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Spatial-temporal Gait Pattern and Motor Strategy in Children with and without Down Syndrome while Walking from Level Surface to Stairs

Xiang Ke

ACCEPTANCE

This dissertation, SPATIAL-TEMPORAL GAIT PATTERN AND MOTOR STRATEGY IN CHILDREN WITH AND WITHOUT DOWN SYNDROME WHILE WALKING FROM LEVEL SURFACE TO STAIRS, by XIANG KE, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the College of Education and Human Development, Georgia State University.

The Dissertation Advisory Committee and the student's Department Chairperson, as representatives of the faculty, certify that this dissertation has met all standards of excellence and scholarship as determined by the faculty. The Dean of the College of Education and Human Development concurs.

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ABSTRACT

This study investigated the spatial-temporal gait patterns and motor strategy in children with and without Down syndrome (DS) when walking from the level ground to the stairs. Six children with DS and eleven typically developing (TD) children aged 5-11 years from the greater Atlanta participated in this study. A full body 35 marker set and a Vicon motion capture system were used for data collection. Three three-step wooden staircases with the riser height of 17 cm (LS), 24 cm (MS), and 31 cm (HS) were randomly presented to the subjects. We examined anticipatory locomotor adjustments in spatial-temporal gait parameters (i.e. step width, step length, step time, step velocity, stance time) while the subject approached a staircase. While going up the stairs, we examined the aforementioned gait parameters and included other variables such as vertical toe clearance and horizontal toe velocity above the edge of stairs. In addition, we categorized motor strategies that were adopted to negotiate a staircase. A series of mixed ANOVA with repeated measures were conducted on each spatial-temporal gait parameter. Our results demonstrated that children with DS displayed some anticipatory locomotor adjustments while approaching a staircase, but the pattern was different from those in TD children. Specifically, while approaching a staircase, TD children maintained a similar step length and velocity but decreased step width, whereas children with DS decreased step length and velocity but maintained step width. While going up a staircase, children with DS chose a crawling strategy more often, and displayed a wider step width and a lower horizontal toe velocity than TD children. Further, children with DS produced a higher toe clearance ("overshooting") from the leading limb than TD children under the LS condition and a lower toe clearance ("undershooting") under the HS condition. Our results suggest that children with DS aged 5-11 years are able to display some anticipatory locomotor adjustments while negotiating a staircase, but still developmentally behind TD children. These findings allow us to understand motor function and the environmentally related locomotion adaptations in children with DS.

INDEX WORDS: Down syndrome, Gait pattern, Anticipatory locomotor adjustment, Adaptive locomotion, Motor strategy

SPATIAL-TEMPORAL GAIT PATTERN AND MOTOR STRATEGY IN CHILDREN WITH AND WITHOUT DOWN SYNDROME WHILE WALKING FROM LEVEL SURFACE TO STAIRS

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CHAPTER 1

BIOMECHANICAL ANALYSIS OF WALKING AND LOCOMOTOR ADJUSTMENTS IN INDIVIDUALS WITH AND WITHOUT DOWN SYNDROME: A LITERATURE REVIEW

1.1 Introduction

Down syndrome (DS) is a chromosomal condition associated with a third copy of chromosome 21, i.e. trisomy of chromosome 21 (Roizen & Patterson, 2003). The incidence of DS is about 1 out of 700 newborn infants in the United States (Parker, Mai, Canfield, et al. 2010). DS is characterized by a number of signs and clinical symptoms, such as craniofacial dysmorphia, congenital heart defects, obesity, intellectual disability, and a tendency to develop Alzheimer's disease at a much younger age (Wiseman, Alford, Tybulewicz, & Fisher, 2009; Galli, Rigoldi, Brunner, et al. 2008; Wu, & Ajisafe, 2014).

Three common clinical features related to neuromuscular function in DS population are muscular hypotonia, ligament laxity, and motor alteration (Roizen, & Patterson, 2003; Palisano, Walter, Russell, et al. 2001; Carmeli, Ayalon, Barchad, et al. 2002; Galli, Rigoldi, Brunner, et al. 2008; Cowley, Ploutz-Snyder, Baynard, et al. 2011). Muscular hypotonia means that individuals with DS have lower muscular resistance to passive muscle stretch than their typically developing peers. Ligament laxity in individuals with DS is considered resulting from the connective tissue disorder (Galli, Rigoldi, Brunner, et al. 2008). Children with DS have significantly greater joint laxity than typically developing children (Caselli, Cohen-Sobel, Thompson, et al. 1991). Although the cause of reduced muscle strength in individuals with DS is unknown (Carmeli, Kessel, Coleman, et al. 2002; Cowley, Ploutz-Snyder, Baynard, et al. 2010), the combination of ligament laxity, muscle strength and tone reduction leads to the presence of musculo-skeletal deformities and is associated with the impairment of physical function in individuals with DS (Galli, Rigoldi, Brunner, et al. 2008; Cowley, Ploutz-Snyder, Baynard, et al. 2011). For example, plano-valgus foot with marked pronation in children with DS is considered to be related with postural stability impairment (Roizen & Patterson, 2003).

