longer to complete the turn of all segments and the turn duration for the head was shorter than that of the thorax in both groups (Fig. 2b). Additionally, the DS group showed slower average and peak angular velocity than the TD group. There was a group main effect ($F(1,24) = 23.88$, $p < 0.001$) and segment main effect ($F(2,48) = 19.04$, $p < 0.001$) for average angular velocity (Fig. 2c), and a group main effect ($F(1,24) = 35.88$, $p < 0.001$) and segment main effect ($F(2,48) = 32.28$, $p < 0.001$) for peak angular velocity (Fig. 2d). Post-hoc analysis demonstrated that both average and peak angular velocities of the head were faster than those of the thorax and pelvis across the two groups.

4. Discussion

In support of our first hypothesis, the DS group required a longer duration to complete the TUG test, similar to previous studies [1,6]. Moreover, the DS group performed each of the five functional tasks at a slower rate than the TD group. Our methodology of beginning the timing of the TUG test at movement initiation and not the “Go” command might have reduced any impact of slower reaction times commonly found in the DS population [19]. Therefore, the longer time to complete the TUG test was not due to a delay in beginning the task.

Partially supporting our hypothesis for the sit-to-stand phase, the DS group reached a slower peak vertical COM velocity compared to the TD group, but similar AP movement. This result suggested an underdeveloped capacity for power generation in children with DS when performing a sit-to-stand task. Considering the knee extensors have been associated with sit-to-stand performance [23], it is unsurprising that the DS group had lower peak knee extension velocity. Additionally, the DS group reached a lower peak hip extension velocity, which might have also contributed to the slower peak vertical COM velocity. These findings suggest that children with DS may adopt a similar strategy in regulating horizontal and vertical COM excursions and joint extension angles; however, power generation from the knee and hip extensors may be the control parameters which limit peak COM and joint velocities during sit-to-stand [23]. Future clinical studies are warranted to

Table 2
Mean (SD) of the COM and joint angle variables during the sit-to-stand phase.

	DS	TD	Statistical results	95% confidence interval
COM variables				
Excursion (cm)				
AP	27.64 (11.82)	39.20 (17.70)	n.s.	[-24.13, 1.01]
ML	2.44 (0.97)	3.73 (1.63)	t(23) = 2.36, p = 0.027	[-2.41, -0.16]
Vertical	11.60 (4.89)	14.89 (7.35)	n.s.	[-8.51, 1.92]
Magnitude of peak velocity (m/s)				
AP	46.25 (21.44)	41.94 (29.98)	n.s.	[-17.42, 26.05]
ML	10.49 (4.88)	5.61 (7.15)	n.s.	[-0.23, 9.99]
Vertical	45.21 (11.54)	62.19 (22.61)	t(23) = 2.33, p = 0.029	[-32.03, -1.92]
Timing of peak velocity (% phase)				
AP	41.56 (23.22)	31.40 (29.02)	n.s.	[-11.70, 32.03]
ML	68.76 (20.61)	67.19 (23.57)	n.s.	[-16.82, 19.97]
Vertical	66.24 (19.70)	72.57 (11.70)	n.s.	[-19.62, 6.94]
Joint angle variables				
Peak extension angle (deg)				
Ankle	9.14 (8.38)	0.40 (10.69)	t(23) = 2.26, p = 0.033	[0.75, 16.73]
Knee	27.53 (8.71)	27.43 (6.82)	n.s.	[-6.35, 6.54]
Hip	36.11 (11.23)	31.50 (5.81)	n.s.	[-2.70, 11.92]
Magnitude of peak extension velocity (deg/s)				
Ankle	217.70 (217.08)	198.90 (81.77)	n.s.	[-174.00, 136.50]
Knee	233.80 (47.33)	290.40 (49.06)	t(23) = 2.38, p = 0.026	[7.46, 105.60]
Hip	195.80 (46.55)	241.70 (41.16)	t(23) = 2.62, p = 0.015	[9.66, 82.24]
Timing of peak extension velocity (% phase)				
Ankle	80.41 (10.59)	79.76 (6.37)	n.s.	[-6.52, 7.81]
Knee	75.68 (17.89)	76.12 (10.65)	n.s.	[-12.49, 11.63]
Hip	73.82 (10.31)	77.59 (5.84)	n.s.	[-10.63, 3.09]

DS: children with Down syndrome; TD: typically developing children. AP: anterior-posterior; ML: medial-lateral. For statistical results of t-tests, n.s. denotes non-significance at $p < 0.05$. The 95% confidence intervals are of the difference between the two groups. If negative, the DS group had a lower value than the TD group. If positive, the DS group had a higher value than the TD group.

