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Huaqing Liang

Xiang Ke

Jianjia Wu

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Huaqing Liang [a], Xiang Ke [a], Jianhua Wu [a,b]*

[a] Department of Kinesiology and Health, [b] Center for Pediatric Locomotion Sciences, Georgia State University, Atlanta, GA, USA 30302

* Corresponding author:

Jianhua Wu, Ph.D.

Department of Kinesiology and Health

Center for Pediatric Locomotion Sciences, Georgia State University

125 Decatur Street, Atlanta, GA 30302, USA

Telephone: 1-404-413-8476; Fax: 1-404-413-8053; Email: jwu11@gsu.edu

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Abstract

Background: Children with Down syndrome (DS) often show underdeveloped motor ability and adaptation. Stair ascent is a common task to examine locomotor function and 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 locomotor adjustments in 5-to-11-year-old children with typical development (TD) and with DS during stair ascent?

Methods: Fourteen children with DS and 14 age- and sex-matched children with TD participated in this study. They walked along a 5-meter walkway and ascended 3-step staircases of different heights (low, moderate, and high) with or without ankle load. A 3D motion capture system was used for data collection. Dependent variables included stance time and toe-to-stair distance before stair ascent, and vertical toe clearance and horizontal toe velocity during stair ascent. Mixed ANOVAs with repeated measures were conducted for statistical analysis.

Results: The DS group presented a longer stance time and a shorter toe-to-stair distance than the TD group before stair ascent. External ankle load affected, to a greater extent, the DS group than the TD group in stance time and toe-to-stair distance. During stair ascent, while the TD group generally maintained toe clearance and decreased horizontal toe velocity with the increase of stair height, the DS group decreased toe clearance and maintained horizontal toe velocity. Particularly, the DS group displayed a greater toe clearance than the TD group in the LS condition but a smaller toe clearance in the HS condition. In addition, external ankle load increased toe clearance and decreased horizontal toe velocity in both groups.

Significance: Children with DS display underdeveloped locomotor adjustments during stair ascent. External ankle load appears to help the DS group regulate toe clearance and horizontal toe velocity for different stair heights.

Keywords

Children; Down syndrome; stairs ascent; minimum toe clearance; external ankle load.

1. Introduction

Down syndrome (DS) is the most common genetic condition [1]. Children with DS often show delayed motor development and modified gait patterns such as a slower walking speed and shorter but wider steps than their typically developing (TD) peers [2, 3]. They also demonstrate underdeveloped anticipatory locomotion adjustments (ALA) with little change in step length and a longer pause in front of an obstacle [4]. An obstacle or a staircase paradigm presents an ideal setting for understanding motor strategy and adaptation. According to the dynamic systems theory, certain patterns can be defined as “attractors” to accommodate different environments and/or motor tasks [5, 6]. Due to their underdeveloped motor ability, children with DS often select a more conservative strategy (i.e., crawling instead of walking) as their attractors [2, 7] and display a higher toe clearance when crossing obstacles [8]. In clinics settings, stairs are often used to assess the gross motor function of children with or without motor disabilities and to evaluate the effectiveness of physical therapy. Practically, stair negotiation has been associated with tripping and unintentional falls in every age group [9, 10]. However, few studies have been conducted in children with DS to understand their locomotor adjustments during stair ascent.

Different from obstacle crossing, stair ascent requires one to continuously lift himself up and constrain step length and foot placement. Further, cutaneous feedback from the feet before ascent may not be useful for the transition steps from level ground to stairs [11]. Consequently, adults often produce a higher toe clearance at the first transition step than the following steps [10, 12, 13]. Adults also display a greater horizontal toe velocity at the first transition step [14], making it difficult to regain balance if tripping occurs [10, 15]. Increasing stair height usually results in a reduction in horizontal toe velocity in adults, reducing the risk of tripping [13]. It is, however, not known if similar locomotor adjustments emerge in children with and without DS during stair ascent.

