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Abstract

Background: Children with Down syndrome (DS) show underdeveloped motor strategy and anticipatory locomotor adjustments (ALA) before crossing an obstacle. Stairs presents another important setting to study environment navigation and motor adaptation. Inclusion of external ankle load is often used to perturb the stability of a system and observe the emergence of new patterns.

Research question: How do stair height and external ankle load affect motor strategy and ALA in 5-to-11-year-old children with typical development (TD) and with DS when approaching the stairs?

Methods: Fourteen children with DS and 14 age- and sex-matched children with TD participated in the study. They walked along a 5-meter walkway and ascended 3-step staircases. There were three staircases (low, moderate, and high heights) and 2 loading conditions (no load and ankle load). A 3D motion capture system was used to collect data. Motor strategy was coded for each trial. Step length, width, time, and velocity, minimum toe clearance, and horizontal toe velocity were calculated for the last four steps before stair ascent. Mixed ANOVAs with repeated measures were conducted for statistical analysis.

Results: The TD group walked up all the stairs, while the DS group displayed a strategy shift from *walking* to *crawling* when the stairs became higher. While the TD group maintained the values of most spatiotemporal variables, the DS group continuously decreased step length and velocity but not step width over the last four approaching steps. Ankle load decreased step length,

step velocity, minimum toe clearance, and horizontal toe velocity in the DS group, to a greater extent, than in the TD group.

Significance: Children with DS show underdeveloped motor strategy and ALA when approaching the stairs, and external ankle load further disrupts these patterns. Stair negotiation appears to be an effective assessment tool for evaluating motor adaptation in children with DS.

Keywords

Children; Down syndrome; walking; stair ascent; ankle load.

1. Introduction

Down syndrome (DS) is the most common genetic condition which affects about 1 out of 700 newborn infants [1]. Individuals with DS are characterized by muscle hypotonia, ligament laxity, hip and knee joint instability, poor postural control, and altered movement patterns [2, 3]. Children with DS show delayed development of motor skills; for example, they usually start walking at two years of age, which is one year later than children with typical development (TD) [2, 4]. Individuals with DS often walk slower with shorter but wider steps and greater foot progression angles [2, 5] and show a reduced range-of-motion of the hip, knee and ankle joints [6, 7]. Furthermore, individuals with DS display a larger movement and greater variability of the center-of-mass in the medial-lateral (ML) direction [7, 8].

Adaption to the environment such as an uneven surface or an obstacle is critical in environment navigation. Healthy adults demonstrate anticipatory locomotor adjustments (ALA) by maintaining spatiotemporal gait parameters such as step length, width, and velocity before stepping over a horizontal obstacle [9], or clearing a platform or stairs [10], or circumventing a vertical obstacle [11]. Children with TD show an adult-like ALA pattern in step length but not step width while approaching a horizontal obstacle [12, 13], and an underdeveloped pattern in step length and velocity before circumventing a vertical obstacle [14]. In contrast, children with DS tend to choose a more conservative motor strategy and a further underdeveloped ALA pattern for environment navigation [7]. For instance, infants with DS within one month after walking onset usually crawl over a horizontal obstacle, whereas infants with TD mostly walk over it even with the possibility of a trip or fall [15]. Children with DS often decrease step length and velocity for the last three steps approaching a horizontal obstacle [16] and pause for a longer duration in front of it [17]. Compared to the number of studies on obstacle negotiation, few study has been conducted using a stair paradigm in children with DS.

A staircase paradigm is different from an obstacle paradigm in that one must constantly control foot placement and step length due to the constraint of the stairs while moving the center-of-mass up. Similar to obstacle crossing, an ALA pattern exists in young adults during stair ascent [18]. However, no study has been conducted on children with and without DS in this regard. From the dynamic systems perspective, adding external load to distal segments perturbs the system by increasing the moment of inertia of the leg and helps elicit the emergence of new ALA patterns. Studies have shown that external foot or ankle load elevates net metabolic rate in adults [19, 20], and increases peak propulsive ground reaction force and general muscular activity in children with and without DS [21, 22]. However, it is not clear to what degree external load will affect motor strategy and ALA pattern in children with and without DS during stair negotiation.

Minimum toe clearance is observed during mid-swing phase in overground walking and the average value is 13-14mm in young adults [23, 24]. At toe clearance, horizontal toe velocity reaches its maximum value and the center-of-mass is in front of the stance foot, making it dangerous if a trip occur [23]. No reference data of minimum toe clearance is available for children with and without DS during stair negotiation.

The purpose of this study was to investigate motor strategy and ALA pattern in children with and without DS when negotiating the stairs with and without external ankle load. Our first hypothesis was that children with DS would choose a more conservative strategy to ascend the stairs compared to children with TD. Our second hypothesis was that when approaching the stairs, children with DS would show undeveloped ALA patterns such that step length and velocity may decrease more rapidly. Our third hypothesis was that external ankle load would affect the children with DS more such that step length and velocity would further decrease.

2. Material and methods

2.1 Subjects

We recruited 14 children with DS between the age of 5-11 years old and 14 age- and sex-matched children with TD (Table 1). The inclusion criteria were that the subjects were able to follow verbal instructions and walk 10 meters without assistance. The exclusion criteria included previous and existing medical conditions, neuromuscular problems, neurological disorders, and uncorrected visual impairment or orthopedic conditions such as hip or knee joint instability and foot disorders that prevented them from participating in this study. This study was approved by the hosting university's institutional review board. A signed permission form was obtained from the parents, and a verbal assent was obtained from each subject.