Table 3
Mean (SD) of normalized gait variables during the walk-out phase.

Variable	DS	TD	Statistical results	95% confidence interval
Step length	0.75 (0.11)	0.81 (0.17)	n.s.	[-0.18, 0.05]
Step width	0.10 (0.09)	0.10 (0.03)	n.s.	[-0.06, 0.06]
Velocity	0.60 (0.10)	0.74 (0.12)	t(24) = 3.36, p = 0.003	[-0.23, -0.06]

DS: children with Down syndrome; TD: typically developing children. Step length and width were normalized by the subject's leg length. Walking velocity was normalized as $v/(g*LL)^{1/2}$, in which v was walking speed, LL was leg length and g was gravitational acceleration 9.81 m/s^2. The 95% confidence intervals are of the difference between the two groups. If negative, the DS group had a lower value than the TD group. If positive, the DS group had a higher value than the TD group.

investigate whether increasing power generation of the knee and hip extensors can improve sit-to-stand performance in individuals with DS.

During gait initiation, there is a ML shift of the COM in preparation of the first step, which increases when asked to walk at faster speeds [24]. Given the greater ML COM excursion in the TD group during the sit-to-stand phase, we postulate that the TD group might anticipate the transition to the walk-out phase with the intent to walk fast. Moreover, the TD group reached greater ankle plantarflexion during the sit-to-stand phase, most likely initiating their first step. Further demonstrating greater anticipation, the TD group initiated the rotation of each segment within the first 15% of the turn-around phase compared to the 20–40% required by the DS group. As children with DS take longer to initiate movement and move slower because they rely on feedback, rather than anticipation [18,19], our results suggest that the limited ability of anticipation while transitioning from one motor task to another ultimately slowed down their performance. However, this population can improve motor skills and adopt more feedforward control after instructed practice [19]. It may be clinically beneficial for individuals with DS to practice sequences of movement to improve their motor anticipation and transition.

During the walk-out phase, the DS group demonstrated a slower normalized velocity than the TD group, consistent with previous studies [9,10]. However, there was no difference of normalized step length or step width, which did not support our hypothesis. Nevertheless, the velocity for the DS group, 1.50 m/s, was faster than normative preferred overground velocity, around 1.04 m/s [21,25]. This result suggests that the DS group comprehended the instructions to complete the TUG test as quickly as possible. However, children with DS may have a reduced ability to modify their gait pattern for a specific task, possibly due to their inefficient push-off strategy [26] or their reluctance to reduce their stability to increase speed [27].

During the turn-around phase, the DS group demonstrated a similar intersegmental coordination pattern compared to the TD group, partially supporting our hypothesis. Specifically, the pelvis initiated rotation before the head, but the head rotated at the fastest angular velocity resulting in the shortest duration. Unlike other populations such as Parkinson's disease who often exhibit a fixed intersegmental coordination during turning [4], the DS group demonstrated the ability to disconnect the rotation of their pelvis from their head in preparation of re-aligning their motion. This finding suggests that children with DS were able to plan their motor behavior when transitioning between tasks, however, this ability is slowed compared to TD children. It is not clear whether intersegmental coordination of the lower extremities [28] contributed to these differences, and further work is warranted.

One limitation of this study is our small sample size. We lost data from nine subjects with DS due to technical problems. Nonetheless, our