When studying motor adaptation, external load is often used to increase the moment of inertia of the lower extremities and consequently the difficulty of locomotor tasks. From the dynamic systems perspective, external load presents a mechanical perturbation to a system and allows for observation of the emergence of new motor patterns. Adding load above the ankles can result in greater leg muscular activity and higher energy cost in young adults during locomotion [16, 17]. Similarly, external ankle load can increase vertical propulsive impulse and general muscular activity in children with DS during treadmill walking [18, 19]. We have found that external ankle load can decrease step velocity and toe clearance, but increase step time and step width in children with TD and DS while approaching the stairs [20]. It is therefore logical to investigate how external ankle load affects locomotor adjustments during stair ascent in children with and without DS.

The purpose of this study was to examine the spatiotemporal parameters in children with and without DS while ascending stairs of different heights with and without external ankle load. Our first hypothesis was that compared to children with TD, children with DS would display a smaller toe-to-stair distance and a longer stance time before stair ascent. Adding ankle load would result in a decreased toe-to-stair distance and an increased stance time in children with DS. Our second hypothesis was that while walking up the stairs, children with DS would show a greater toe clearance but a slower horizontal toe velocity than their TD peers. Ankle load would increase toe clearance and decrease horizontal toe velocity in both groups. Our previous work shows that children with DS primarily choose a walking strategy to ascend the low stairs, but a crawling strategy for the high stairs [20]. Our third hypothesis was that the DS group would display a greater toe clearance and horizontal toe velocity when walking up compared to crawling up the stairs.

2. Material and methods

2.1 Participants

Fourteen children with DS and fourteen age- and sex-matched children with TD were recruited for the study. The inclusion criteria were that the participants were able to follow verbal instructions and walk 10 meters without using assistive devices. The exclusion criteria included any previous or existing neurological disorders, musculoskeletal problems, uncorrected visual impairment, or any other medical conditions 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 participant. Both groups had similar age and body mass, but the TD group were taller and had a greater leg length than the DS group (Table 1).

2.2 Procedure

All participants came to the laboratory for one session. Thirty-five reflective markers were placed at the bilateral front head, back head, shoulder, elbow, wrist, hand, anterior superior iliac spine, posterior superior iliac spine, thigh, knee, shank, ankle, heel, and toe; and at C7, T10, clavicle, sternum, and the right scapula based on the Vicon full-body PSIS plug-in-gait model [21, 22]. Data was collected using an 8-camera Vicon motion capture system (Vicon, Centennial, CO) at a sampling rate of 100 Hz.

Participants walked along a 5-meter walkway, and then ascended a 3-step staircase. There were 3 custom wooden staircases with different riser heights: 17cm (low stairs; LS), 24cm (medium stairs; MS), or 31cm (high stairs; HS). Our LS, MS, and HS conditions were lower, similar, and higher than the common residential stair height (20-22cm) [23], respectively. Each staircase had a standard depth of 26cm and a width of 86cm [23], but without handrails. Three reflective markers were placed at the outer edge of each step as a reference of the stair surface. There were 2 loading conditions: without ankle load (NL) or with ankle load (AL) equaling to 2% of the bodyweight on each side. Therefore, a total of 6 conditions were tested and a randomized block design was used for these conditions. Participants completed 5 trials for each condition (block) and were given sufficient rest time between conditions. Three participants in the DS group had difficulties walking with ankle load even on level ground, so external ankle load was not included in their data collection.

2.3 Data analysis

We focused on the spatiotemporal parameters of the last two steps before stairs ascent for ascent preparation and the first two steps of ascending for locomotor adjustments. In each trial, the leading foot was defined as the first foot ascending the staircase, and the other foot was considered as the trailing foot.

2.3.1 Ascent preparation

Stance time was defined as the duration of the stance phase for each foot separately. Toe-to-stair distance was calculated to quantify the placement of each foot with respect to the stairs.

2.3.2 Locomotor adjustments

The two groups used different motor strategies while negotiating the stairs such that the TD group walked up all the stairs, whereas the DS group switched from primarily walking to crawling when the stairs became higher (LS: walking 65%, crawling 33%; MS: walking 47%, crawling 51%; and HS: walking 19%, crawling 79%) [20]. Therefore, two sets of comparisons were conducted: (1) between the TD and DS groups for all the walking trials, and (2) within the DS group between the walking and crawling trials. Dependent variables included vertical toe clearance and horizontal toe velocity for the first two ascending steps. Toe marker was found to be the lowest point of the leg when either a walking or a crawling strategy was used. Toe clearance was identified when the toe marker was above the stair edge and calculated as the vertical difference between the toe marker and the marker on the stair. Since leg length was different between the two groups, toe clearance was also normalized by each participant's leg length to account for this anthropometric difference. Horizontal toe velocity was calculated at toe clearance and the percentage of change was calculated from the unloaded to the loaded condition for each stair condition in each group.