Motor alteration, is widely observed in individuals with DS. Genes localized in chromosome 21 possibly affect the structure or function of central nervous system and brain development, and may have a role of the neuropathogenesis of motor dysfunction in individuals with DS (Capone, 2001). Motor alteration in individuals with DS results in altered co-contraction patterns of agonist and antagonist muscles, balance control deficits, postural instability, and altered movement patterns (Shumway-Cook, & Woollacott, 1985; Aruin, Almeida, Latash, 1996; Almeida, Corcos, & Latash, 1994; Rigoldi, Galli, & Albertini, 2011; Rigoldi, Galli, Mainardi, et al. 2011; Vimercati, Galli, Rigoldi, et al. 2013). Individuals with DS are usually considered to have developed their best motor skills by the preadolescent period. But due to the presence of an extra chromosome 21, children with DS display a significantly delayed developmental trajectory than typically developing children in the motor domain (Palisano, Walter, Russell, et al. 2001). Children with DS often show a "Chaplinesque" gait pattern, with the features of the external rotation of hip, increased flexion and valgus of knee, and the external rotation of the tibia (Roizen & Patterson, 2003; Caselli, Cohen-Sobel, Thompson, et al. 1991).

This literature review discusses the biomechanical studies on the gait patterns of individuals with DS when walking over ground or negotiating an environment with constraints such as an obstacle or a staircase. This literature review will provide us with the information on the emergence of anticipatory locomotor adjustments and motor strategy in children with and without DS. This information will serve as the foundation for the proposed study, i.e., walking from level surface to stairs, in children with and without DS. In general, walking from level surface to stairs can be analyzed at two phases: an approaching phase (i.e. walking over the level ground to the stairs) and an ascent phase (i.e. going up the stairs). Therefore, this literature review was organized in following five sections to elucidate anticipatory locomotor adjustments and motor strategies: (1) brain structure and function related to locomotion, (2) biomechanical pattern of walking in an environment without constraints, (3) biomechanical pattern of walking in an environment with constraints: approaching phase, (4) biomechanical pattern of walking in an environment with constraints: crossing phase, and (5) motor strategy adopted to negotiate an environment with constraints.

1.2 Review of the literature

1.2.1 Neuro-anatomical structural changes in individuals with DS

Although the neural mechanics of how the central nervous system (CNS) implements anticipatory locomotor adjustments (ALAs) during adaptive locomotion is still not clearly known, it is generally considered that the motor cortex, cerebellum, and spinal cord are interplayed to accommodate changes in the constraints of environment (Taga, 1998). However, the basis of neural control for locomotion, i.e. the brain structure and organization, is reported to be atypical in individuals with DS.

According to a previous study in children with DS, total brain weight was on average about 76% of that in typically developing children, and further, children with DS showed a smaller brainstem and cerebellum (on average 66% of the normal one) (Davis, Ounpuu, Tyburski, & Gage, 1991). Smaller overall brain volume and significantly reduced cerebrum and cerebellum volume in individuals with DS were also reported by other studies (Aylward, Habbak, Warren, et al. 1997; Jernigan, & Bellugi, 1990; Jernigan, Bellugi, Sowell, et al. 1993). The cerebellum receives information from the vestibular system and the motor apparatus, so as to involve the coordination of posture and movement. The occurrence of cerebellum reduction in DS may lead to the deficits in balance and coordination of movement. The localized volume reductions were also observed in the frontal cortex and limbic areas, along with significant right-left cerebral asymmetries in the limbic region and a larger parahippocampal gyrus (Jernigan, Bellugi, Sowell, et al. 1993; Raz, Torres, Briggs, et al. 1995; Kesslak, Nagata, Lott, & Nalcioglu, 1994).