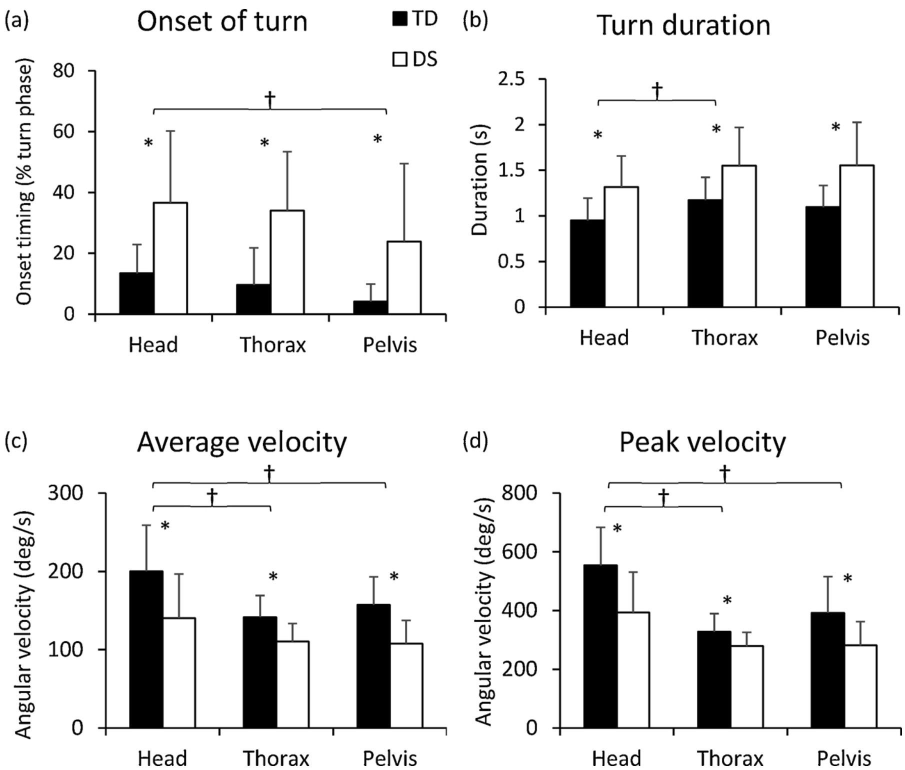

Fig. 2. Mean and standard deviation of head, thorax, and pelvis turning movement during the turn-around phase: (a) timing of onset of turn, normalized as percentage within the turn-around phase, (b) turn duration (in sec), defined as difference between onset and offset of turn, (c) average angular velocity (in m/s) in the transverse plane throughout the turn-around phase, and (d) peak angular velocity (in m/s) in the transverse plane throughout the turn-around phase. Symbol * indicates a group difference between the TD and DS groups and symbol † indicates a difference between segments for both groups at $p < 0.05$.

remaining 13 subjects for each group are comparable to previous studies on individuals with DS [29,30]. Another limitation is that we did not evaluate IQ of our subjects, which might impact TUG performance. Moreover, our analytical breakdown of the TUG test provides detailed insights to understand each functional activity and task transition in children with DS. This biomechanical analysis can be generalized to study other clinical populations that present similar or different physiological symptoms. It will help understand how specific physiological conditions manifest into motor deficits in task execution and transition during daily functional activities.

The results of this study demonstrated that the slower performance of the TUG test in children with DS was not influenced by an ineffective biomechanical strategy during a single phase of the test. Rather, children with DS took longer to complete each phase and illustrated a reduced capacity to anticipate transitioning from one motor task to the next. Therefore, physical interventions might focus on sequences of motor tasks to improve feed-forward control and anticipation in children with DS. Moreover, this study highlights turning as a prime motor task to sequence due to the similar intersegmental coordination pattern of the upper body found in children with and without DS. Therefore, children with DS would be practicing an acceptable motor pattern while improving their ability to motor plan and anticipate transitioning between locomotion and turning.

Author contribution

Matthew Beerse contributed to Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Original draft writing; Review & editing.

Michael Lelko contributed to Formal analysis; Investigation; Methodology; Software; Supervision; Validation; Visualization; Original draft writing.

Jianhua Wu contributed to Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Original draft writing; Review & editing.

Conflicts of interest statement

There were no conflicts of interest when completing this study.