2.4 Statistical analysis

Four 4-way (2 group × 3 stair × 2 load × 2 foot) mixed ANOVAs with repeated measures on the last three factors were conducted on (1) stance time and toe-to-stair distance for all the trials, and (2) vertical toe clearance and horizontal toe velocity for all the walking trials between the two groups. Two 4-way (2 strategy × 3 stair × 2 load × 2 foot) mixed ANOVAs with repeated measures on all four factors were conducted for the walking and crawling trials within the DS group. Post-hoc pairwise comparisons with Bonforreni adjustments were conducted when appropriate. 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 Ascent preparation

Both groups generally showed a longer stance time for the trailing foot than the leading foot (Fig.1a-b). There was a group by load ($F(1,23)=18.21$, $p<0.001$), a group by foot ($F(1,26)=53.63$, $p<0.001$), and a load by stair ($F(2,46)=3.25$, $p=0.048$) interaction. Post-hoc analysis revealed that external ankle load increased stance time only in the DS group. The DS group displayed a longer stance time than the TD group across the two feet (TD: 0.96 seconds; DS: 2.42 seconds), a larger difference between the two feet (leading/trailing foot: TD: 0.90/1.02 seconds; DS: 2.34/2.51 seconds), and a larger difference with/without ankle load (TD: 1.03/0.89 seconds; DS: 2.84/2.01 seconds).

Both groups placed the leading foot farther to the stairs than the trailing foot and it was independent of stair height (Fig. 1c-d). There was a group by foot ($F(1,26)=681.54$, $p<0.001$) and a load by foot ($F(1,23)=5.81$, $p=0.024$) interaction. Post-hoc analysis revealed that external ankle load decreased the toe-to-stair distance only for the leading foot, particularly in the DS group. The DS group had a shorter toe-to-stair distance across the two feet (TD: 0.58m; DS: 0.24m) and a smaller difference between the two feet (leading/trailing foot: TD: 0.85/0.30m; DS: 0.32/0.15m) than the TD group. Moreover, different strategies (walking versus crawling) in the DS group did not affect stance time or toe-to-stair distance.

3.2 Locomotor adjustments for walking trials between two groups

Results of absolute and normalized toe clearance were similar (Fig. 2a-d). Both groups generally exhibited a greater toe clearance of the leading foot than the trailing foot (leading/trailing foot: TD: 61.4/53.7mm; DS: 70.2/54.6mm). Toe clearance across all the stair conditions was similar for the TD group (57.6mm); however, the DS group displayed a greater toe clearance in the LS condition (70.7mm) than the MS (62.3mm) and HS (54.2mm) conditions, particularly without ankle load. For the absolute toe clearance, there was a group by stair by load ($F(2,31)=3.63$, $p=0.038$) and a group by stair by foot ($F(2,40)=10.58$, $p<0.001$) interaction. For the normalized toe clearance, there was a group by stair by foot ($F(2,40)=10.34$, $p<0.001$) and a stair by load ($F(2,31)=3.60$, $p=0.039$) interaction. Post-hoc analysis revealed that both groups showed a greater toe clearance with external ankle load, particularly in the MS and HS conditions in the DS group.

The DS group displayed a slower horizontal toe velocity (1.33m/s) than the TD group (1.87m/s) across all the conditions, and external ankle load decreased this variable for both groups (Table 2). While the TD group decreased horizontal toe velocity with higher stair height, the DS group generally maintained this variable. There was a group by stair by foot interaction ($F(2,40)=4.32$, $p=0.02$) and a load effect ($F(1,19)=101.99$, $p<0.001$). Post-hoc analysis revealed that the TD group displayed a smaller horizontal toe velocity for the trailing foot than the leading foot in the LS and MS conditions, while the DS group showed no difference.