2.2 Procedure

All subjects came to our laboratory for one session. A Vicon full-body PSIS plug-in-gait model [25, 26] was used to attach 35 reflective markers to the front head, back head, shoulder, elbow, wrist, hand, anterior superior iliac spine, posterior superior iliac spine, thigh, knee, shank, ankle, heel, and toe on both sides, and at C7, T10, clavicle, sternum, and the right scapula of the subject. An 8-camera Vicon motion capture system (Vicon, Centennial, CO) was used to record the reflective markers at a sampling rate of 100Hz.

The subjects walked along a 5-meter walkway and ascended a 3-step staircase. There were three custom wooden staircases with different riser heights: 17cm (low stairs: LS), 24cm (moderate stairs: MS), or 31cm (high stairs: HS). These three staircase conditions represented a respective lower, similar, and higher riser-height compared to the common residential one (20-22cm) [27]. Each of the staircase had a standard depth of 26cm and a width of 86cm [28], but without handrails. There were two loading conditions: no load (NL) and bilaterally ankle load (AL) equaling to 2% of the subject's bodyweight on each side. A randomized block design was used for a total of six conditions in this study. Subjects completed five trials for each block (condition) and rested adequately between blocks (conditions). Three subjects in the DS group had difficulty walking with ankle load even on level ground, so external ankle load was not included in their data collection.

2.3 Data analysis

2.3.1 Motor strategy

Three motor strategies were categorized for stair negotiation: *avoidance*, *crawling*, and *walking* (Table 2). If the subject stopped in front of or walked around the stairs, it was defined as an *avoidance* strategy. When the subject used both upper and lower limbs to ascend the stairs, it was categorized as a *crawling* strategy. When the subject walked up the stairs, it was classified as a *walking* strategy. Two independent researchers coded the motor strategy of each Vicon trial and the agreement was on more than 95% of the trials. Upon a disagreement, a third researcher was consulted until an agreement had reached. The strategy proportion was calculated as the number of trials that each strategy was selected divided by the total number of trials for that condition for each subject.

2.3.2 Spatiotemporal variables

We focused on motor strategy and spatiotemporal variables over the last four steps before stair ascent, coded as step -4 to -1 from farthest to closest to the stairs. Bilateral heel markers were used to calculate step length, step width, step time, and step velocity for these four steps.

Step length and width were normalized by each subject's leg length. Step time and velocity were normalized as below [29]:

$$Normalized\ step\ time = step\ time/\sqrt{leg\ length/g}\ ,$$

$$Normalized\ step\ velocity = step\ velocity/\sqrt{g * leg\ length}\ ,$$

where g is the gravitational acceleration (9.81 m/s^2). Position of the toe marker was used to determine the minimum vertical toe clearance above the floor during the swing phase and to calculate horizontal toe velocity at that moment [23]. Several children with DS shuffled their feet before stair ascent and generated no valid data of toe clearance for those steps (17.3% of all steps in the DS group).

2.4 Statistical analysis

A series of 4-way (2 group × 3 stair × 2 load × 4 step) mixed ANOVAs with repeated measures on the last three factors were conducted on each spatiotemporal variable. Post-hoc pairwise comparisons with Bonforreni adjustments were conducted when necessary. Normality of the data was assessed using the Shapiro-Wilk test and a log transformation of the data was applied when necessary. Statistical significance was set at α=0.05.

3. Results

3.1 Motor strategy

Within the *crawling* and *walking* strategies, two different ascending methods were observed: a step-on-step method (i.e., both feet placed on the same step) and a step-over-step method (i.e., no two feet placed on the same step at any time). We further defined subcategories of *walking* strategy based on the occasional use of hand assistance, which was apparent in the DS group. Therefore, a total of seven strategies were defined for this study (see Table 2).

Both groups showed a similar strategy distribution between the two load conditions. The TD group mainly walked up the stairs using a step-over-step method (strategy 3d; 91%) across all conditions (Fig. 1a). In contrast, the DS group primarily walked up the stairs (65%) in the LS condition, nearly equally chose between *walking* (47%) and *crawling* (51%) strategies in the MS condition, and mainly crawled up (79%) in the HS condition (Fig. 1b). Proportion of *walking* with a step-over-step method (strategy 3d) was 19% for LS, 9% for MS, and 0% for HS condition in the DS group.

3.2 Spatiotemporal variables

Across steps -4 to -1, the DS group displayed a shorter normalized step length than the TD group (Fig. 2a). While the TD group maintained step length, the DS group reduced it in sequence. Statistical analysis showed that there was a group by load ($F(1,23)=48.89$, $p<0.001$) and a group by step interaction ($F(3,77)=116.18$, $p<0.001$). Post-hoc analysis revealed that the DS group decreased step length with ankle load, and each step length was shorter than the preceding one; whereas the TD group maintained it regardless of load conditions or steps.