Other neuro-anatomical structural changes in individuals with DS include (1) delayed myelination of neurons in the CNS, which may be related to cognitive delay in DS (Koo, Blase, Harwood-Nash, et al. 1992), (2) white matter abnormalities, which may affect the information transfer (Wang, Doherty, Hesselink, & Bellugi, 1992), (3) abnormal potential responses in frontal cortex areas of children with DS, which may affect the processing of visual tasks (Karrer, Wojtascek, & Davis, 1995), and (4) atypical hippocampal volume (Lincoln, Courchesne, Kilman, & Galambos, 1985). These neuro-anatomical abnormalities may cause delayed sensorimotor processing and movement disturbances in individuals with DS.

Rigoldi et al (2009) used high-resolution contiguous axial T1-weighted MRIs to study the possible relationship between cerebral volumes and walking patterns in ten children with DS, and found that better functioning gait was associated with lower cerebral volume reduction in children with DS (Rigoldi, Galli, Condoluci, et al. 2009). Moreover, a strong relationship between gait quality and the reduction of cerebellar vermis volume, and a relationship between the asymmetrical gait and the reduction of grey matter volume in some cerebral areas, were also identified in children with DS (Rigoldi, Galli, Condoluci, et al. 2009). The presence of perceptual-motor processing difficulties in individuals with DS results in different ALAs in comparison with those of healthy people.

1.2.2 Biomechanical pattern of walking in an environment without constraints

The biomechanical features of level walking without constraints in individuals with DS are reviewed from both the kinematic and kinetic perspectives.

1.2.2.1 Kinematic characteristics of walking in an environment without constraints

Galli et al (2008) found that children with DS aged 6-15 years walk with a significantly slower speed and a shorter stride length over ground, compared to typically developing children (Galli, Rigoldi, Brunner, et al. 2008). Individuals with DS aged 8-36 years were also reported to display a slower speed and a shorter stride length while walking on a treadmill when compared to healthy controls (Cioni, Cocilovo, Rossi, et al. 2001). Similar findings on gait patterns have been reported from a study with children with DS aged 7-10 years during both over-ground and treadmill walking (Wu, Beerse, Ajisafe, 2014). In addition, children with DS increased stride length and decreased stride time, to a lesser extent, than typically developing children when walking on a treadmill at a fast-speed (Wu, Beerse, Ajisafe, 2014).

One research that studied the hip, knee, and ankle joint kinematics in the sagittal plane found children with DS walked with (1) a greater hip flexion at initial contact and reduced range of motion at the hip, (2) a greater knee flexion at initial contact, a greater knee extension at mid-stance, a decreased knee flexion in swing, and a limited knee range of motion, and (3) the reduced first rocker of ankle joint and peak of ankle plantar-flexion at toe-off in the sagittal plane (Galli, Rigoldi, Brunner, et al. 2008). Similar gait changes, i.e. a greater hip flexion during the whole gait cycle, a greater knee flexion at the initial contact, and reduced ankle plantar-flexion ability at toe-off, were also reported in children with DS (Galli, Albertini, Tenore, & Crivellini, 2001). A poor heel-toe rocking during the stance phase, along with an increased abduction of the lower limb to facilitate foot clearance, was found in children with DS (Parker & Bronks, 1980). Based on these results, it was suggested that individuals with DS may have stiffer hips and less stiff ankles during walking (Galli, Rigoldi, Brunner, et al. 2008).

Additionally, a plano-valgus foot with a greater pronation in children with DS was considered to be related to their postural stability impairment (Roizen & Patterson, 2003). Severe hallux valgus, "hammer toe" deformities, plantar fasciitis fatigue, and early onset of foot arthritis associated with severe flat feet, are considered to restrict ambulation in adolescents and adults with DS (Roizen & Patterson, 2003). Generally, a “Chaplinesque” gait pattern was observed in individuals with DS such that they walk with increased external rotation of hip, increased flexion and valgus of knee, and the external rotation of the tibia (Roizen & Patterson, 2003; Caselli, Cohen-Sobel, Thompson, et al. 1991).

1.2.2.2 Kinetic characteristics of walking in an environment without constraints

Children with DS generally display different kinetic gait characteristics from typically developing children. Wu et al (2014) found there were differences in frequency contents of vertical ground reaction force (GRF) between children with and without DS aged 7-10 years when walking on a treadmill at a slower speed, but these differences disappeared at a faster speed while wearing external ankle load (Wu, Beerse, Ajisafe, 2014). In addition, children with DS aged 7-10 years produced a shorter duration of propulsion, a lower second peak GRF, and a lower vertical propulsive impulse and unloading rate, but a higher loading rate than typically developing children while walking on a treadmill (Wu, Beerse, Ajisafe, 2014).