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References

[1] K. Martin, M. Natarus, J. Martin, S. Henderson, Minimal detectable change for TUG and TUDS tests for children with Down syndrome, Pediatr. Phys. Ther. 29 (2017) 77–82.
[2] S. Bajelan, M.R. Azghani, Musculoskeletal modeling and simulation of three various sit-to-stand strategies: an evaluation of the biomechanical effects of the chair-rise strategy modification, Technol. Health Care 22 (2014) 627–644, https://doi.org/10.3233/THC-140834.
[3] W. Mathiyakom, J.L. McNitt-Gray, P. Requejo, K. Costa, Modifying center of mass trajectory during sit-to-stand tasks redistributes the mechanical demand across the lower extremity joint, Clin. Biomech. 20 (2005) 105–111, https://doi.org/10.1016/J.CLINBIOMECH.2004.08.005.
[4] F. Huxham, R. Baker, M.E. Morris, R. Iansek, Head and trunk rotation during walking turns in Parkinson's, Mov. Disord. 23 (2008) 1391–1397, https://doi.org/10.1002/MDS.21943.
[5] B. Bowser, S. O'Rourke, C.N. Brown, L. White, K.J. Simpson, Sit-to-stand biomechanics of individuals with multiple sclerosis, Clin. Biomech. 30 (2015) 788–794, https://doi.org/10.1016/J.CLINBIOMECH.2015.06.012.
[6] R.D. Nicolini-Panisson, M.V.F. Donadio, Normative values for the timed 'up and go' test in children and adolescents and validation for individuals with Down syndrom, Dev. Med. Child Neurol. 56 (2014) 490–497, https://doi.org/10.1111/DMCN.12290.
[7] P.M. Cowley, S. Keslacy, F.A. Middleton, L.R. DeRuisseau, B. Fernhall, J.A. Kanaley, K.C. DeRuisseau, Functional and biochemical characterization of soleus muscle in Down syndrome mice: insight into the muscle dysfunction seen in the human condition, Am. J. Physiol. Regul. Integr. Comp. Physiol. 303 (2012) R1251–R1260, https://doi.org/10.1152/ajpregu.00312.2012.
[8] M. Galli, C. Rigoldi, R. Brunner, N. Virji-Babul, A. Giorgio, Joint stiffness and gait pattern evaluation in children with Down syndrome, Gait Posture 28 (2008) 502–506, https://doi.org/10.1016/j.gaitpost.2008.03.001.
[9] M.E. Block, Motor development in children with Down syndrome: a review of the literature, Adapt. Phys. Activ. Q. 8 (1991) 179–209, https://doi.org/10.1123/apaq.8.3.179.