The DS group showed a larger normalized step width than the TD group, and both groups increased step width with ankle load (Fig. 2b). While the TD group decreased step width gradually, the DS group mostly maintained this variable. Statistical analysis showed that there was a group by load by step ($F(3,67)=3.07$, $p=0.034$) and a group by load by height interaction ($F(2,46)=6.12$, $p=0.004$). Post-hoc results revealed that for both load conditions, only the TD group decreased step width from step -3 to steps -2 and -1, and this adjustment began even earlier (from step -4 to -3) with ankle load.

Both groups showed a similar normalized step time across all the conditions and increased it from step -4 to -1 and with ankle load (Fig. 2c). Statistical analysis showed that there was a load effect ($F(1,23)=26.71$, $p<0.001$) and a step effect ($F(3,77)=7.83$, $p<0.001$). Both groups took a longer time at step -1 than the preceding three steps.

The DS group had a slower normalized step velocity than the TD group (Fig. 2d). While TD mostly maintained step velocity until the last step, the DS group decreased this variable consecutively. Statistical analysis showed that there was a group by step ($F(3,77)=62.65$, $p<0.001$) and a group by load interaction ($F(1,23)=42.92$, $p<0.001$). Specifically, the DS group decreased step velocity from step -4 to -1 in sequence, and decreased step velocity more with ankle load than the TD group. In addition, there was a stair main effect ($F(2,52)=3.51$, $p=0.037$) such that both groups had a slower step velocity in the HS than the other two conditions.

3.3 Minimum toe clearance and horizontal toe velocity

Minimum toe clearance was similar between both groups across the steps and stairs. However, while the TD group generally increased minimum toe clearance from step -4 to -1, the DS group decreased this variable (Fig. 3a). Also, while the TD group showed comparable toe clearance across stair heights, the DS group decreased this variable with stair height (Fig. 3b). Both group decreased toe clearance with ankle load. Statistical analysis showed that there was a group by step ($F(3,74)=14.62$, $p<0.001$) and a group by stair ($F(2,50)=3.69$, $p=0.032$) interaction, and a load main effect ($F(1,23)=27.05$, $p<0.001$). Post-hoc results revealed that toe clearance was lower at steps -1 and -2 than steps -3 and -4 in the DS group, but was greater at steps -1, -2 and -3 than step -4 in the TD group. Only the DS group decreased it from the LS to HS condition.

The DS group showed an overall slower horizontal toe velocity at minimum toe clearance than the TD group, and both groups decreased it with ankle load (Fig. 3c). Horizontal toe velocity decreased from step -4 to -1 in the DS group, but generally maintained its values in the TD group (Fig. 3c and d). Statistical analysis showed that there was a group by step

($F(3,74)=20.96$, $p<0.001$) and a group by load by stair interaction ($F(2,44)=4.42$, $p=0.018$). All the raw parameters without normalization are presented in the Appendix Table A1.

4. Discussion

4.1 Motor strategy

The results that children with DS chose a more conservative strategy for stairs ascending support our first hypothesis and are consistent with Mulvey et al. study [15]. In contrast to a consistent *walking* strategy (strategy *3d*) used in the TD group, children with DS displayed a clear strategy shift from *walking* to *crawling* with the increase of stair height. One interesting observation was that more than half of the DS group, regardless of their ages or heights, switched the strategy from *walking* to *crawling* in the same condition after one or two trials, particularly for the MS and HS conditions. As our stair settings presented physical challenges and demanded appropriate neuromuscular adaptation, our results suggest that children with DS can update their perceived affordance of a staircase and select an appropriate strategy (*crawling* over *walking*) to accommodate for their physical and neuromuscular limitations. Moreover, children with DS often took small shuffling steps or stopped before stair ascent, particularly in the MS condition. As the *crawling* and *walking* strategies were equally selected for the MS condition, our results suggest that children with DS need an extended time to process the competing information on the affordance of a staircase before selecting an adaptive strategy for the ascent.

4.2 Spatiotemporal parameters

Our second hypothesis was supported in that children with DS continuously decreased step length and velocity when approaching the stairs, while children with TD decreased step velocity only at the last step. In the ML direction, a decrease in step width from step -4 to -1 in children with TD suggests that their ML balance control allowed them to transfer mechanical power from the frontal to the sagittal plane in preparation of stair ascent. Children with DS typically have muscle hypotonia, ligament laxity, and orthopedic problems, which may lead to instability during walking [2]. In this study, children with DS exhibited a wider and consistent step width across the steps, suggesting weaker ML balance control and an underdeveloped mechanical power transfer from one anatomical plane to another. This further implies that children with DS may prioritize their stability in the frontal plane over the sagittal plane to accommodate for the perceived affordance of a staircase and assure a safe ascent [7, 30].

The minimum toe clearance of children with DS (20.2mm) was higher than the reference numbers in young adults (13-14mm) [23, 24], suggesting that children with DS used a safe margin to avoid tripping before stair ascent (Fig. 3 and Table A1). While children with TD increased minimum toe clearance at the last step before stair ascent, children with DS decreased this variable at the last two steps and decreased it even more for shuffling steps, especially in the HS condition. This suggests that children with DS may not be able to concurrently process the stair information and regulate toe clearance when approaching a staircase, which led to an interruption of continuous motion before stair ascent. Further, their slower horizontal toe velocity when approaching the stairs suggests that children with DS may take cautious steps to ensure safety of environment navigation and give themselves an extended time to process the perceived staircase and select an appropriate motor strategy.