3.3 Locomotor adjustments between the walking and crawling trials in the DS group

Motor strategies did not affect toe clearance (walking: 63.5mm; crawling: 54.1mm) in the DS group (Fig. 3a-b). Regardless of motor strategy and ankle load, the DS group generally decreased toe clearance with higher stair height and had a higher toe clearance for the leading than the trailing foot. There was a stair effect ($F(2,26)=12.42$, $p<0.001$) and a foot effect ($F(1,13)=18.43$, $p<0.001$). Post-hoc analysis revealed that the DS group displayed a greater toe clearance in the LS than the MS and HS conditions.

Horizontal toe velocity was similar between the walking (1.33m/s) and crawling (1.10m/s) trials in the DS group (Fig. 3c-d). Regardless of motor strategy, the DS group generally deceased horizontal toe velocity with higher stair height, and decreased this variable with external ankle load for both feet. There was a load effect ($F(1,10)=49.19$, $p<0.001$) and a stair effect ($F(2,26)=12.81$, $p<0.001$). Post-hoc analysis revealed that the DS group had a lower horizontal toe velocity in the HS than the LS and MS conditions.

4. Discussion

4.1 Ascent preparation

Our first hypothesis was generally supported in that the DS group had a longer stance time and a shorter toe-to-stair distance than the TD group. Our results are consistent with previous studies that children with DS show delayed ALA than children with TD [20, 24]. Furthermore, our result of a constant toe-to-stair distance in the two groups regardless of stair heights is similar to previous findings such that the trailing foot is placed with a similar distance from obstacles of different heights in young adults and children with and without DS [8, 25]. However, Vimercati et al. [25] reported a decreased distance of the leading foot with higher obstacles in young adults with DS. Our results suggested that a consistent foot placement, particularly the trailing foot, may help effectively plan the following locomotor adjustments for stair ascent. A shorter toe-to-stair distance in the DS group, together with the observed shuffling steps in front of the stairs, suggests the underdeveloped locomotor ability and motor adaptation in this population.

Similar to previous studies [26, 27], our results implied that children with DS displayed higher variability of motor tasks than their TD peers, particularly in stance time. Interestingly, children with DS displayed the largest difference in stance time between the leading and trailing feet in the MS condition. With external ankle load, stance time for the MS condition was longer than the HS condition in the DS group. Given that the DS group had a predominant preference in strategy in the LS (walking) and HS (crawling) conditions [20], we postulated that the DS group might have difficulty deciding between these two equally-selected strategies for the MS condition. In the MS condition, some children with DS switched from walking to crawling in the middle of the first ascending step. A longer stance time, particularly for the trailing foot, may be essential to facilitate this strategy alteration.

4.2 Locomotor adjustments between two groups when walking up the stairs

Our second hypothesis was generally supported in that the DS group displayed a larger toe clearance and a slower horizontal toe velocity than the TD group, particularly in the LS condition. This suggested a more conservative strategy for safely walking up the LS stairs in the DS group, but physical and motor limitations in the DS group may have prevented them from continuing to produce a greater toe clearance than the TD group in the MS and HS conditions. Consistent with previous studies [8, 28], the TD group showed a consistent toe clearance independent of height, suggesting their capability of scaling toe clearance to stair height. Even though the DS group were unable to do so, they still managed to clear the stairs with a similar or higher margin, and a slower toe velocity than children with TD to ensure safety.

The finding that external ankle load increased toe clearance and decreased horizontal toe velocity for both groups suggests that adding external load may help increase a safety margin during stair ascent. Previous studies showed that ankle load can decrease step velocity and toe clearance and increase step width when approaching the stairs [20], but increase vertical propulsive impulse and facilitate leg pendulum swing during walking [16-18]. We therefore argue that when walking with external ankle load, both groups might increase muscle activation to overcome the increased leg inertia and generate a larger safety margin. Within the DS group, external ankle load helped to increase toe clearance in the MS and HS conditions. From the dynamic systems perspective, this suggests that external ankle load may be a critical control parameter to perturb the neuromuscular system of children with DS and facilitate the emergence of an adaptive motor pattern during stair ascent.