Galli et al (2008) examined joint kinetics of lower limbs in children with and without DS aged 5-16 years (Galli, Rigoldi, Brunner, et al. 2008). It was found that: (1) maximum hip flexor moment at initial contact increased but subsequently decreased at around 15% of gait cycle, whereas maximum hip extensor moment increased during most of stance phase in children with DS; (2) the first peak of knee extensor moment was absent in children with DS; (3) a shorter dorsiflexion peak of ankle joint appeared at loading response in children with DS, corresponding to a decreased power generation of ankle joint at push-off.

Another study with individuals with DS aged 8-36 years reported that individuals with DS might have an ankle kinetic dysfunction due to the reduced power at the ankle joint (Cioni, Cocilovo, Rossi, et al. 2001). Specifically, the ankle power of energy absorption decreased during mid-stance phase and terminal stance at either a higher walking speed or a lower walking speed; the ankle power of energy generation reduced at a higher walking speed; and the duration of energy generation prolonged until pre-swing phase in individuals with DS (Cioni, Cocilovo, Rossi, et al. 2001). In addition, Galli et al (2008) reported that there was a significant increase of hip joint stiffness whereas a significant decrease of ankle joint stiffness in children with DS compared to typically developing children, but the differences disappeared when joint stiffness measures were normalized to gait velocity (Galli, Rigoldi, Brunner, et al. 2008).

Wu et al (2015) compared walking dynamic in general muscular activation in children with and without DS aged 7-10 years (Wu, Beerse, Ajisafe, & Liang, 2015). The study used a force-driven harmonic oscillator (FDHO) model and calculated the ratio between elastic (spring) and gravitational (pendulum) restoring torques (K/G ratio) to quantify the level of general muscle activity. It was found that (1) during over-ground walking, children with DS walked with a similar K/G ratio as TD children, but increased K/G ratio when walking at a faster speed, and

(2) during treadmill walking at a faster speed, children with DS walked with a lower K/G ratio than TD children without ankle load, but showed a similar K/G ratio when walking with ankle load (Wu, Beerse, Ajisafe, & Liang, 2015).

1.2.3 Biomechanical pattern of walking in an environment with constraints: approaching phase

Gait pattern over the level ground without any constraints is basic locomotion pattern and is considered as the foundation for adaptive locomotion in an environment with constraints. When walking in an environment with constraints such as an obstacle or a staircase, one needs to adjust his locomotion pattern to accommodate the constraints of the environment. This is generally referred to as adaptive locomotion, an important motor skill for motor exploration and execution. Motor planning of adaptive locomotion occurs anticipatorily before negotiating the environment.

Anticipatory locomotor adjustments (ALAs) are modified gait pattern in this motor planning phase of adaptive locomotion in order to successfully accommodate the constraints of the environment. The literature review below is focused on two different environmental settings: (1) an obstacle and (2) a staircase. Walking over an obstacle and walking from level surface to stairs are two different walking tasks in that subjects stay on the same level surface while walking over an obstacle, whereas subjects moves up for each step while walking up a staircase, respectively. Gait patterns of these two tasks should thus be different. However, in both motor tasks, the CNS extracts the environmental properties information, plans and executes an adaptive movement to accommodate the constraints. Under these two environmental conditions, gait pattern during the approaching phase (i.e. walking to an obstacle or a staircase) may be therefore similar.

Since little study has been conducted for a staircase setting in children with and without DS, the ALA finding from an obstacle setting may provide necessary information to understand the approaching phase while walking from level surface to stairs. For example, when walking crossing an obstacle or walking from level surface to stairs, one must have enough toe clearance to step over the obstacle or the edge of the stairs while progressing forward at the same time.

1.2.3.1 Characteristics of ALAs in typically developing children and adults during obstacle negotiation

It was suggested that age plays an important role in the implementation of ALAs. Typically developing children are considered to be able to make task-specific ALAs by modulating step length and toe clearance (Berard & Vallis, 2006). Particularly, it is reported that typically developing children at 8-12 years of age display ALAs at the last three steps before clearing an obstacle (Vallis & McFadyen, 2005). They demonstrated reduced walking speed two steps prior to the obstacle and decreased step length one step before the obstacle (Vallis & McFadyen, 2005). But McFadyen et al (2001) stated anticipatory strategies are still maturing in children between 7 and 9 years, although they are capable of clearing an obstacle of moderate height (McFadyen, Malouin, & Dumas, 2001). Similarly, another study also suggests that TD children at the age of 7 may not have fully developed anticipatory locomotor adjustments (Berard & Vallis, 2006).