4.3 Effect of ankle load

Our third hypothesis was mostly supported in that children with DS reduced step length, velocity, and toe clearance, but increased step width and time with external ankle load, while ankle load had a similar but lesser effect on children with TD except for step length. This suggests that children with TD aged 5-11 years do not have adult-like control of foot placement when perturbed by ankle load during walking [19]. It is logical to propose that external ankle load may increase neuromuscular demand for both groups, particularly for children with DS due to their muscle hypotonia. However, our previous study found that external ankle load helped children with DS increase the elastic restoring muscular torque during walking on a treadmill [22]. This suggests that external ankle load may facilitate the biomechanics of walking (particularly at the push-off phase), but the complexity of stair approaching (i.e., concurrently monitor ALA and motor strategy) may hinder the benefit of walking with external ankle load, particularly in children with DS.

One limitation of our study was that the same staircases were used for all the subjects. It would have been ideal if we had individualized the riser height relative to each subject's leg length. However, adjusting the height of a horizontal obstacle could be easily done for an obstacle study, but not practical for a stairs study. Although the DS group was shorter in height, the three stair heights provided similar ratios to leg length between the two groups: 24-45% in the TD group and 27-50% in the DS group. We deemed that the differences in motor strategy and ALA pattern between the two groups were primarily due to underdeveloped biomechanical and neuromuscular functions in children with DS. Stair negotiation appears to be an effective paradigm for assessing motor adaptation in children with DS, particularly before and after medical and/or physical interventions.

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6. Table(s)

Table 1: Mean (SD) of physical characteristics of the participants

Group	Gender	Age (years)	Height (m)	Body mass (kg)	Leg length (m)
TD	4M / 10F	8.2 (2.0)	1.31 (0.11)*	29.4 (7.0)	0.70 (0.08)*
DS	4M / 10F	8.6 (1.9)	1.18 (0.12)*	27.2 (10.4)	0.62 (0.08)*

DS: Down syndrome; TD: typical development. A symbol * denotes that the DS group had a similar body mass, but was shorter in height and leg length than the TD group at $p<0.05$.

Table 2: Categories and definitions of motor strategies for stair negotiation

Strategy	Definition
1. Avoidance	1. Stop in front of the stairs and refuse to negotiate the stairs; or walk around the stairs
2. Crawling	2a. Crawl up the stairs, hands are placed on the stairs for support throughout the ascending process, ascending with a step-on-step method
	2b. Crawl up the stairs, hands are placed on the stairs for support throughout the ascending process, ascending with a step-over-step method
3. Walking	3a. Walk up the stairs, hands slightly touch the stairs occasionally, ascending with a step-on-step method
	3b. Walk up the stairs, hands slightly touch the stairs occasionally, ascending with a step-over-step method
	3c. Walk up the stairs, hands never touch the stairs throughout the ascending process, ascending with a step-on-step method
	3d. Walk up the stairs, hands never touch the stairs throughout the ascending process, ascending with a step-over-step method

Note that a step-on-step method describes a strategy in which the subject places one foot onto one step of a staircase and the other foot onto the same step, meaning that the two feet are on the same step of a staircase in sequence before ascending to the next step of the staircase. In comparison, a step-over-step method describes a strategy in which the subject places one foot onto one step of a staircase and the other foot onto the next step of the staircase, meaning that the two feet are not on the same step at any time.

Appendix:

Table A1: Mean (SD) of the raw spatiotemporal variables without normalization

Group	Loading	Stair-height	Step code	Step length (m)	Step width (m)	Step time (s)	Step velocity (m/s)	Minimum toe clearance (mm)	Horizontal toe velocity (m/s)
TD	NL	LS	-4	0.51 (0.04)	0.07 (0.02)	0.45 (0.05)	1.14 (0.15)	15.8 (7.5)	3.70 (0.30)
			-3	0.57 (0.06)	0.08 (0.02)	0.44 (0.05)	1.31 (0.16)	22.3 (8.3)	4.09 (0.38)
			-2	0.58 (0.06)	0.06 (0.02)	0.45 (0.05)	1.27 (0.16)	19.5 (8.0)	3.98 (0.43)
			-1	0.57 (0.05)	0.06 (0.02)	0.46 (0.05)	1.24 (0.16)	21.7 (10.2)	3.80 (0.47)
	NL	MS	-4	0.54 (0.06)	0.08 (0.02)	0.41 (0.03)	1.33 (0.16)	18.2 (8.7)	4.15 (0.35)
			-3	0.54 (0.06)	0.08 (0.02)	0.43 (0.04)	1.27 (0.14)	22.4 (8.9)	4.11 (0.39)
			-2	0.56 (0.06)	0.07 (0.02)	0.44 (0.04)	1.30 (0.13)	21.1 (5.4)	3.95 (0.40)
			-1	0.56 (0.05)	0.07 (0.02)	0.46 (0.04)	1.23 (0.14)	23.7 (8.4)	3.81 (0.47)
	NL	HS	-4	0.53 (0.03)	0.07 (0.03)	0.42 (0.06)	1.27 (0.19)	18.4 (8.9)	3.96 (0.47)
			-3	0.55 (0.07)	0.07 (0.02)	0.44 (0.05)	1.26 (0.19)	22.4 (9.9)	3.97 (0.51)
			-2	0.57 (0.08)	0.06 (0.02)	0.45 (0.04)	1.27 (0.16)	21.4 (7.6)	3.95 (0.44)
			-1	0.55 (0.10)	0.06 (0.02)	0.48 (0.05)	1.16 (0.23)	24.8 (8.2)	3.66 (0.58)
	AL	LS	-4	0.51 (0.04)	0.14 (0.04)	0.44 (0.06)	1.19 (0.13)	14.9 (9.2)	3.67 (0.34)
			-3	0.55 (0.04)	0.11 (0.02)	0.47 (0.04)	1.20 (0.14)	22.6 (6.5)	3.55 (0.41)
			-2	0.56 (0.04)	0.08 (0.03)	0.47 (0.05)	1.20 (0.13)	18.1 (5.2)	3.59 (0.42)
			-1	0.55 (0.06)	0.10 (0.03)	0.49 (0.05)	1.14 (0.16)	18.3 (6.9)	3.43 (0.47)
	AL	MS	-4	0.52 (0.04)	0.10 (0.05)	0.44 (0.07)	1.22 (0.25)	18.2 (12.5)	3.70 (0.45)