4.3 Locomotor adjustment between walking and crawling strategies in the DS group

Our third hypothesis was not supported in that different strategies did not affect toe clearance and horizontal toe velocity within the DS group. Although walking is a more advanced locomotion mode than crawling [29], the DS group decreased horizontal toe velocity during stair ascent regardless of motor strategy, suggesting a perceived priority of safety for stair ascent. Moreover, we found similar foot displacement and stance time before stair ascent between the two strategies in the DS group, suggesting a relatively coordinated spatiotemporal pattern during ascent preparation and a smooth transition during stair ascent.

One limitation of this study was that the staircases had only three steps, which did not allow for the analysis beyond the first two steps. However, as fall risk was the highest for the first two transition steps [30], our study still provided important information of the critical transition steps in children with and without DS. Another limitation was that the same staircases were used for all the participants. 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 locomotor adjustments between the two groups were primarily due to the underdeveloped biomechanical and neuromuscular functions in children with DS. Stair ascent appears to be a useful paradigm for assessing motor function and adaption in children with DS, and external ankle load might help improve their motor pattern during stair ascent.

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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)*

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

Table 2: Mean (SD) of horizontal toe velocity (unit: m/s) of the participants

Stair Height	Group	Leading foot			Trailing foot		
		No Load	Ankle Load	% Change	No Load	Ankle Load	% Change
LS	TD	2.42 (0.32)	2.01 (0.37)	-16.7%	2.13 (0.26)	1.72 (0.21)	-19.0%
	DS	1.41 (0.33)	1.23 (0.12)	-12.3%	1.44 (0.26)	1.20 (0.35)	-16.5%
MS	TD	2.17 (0.32)	1.83 (0.34)	-15.7%	1.96 (0.30)	1.67 (0.18)	-14.6%
	DS	1.47 (0.21)	1.21 (0.20)	-17.9%	1.43 (0.24)	1.35 (0.25)	-5.9%
HS	TD	1.81 (0.22)	1.50 (0.29)	-17.3%	1.74 (0.21)	1.48 (0.20)	-15.1%
	DS	1.42 (0.32)	1.10 (0.26)	-22.8%	1.31 (0.33)	0.80 (0.37)	-38.7%

TD: typical development; DS: Down syndrome. LS: low stairs; MS: medium stairs; HS: high stairs. % change was calculated from the no load condition to the ankle load condition for each stair height in each group.

Figure caption

Figure 1: Mean and standard deviation of stance time and toe-to-stair distance of the leading foot and the trailing foot before negotiating a staircase in children with Down syndrome (DS) and typical development (TD). (a) Stance time without ankle load; (b) stance time with ankle load; (c) toe-to-stair distance without ankle load; and (d) toe-to-stair distance with ankle load. LS: low stairs; MS: medium stairs; HS: high stairs. A symbol * denotes a difference between the TD and DS groups at $p<0.05$. A symbol ** signifies a difference between two height conditions across the two groups at $p<0.05$. A symbol † indicates a difference between the two feet within a group at $p<0.05$.

Figure 2: Mean and standard deviation of toe vertical clearance and normalized toe vertical clearance by leg length in children with Down syndrome (DS) and typical development (TD) when they walked up the stairs. (a) Toe clearance without ankle load; (b) toe clearance with ankle load; (c) normalized toe clearance without ankle load; and (d) normalized toe clearance with ankle load. LS: low stairs; MS: medium stairs; HS: high stairs. A symbol * denotes a difference between the TD and DS groups at $p<0.05$. A symbol † indicates a difference between the two feet within a group at $p<0.05$. A right arrow above the graph signifies a linearly decreasing trend with stair height within a group at $p<0.05$.

Figure 3: Mean and standard deviation of vertical toe clearance and horizontal toe velocity in the DS group between the walking and crawling trials. (a) Toe clearance without ankle load; (b) toe clearance with ankle load; (c) horizontal toe velocity without ankle load; and (d) horizontal toe

velocity with ankle load. LS: low stairs; MS: medium stairs; HS: high stairs. A symbol ** denotes a difference between two stair heights across the two groups at $p<0.05$.