[10] C. Rigoldi, M. Galli, L. Mainardi, M. Crivellini, G. Albertini, Postural control in children, teenagers and adults with Down syndrome, Res. Dev. Disabil. 32 (2011) 170–175, https://doi.org/10.1016/j.ridd.2010.09.007.
[11] P.M. Cowley, L.L. Ploutz-Snyder, T. Baynard, K.S. Heffernan, S.Y. Jae, S. Hsu, M. Lee, K.H. Pitetti, M.P. Reiman, B. Fernhall, Physical fitness predicts functional tasks in individuals with Down syndrome, Med. Sci. Sports Exerc. 42 (2010) 388–393.
[12] E.S. Park, C. Park, H.J. Lee, D.Y. Kim, D.S. Lee, S.-R. Cho, The characteristics of sit-to-stand transfer in young children with spastic cerebral palsy based on kinematic and kinetic data, Gait Posture 17 (2003) 43–49, https://doi.org/10.1016/S0966-6362(02)00055-3.
[13] A.N.d. Santos, S.L. Pavao, P.R.P. Santiago, Td.F. Salvini, N.A.C.F. Rocha, Sit-to-stand movement in children with hemiplegic cerebral palsy: relationship with knee extensor torque and social participatio, Res. Dev. Disabil. 34 (2013) 2023–2032, https://doi.org/10.1016/J.RIDD.2013.03.021.
[14] P. Thanapan, S. Prasertsukdee, R. Vachalathiti, Comparison of body segmental kinematic characteristics between children with cerebral palsy performing sit-to-stand with and without a walker, Disabil. Rehabil. Assist. Technol. 8 (2013) 145–150, https://doi.org/10.3109/17483107.2012.737138.
[15] P.C. Dixon, J. Stebbins, T. Theologis, A.B. Zavatsky, Spatio-temporal parameters and lower-limb kinematics of turning gait in typically developing childre, Gait Posture 38 (2013) 870–875, https://doi.org/10.1016/J.GAITPOST.2013.04.010.
[16] P.C. Dixon, K. Jansen, I. Jonkers, J. Stebbins, T. Theologis, A.B. Zavatsky, Muscle contributions to centre of mass acceleration during turning gait in typically developing children: a simulation stud, J. Biomech. 48 (2015) 4238–4245, https://doi.org/10.1016/J.JBIOMECH.2015.10.028.
[17] E. Carmeli, S. Bar-Chad, M. Lotan, J. Merrick, R. Coleman, Five clinical tests to assess balance following ball exercises and treadmill training in adult persons with intellectual disability, J. Gerontol. Ser. A 58 (2003) M767–M772, https://doi.org/10.1093/gerona/58.8.M767.
[18] U. Frith, C.D. Frith, Specific motor disabilities in Down's syndrome, J. Child Psychol. Psychiatry 15 (1974) 293–301.
[19] M.L. Latash, G.L. Almeida, D.M. Corcos, Preprogrammed reactions in individuals with Down syndrome: the effects of instruction and predictability of the perturbation, Arch. Phys. Med. Rehabil. 74 (1993) 1532–1821.
[20] E.M. Gutierrez-Farewik, Å. Bartonek, H. Saraste, Comparison and evaluation of two common methods to measure center of mass displacement in three dimensions during gai, Hum. Mov. Sci. 25 (2006) 238–256, https://doi.org/10.1016/J.HUMOV.2005.11.001.
[21] B.D. Ulrich, V. Haehl, U.H. Buzzi, M. Kubo, K.G. Holt, Modeling dynamic resource utilization in populations with unique constraints: preadolescents with and without Down syndrom, Hum. Mov. Sci. 23 (2004) 133–156, https://doi.org/10.1016/J.HUMOV.2004.06.002.
[22] M. Lotfian, M.M. Mirbagheri, M.R. Kharazi, F. Dadashi, R. Nourian, A. Irani, A. Mirbagheri, Pendulum test measure correlates with gait parameters in children with cerebral palsy, 2016 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBC (2016) 1708–1711, https://doi.org/10.1109/EMBC.2016.7591045.
[23] K. Crockett, K. Ardell, M. Hermanson, A. Penner, J. Lanovaz, J. Farthing, C. Arnold, The relationship of knee-extensor strength and rate of torque development to sit-to-stand performance in older adults, Physiother. Can. 65 (2013) 229–235, https://doi.org/10.3138/ptc.2012-04.
[24] P. Corbeil, E. Anaka, Combined effects of speed and directional change on postural adjustments during gait initiatio, J. Electromyogr. Kinesiol. 21 (2011) 734–741, https://doi.org/10.1016/J.JELEKIN.2011.05.005.
[25] B.A. Smith, M. Kubo, B.D. Ulrich, Gait parameter adjustments for walking on a treadmill at preferred, slower, and faster speeds in older adults with Down syndrome, Curr. Gerontol. Geriatr. Res. 2012 (2012) 782671, https://doi.org/10.1155/2012/782671.
[26] J. Wu, M. Beerse, T. Ajisafe, H. Liang, Walking dynamics in preadolescents with and without Down syndrome, Phys. Ther. 95 (2015) 740–749, https://doi.org/10.2522/ptj.20140210.
[27] B.A. Smith, J.A. Ashton-Miller, B.D. Ulrich, Gait adaptations in response to perturbations in adults with, Gait Posture 32 (2010) 149–154, https://doi.org/10.1016/J.GAITPOST.2010.04.004.
[28] C. Bonnyaud, D. Pradon, I. Vaugier, N. Vuillerme, D. Bensmail, N. Roche, Timed up and go test: comparison of kinematics between patients with chronic stroke and healthy subject, Gait Posture 49 (2016) 258–263, https://doi.org/10.1016/J.GAITPOST.2016.06.023.
[29] M. Horvat, R. Croce, J. Zagrodnik, B. Brooks, K. Carter, Spatial and temporal variability of movement parameters in individuals with Down syndrome, Percept. Mot. Skills 114 (2012) 774–782, https://doi.org/10.2466/25.15.26.PMS.114.3.774-782.
[30] G.V. Mendonça, F.D. Pereira, B. Fernhall, Walking economy in male adults with Down syndrome, Eur. J. Appl. Physiol. 105 (2009) 153–157, https://doi.org/10.1007/S00421-008-0884-6.