			-3	0.54 (0.05)	0.12 (0.02)	0.46 (0.06)	1.18 (0.18)	22.0 (6.5)	3.62 (0.40)
			-2	0.57 (0.09)	0.08 (0.03)	0.47 (0.05)	1.24 (0.25)	21.1 (6.8)	3.62 (0.49)
			-1	0.55 (0.07)	0.09 (0.03)	0.50 (0.07)	1.13 (0.19)	23.5 (10.3)	3.40 (0.55)
	AL	HS	-4	0.53 (0.05)	0.13 (0.03)	0.44 (0.06)	1.15 (0.19)	16.7 (6.8)	3.52 (0.51)
			-3	0.53 (0.07)	0.11 (0.02)	0.47 (0.05)	1.14 (0.17)	19.0 (7.6)	3.53 (0.37)
			-2	0.54 (0.10)	0.09 (0.03)	0.47 (0.05)	1.14 (0.20)	18.6 (6.9)	3.43 (0.50)
			-1	0.53 (0.12)	0.10 (0.03)	0.50 (0.06)	1.06 (0.24)	20.5 (8.1)	3.25 (0.57)
DS	NL	LS	-4	0.41 (0.11)	0.13 (0.04)	0.39 (0.06)	1.12 (0.39)	29.4 (17.4)	3.54 (0.68)
			-3	0.38 (0.10)	0.14 (0.04)	0.48 (0.31)	0.97 (0.30)	24.8 (12.6)	3.27 (0.47)
			-2	0.27 (0.10)	0.14 (0.04)	0.43 (0.06)	0.69 (0.24)	18.5 (3.8)	2.81 (0.56)
			-1	0.21 (0.11)	0.14 (0.05)	0.43 (0.06)	0.51 (0.27)	19.9 (8.6)	2.78 (0.77)
	NL	MS	-4	0.41 (0.10)	0.12 (0.05)	0.42 (0.06)	1.05 (0.37)	25.7 (10.5)	3.32 (0.84)
			-3	0.37 (0.11)	0.13 (0.05)	0.43 (0.06)	0.91 (0.36)	24.9 (11.5)	2.99 (0.88)
			-2	0.30 (0.11)	0.11 (0.04)	0.44 (0.08)	0.74 (0.34)	18.6 (9.6)	2.52 (1.00)
			-1	0.22 (0.10)	0.13 (0.04)	0.45 (0.07)	0.50 (0.30)	18.6 (9.7)	2.36 (0.65)
	NL	HS	-4	0.41 (0.10)	0.12 (0.04)	0.44 (0.10)	1.01 (0.36)	22.3 (10.0)	3.39 (0.63)
			-3	0.36 (0.10)	0.12 (0.03)	0.46 (0.15)	0.87 (0.32)	22.4 (7.4)	2.95 (0.75)
			-2	0.28 (0.11)	0.12 (0.05)	0.42 (0.07)	0.69 (0.31)	16.8 (7.3)	2.71 (0.74)
			-1	0.20 (0.10)	0.13 (0.04)	0.45 (0.08)	0.46 (0.23)	23.0 (14.5)	2.12 (0.67)
	AL	LS	-4	0.33 (0.10)	0.15 (0.03)	0.46 (0.06)	0.73 (0.24)	20.0 (8.6)	2.59 (0.51)
			-3	0.29 (0.11)	0.14 (0.04)	0.48 (0.08)	0.62 (0.27)	18.5 (5.8)	2.39 (0.48)
			-2	0.21 (0.12)	0.16 (0.03)	0.46 (0.07)	0.46 (0.23)	20.0 (18.7)	2.16 (0.58)