Figure 1

Figure 1

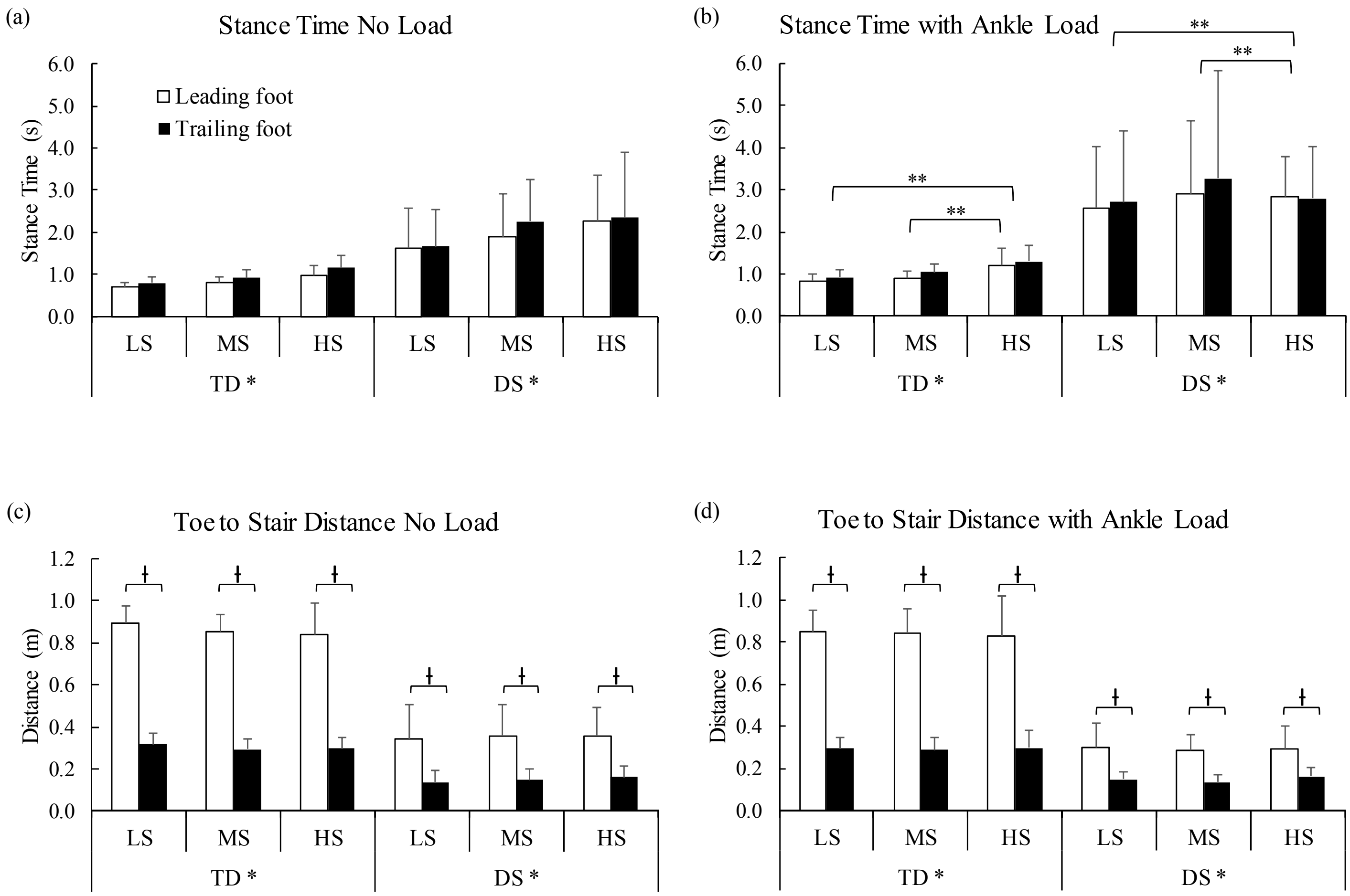


Figure 2

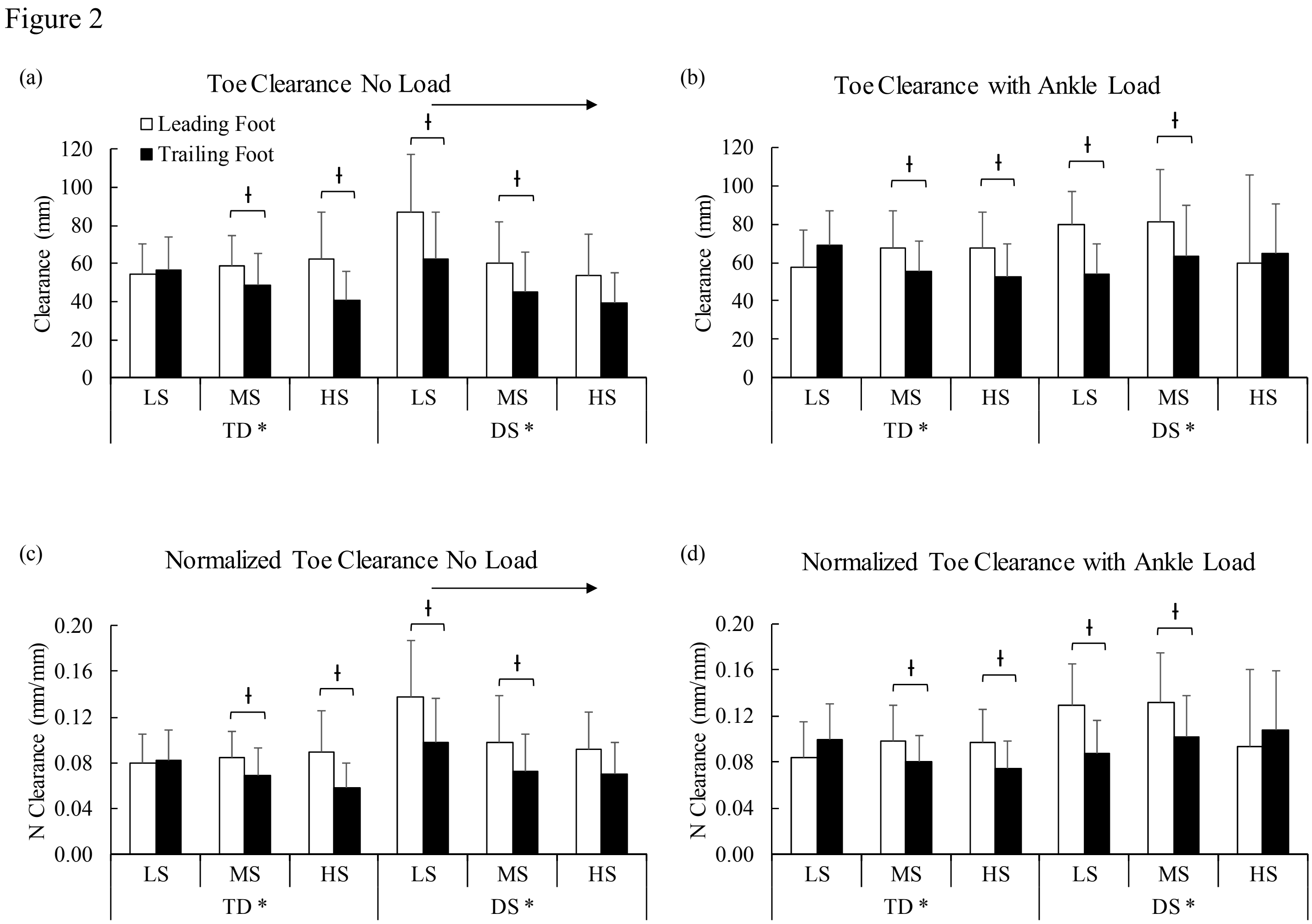
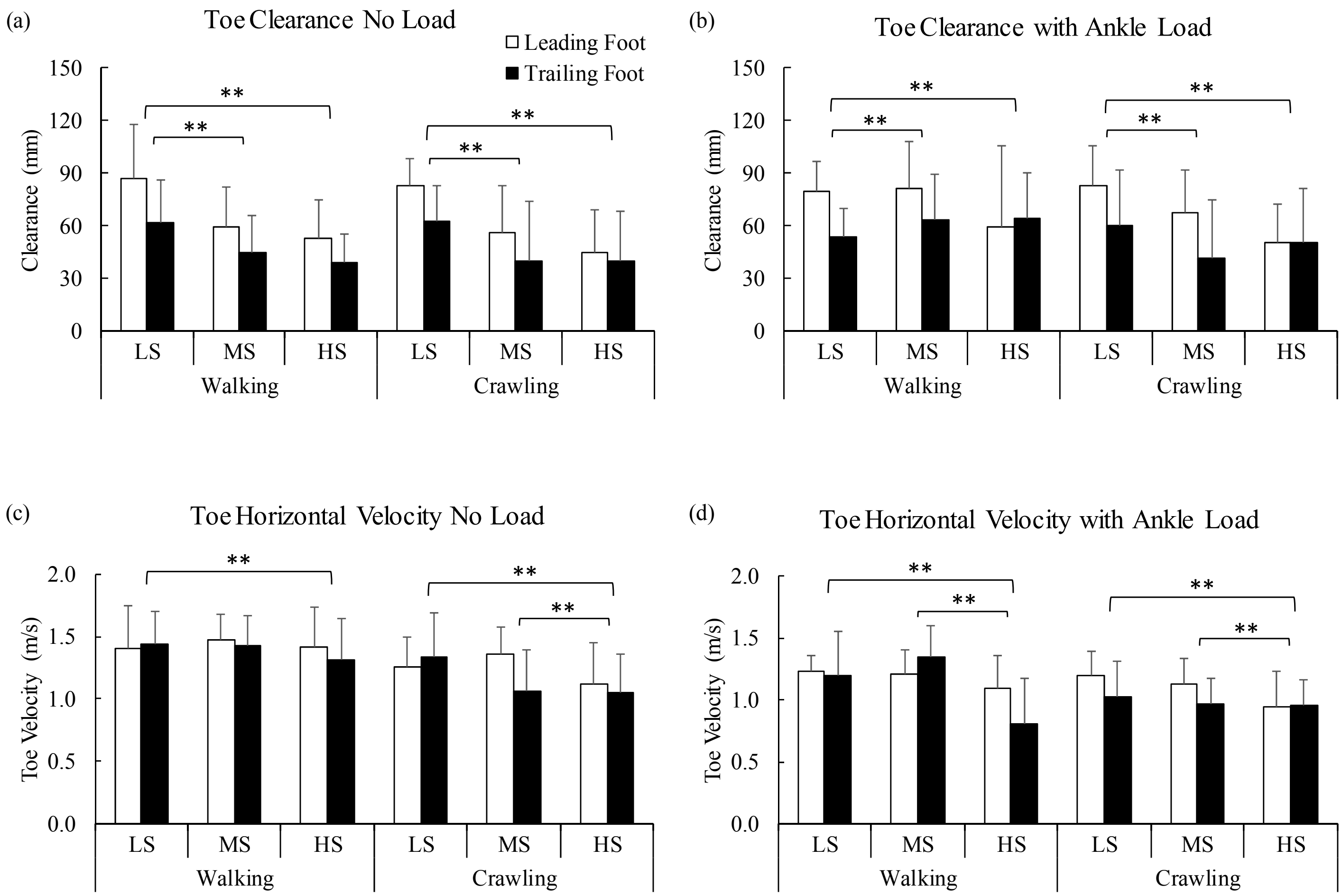


Figure 2
(a)
Toe Clearance No Load
Leading Foot
Trailing Foot
Clearance (mm)
120
100
80
60
40
20
0
LS
MS
HS
LS
MS
HS
TD *
DS *
(b)
Toe Clearance with Ankle Load
Clearance (mm)
(c)
Normalized Toe Clearance No Load
N Clearance (mm/mm)
0.20
0.16
0.12
0.08
0.04
0.00
(d)
Normalized Toe Clearance with Ankle Load

Figure 3

Figure 3



*Research Highligts

Highlights

- Children with DS stand longer and place the feet closer to the stairs before ascent.
- Children with DS decrease vertical toe clearance with the increase of stair height.
- Children with DS maintain horizontal toe velocity with the increase of stair height.
- Children with DS show similar toe clearance when walking or climbing up the stairs.
- External ankle load increases toe clearance more in children with DS than with TD.