		-1	0.17 (0.09)	0.15 (0.05)	0.51 (0.10)	0.33 (0.19)	17.2 (8.0)	1.66 (0.55)
AL	MS	-4	0.35 (0.08)	0.15 (0.04)	0.50 (0.08)	0.74 (0.18)	21.1 (8.0)	2.60 (0.56)
		-3	0.31 (0.11)	0.16 (0.04)	0.49 (0.05)	0.64 (0.22)	19.1 (7.7)	2.33 (0.54)
		-2	0.22 (0.12)	0.17 (0.03)	0.49 (0.13)	0.47 (0.22)	14.9 (8.1)	2.23 (0.54)
		-1	0.15 (0.08)	0.16 (0.05)	0.56 (0.20)	0.32 (0.16)	14.5 (8.4)	1.37 (0.66)
AL	HS	-4	0.32 (0.10)	0.15 (0.04)	0.46 (0.06)	0.73 (0.22)	16.9 (6.2)	2.43 (0.71)
		-3	0.31 (0.14)	0.15 (0.05)	0.47 (0.08)	0.67 (0.30)	21.2 (8.5)	2.53 (0.73)
		-2	0.22 (0.10)	0.15 (0.03)	0.46 (0.09)	0.50 (0.22)	14.3 (5.0)	2.06 (0.69)
		-1	0.14 (0.10)	0.17 (0.04)	0.53 (0.21)	0.29 (0.20)	12.3 (8.5)	1.62 (0.50)

TD: typical development; DS: Down syndrome. NL: no load; AL: ankle load. LS: low-height stairs; MS: moderate-height stairs; HS: high-height stairs. Step -4 to -1: the last four steps in sequence from farthest to closest to the stairs before negotiating the stairs. Horizontal toe velocity was measured at the minimum toe clearance during each approaching step.

Figure caption

Figure 1: Mean (SD) of the proportion of motor strategies for stair negotiation. Strategies were defined as: (1) Avoidance; (2a) Crawling with a step-on-step method; (2b) Crawling with a step-over-step method; (3a) Walking with a step-on-step method, with hands occasionally touching the stairs; (3b) Walking with a step-over-step method, with hands occasionally touching the stairs; (3c) Walking with a step-on-step method, with no hand contact with the stairs; and (3d) Walking with a step-over-step method, with no hand contact with the stairs. Three stair-height conditions were: low-height stairs (LS), moderate-height stairs (MS), and high-height stairs (HS). DS: Down syndrome; TD: typical development. Results were combined across two loading conditions.

Figure 2: Mean (SD) of the spatiotemporal gait parameters during the approaching phase before stair negotiation: (a) normalized step length; (b) normalized step width; (c) normalized step time; and (d) normalized step velocity. NL: no ankle load; AL: ankle load equaling to 2% of the subject's body weight on each side. DS: Down syndrome; TD: typical development. A symbol * denotes a difference between the TD and DS groups at $p<0.05$. A symbol † indicates a difference between the two load conditions at $p<0.05$. Results were combined across the three stair-height conditions.

Figure 3: Mean (SD) of minimum toe clearance and normalized horizontal toe velocity during the approaching phase before stair negotiation: (a) minimum toe clearance at different loading conditions; (b) minimum toe clearance at different stair-height conditions; (c) normalized

horizontal toe velocity at different loading conditions; and (d) normalized horizontal toe velocity at different stair-height conditions. NL: no ankle load; AL: ankle load equaling to 2% of the subject's body weight on each side. DS: Down syndrome; TD: typical development. LS: low-height stairs; MS: moderate-height stairs; HS: high-height stairs. A symbol * denotes a difference between the TD and DS groups at $p<0.05$. A symbol † indicates a difference between the two load conditions in Fig. 3a/3c or between two stair-height conditions in Fig. 3b/3d at $p<0.05$.

Figure 1

Figure 1:

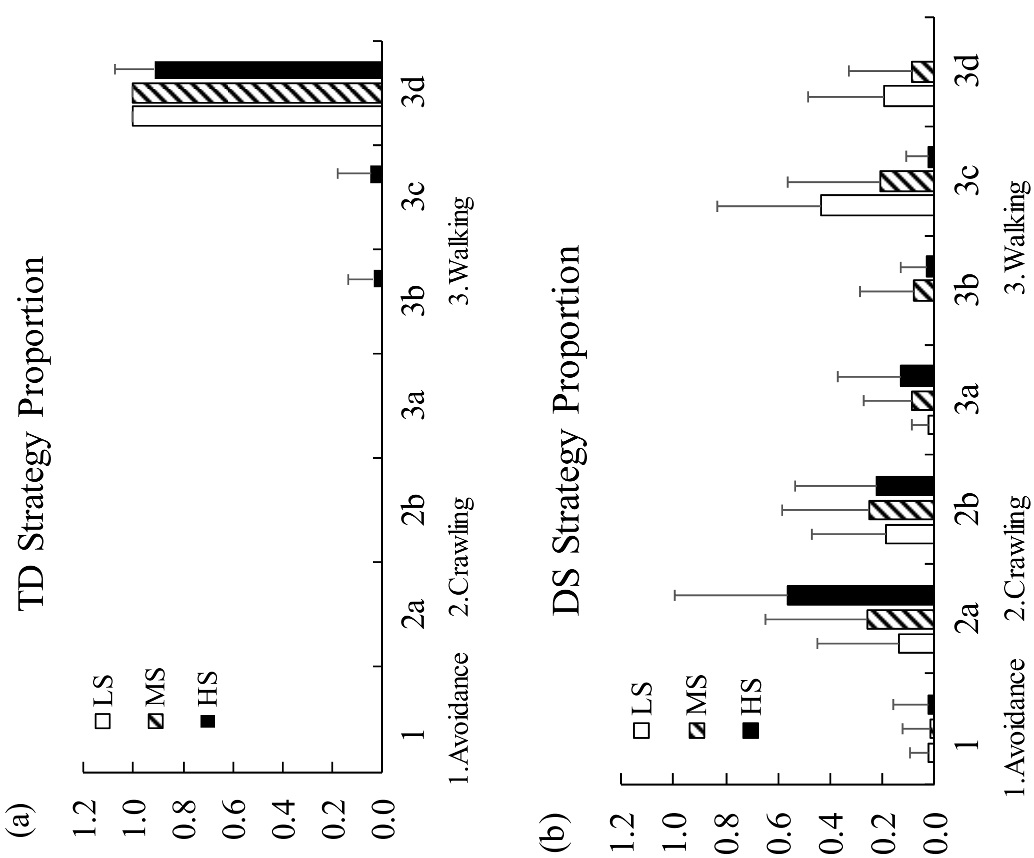

Figure 2

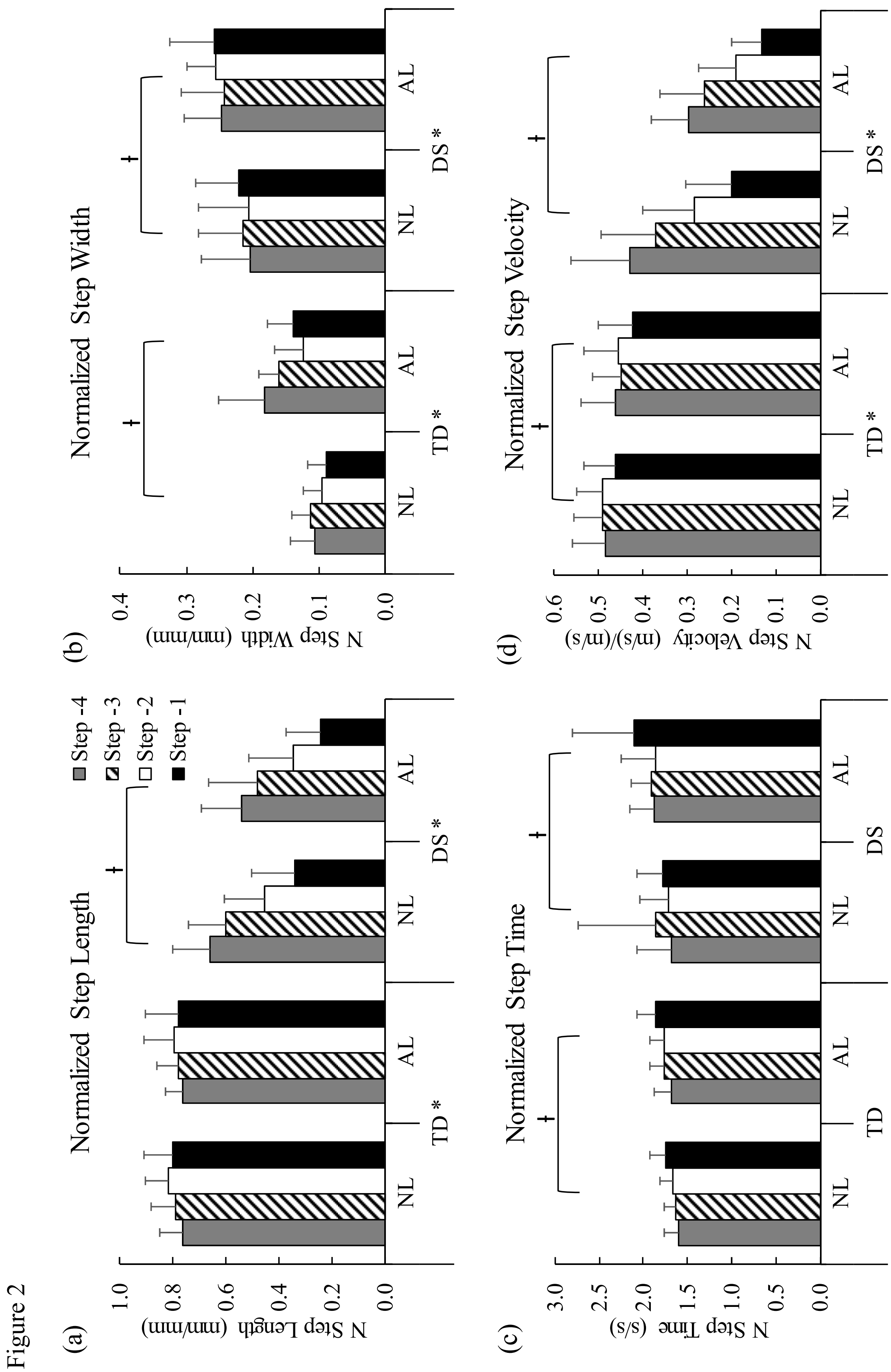
Figure 2
(a) Normalized Step Length
N Step Length (mm/mm)
1.0 0.8 0.6 0.4 0.2 0.0
NL TD * AL NL DS * AL
Step -4
Step -3
Step -2
Step -1
(b) Normalized Step Width
N Step Width (mm/mm)
0.4 0.3 0.2 0.1 0.0
NL TD * AL NL DS * AL
(c) Normalized Step Time
N Step Time (s/s)
3.0 2.5 2.0 1.5 1.0 0.5 0.0
NL TD AL NL DS AL
(d) Normalized Step Velocity
N Step Velocity (m/s)/(m/s)
0.6 0.5 0.4 0.3 0.2 0.1 0.0
NL TD * AL NL DS * AL

Figure 3

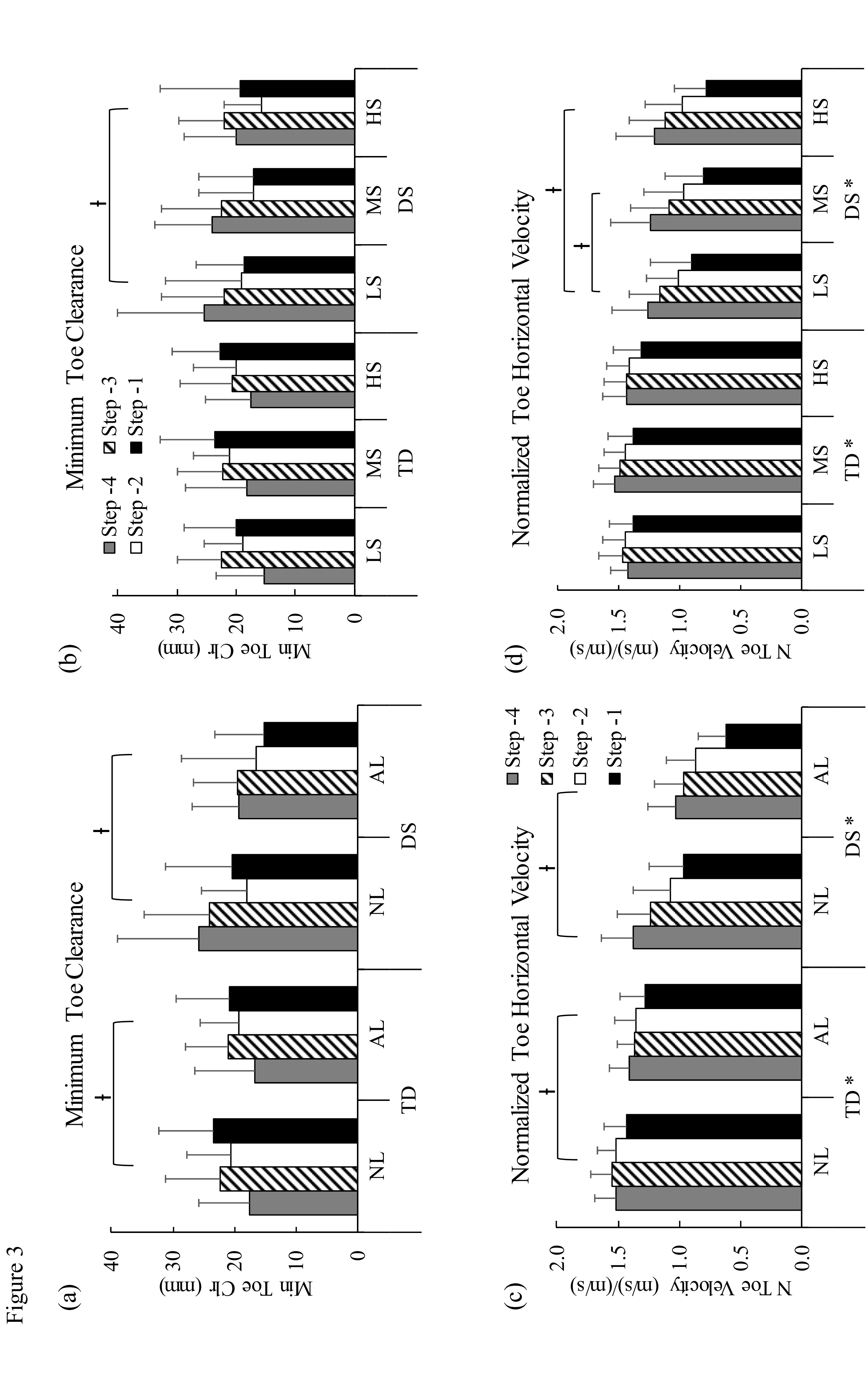

Figure 3
(a)
Minimum Toe Clearance
Min Toe Clr (mm)
40
30
20
10
0
NL
AL
TD
DS
(b)
Minimum Toe Clearance
Step -4
Step -3
Step -2
Step -1
LS
MS
HS
TD
DS
(c)
Normalized Toe Horizontal Velocity
N Toe Velocity (m/s)/(m/s)
2.0
1.5
1.0
0.5
0.0
TD *
DS *
(d)
Normalized Toe Horizontal Velocity

Highlights

- Children with DS choose a more conservative strategy to safely ascend the stairs.
- Children with DS decrease step length and velocity for last four approaching steps.
- Children with DS decrease vertical toe clearance for last four approaching steps.
- Children with DS decrease horizontal toe velocity for last four approaching steps.
- Ankle load affects children with DS more in motor strategy and locomotor pattern.