Vallis and McFadyen (2005) investigated 5 TD children (aged 10.3 ± 1.5 years) and 6 adults (26.3 ± 2.9 years) during unobstructed walking and obstructed walking to study typically developing children's obstacle negotiation (Vallis & McFadyen, 2005). The main spatiotemporal results of this study include: (1) Children showed a slower walking speed than adults in all walking conditions. Particularly, children walked with a significantly reduced speed than adults for the two steps before obstacle crossing. (2) Children significantly decreased their step length for the step prior to obstacle crossing. However, adults walked with a similar step length during their unobstructed walking and obstructed walking. (3) Children displayed a wider and more variable step width beginning with the two steps prior to obstacle crossing. It was revealed that TD children showed minimal medial-lateral displacement of center of mass (COM), 7.11 (± 2.47) cm, during the unobstructed walking. Children had more medial-lateral COM displacement prior to obstacle crossing, averaged 49.13 (± 10.02) cm. There was no difference in medial-lateral COM trajectories between TD children and adults.

As for the segmental angular trajectories, Vallis and McFadyen (2005) reported that TD children displayed minimal trunk roll angles (5.85° ± 1.22) during obstructed walking (Vallis & McFadyen, 2005). There was no difference between TD children and adults during obstructed walking, although children displayed higher head and trunk twisting angles than adults during unobstructed walking. TD children also showed a similar head roll angle to adults during both unobstructed and obstructed walking. Specifically, children displayed the sequence of re-orientation as the onset of medial-lateral COM movement (1.90 s), the initiation of head yaw movement (2.74 s), and the beginning of trunk twisting movements (2.83 s) during obstructed walking.

Children are considered to extract visual information differently from adults when avoiding an obstacle in their travel path, and are more dependent on visual information than adults to place their feet in the obstructed environment (Berard & Vallis, 2006; Vallis & McFadyen, 2005). Different head and trunk anticipatory segmental coordinations were found between adult and children subjects (Vallis & McFadyen, 2005). One study about the development of anticipatory orienting strategies during walking around a 90° right corner in TD children aged 3.5-8 years old stated the emergence of predictive head orienting movements of the trajectory and the feed-forward control of goal-directed locomotion (Grasso, Assaiante, Prévost, & Berthoz, 1998). Another study investigated anticipatory postural adjustments during gait initiation in children aged 2.5-8 years old, and found that ALAs were shown in the youngest age group, consistent with the observation in children aged 6 years and above (Ledebt, Bril, & Brenière, 1998).

1.2.3.2 Characteristics of ALAs in children and adults with DS during obstacle negotiation

Salami et al (2014) investigated spatiotemporal parameters in the level ground walking and walking over an obstacle (with the height equal to 10% of the subject's height) in twenty young adults with DS (aged 21.6 ± 7 years). Adults with DS showed reduced walking speed, increased step width, decreased and more variable step length, compared to eighteen young adults (aged 25.1 ± 2.4 years) (Salami, Vimercati, Rigoldi, et al. 2014). Vimercati et al (2013) also studied spatiotemporal parameters between ten young adults with DS (aged 22 ± 6 years) and sixteen age-matched young adults without DS (aged 25 ± 3 years) when walking in three different conditions: unobstructed ground walking, walking over an obstacle at ground level, walking over an obstacle at 10% of the subject's height. It was found that the subjects with DS walked at a slower speed than the subjects without DS in each of the three conditions (Vimercati, Galli, Rigoldi, & Albertini, 2013). Further, the subjects with DS decreased their speed to a greater extent when walking over an obstacle at 10% of the subject's height, whereas the subject without DS were able to walk at an unvaried speed across all conditions (Vimercati, Galli, Rigoldi, & Albertini, 2013).

Step lengths of the subjects with DS at the step before the obstacle and at the step after the obstacle were shorter and more variable especially when walking with the obstacle at 10% of their heights; whereas the subjects without DS maintained step length throughout the walking trial (Vimercati, Galli, Rigoldi, & Albertini, 2013). Similar results were reported by another study with young adults with DS (Vimercati, Galli, Rigoldi, et al. 2012). About the foot position, the leading foot of subjects with DS tended to land closer to the obstacle before the obstacle, and their trailing foot tended to land closer to the obstacle after the obstacle (Vimercati, Galli, Rigoldi, & Albertini, 2013).

Since the deficits which affect ALAs, such as visual perception and attention-related process, exist in children with DS, the ALAs of children with DS were found different from those of TD children population. One study about obstructed walking in infants with DS (aged about 10 months) found these toddlers demonstrated ALAs, such as reduced walking speed, cadence and step length, and increased step width in the last three pre-obstacle steps before stepping over an obstacle (Wu, Ulrich, Looper, et al. 2008).

Another study explored the mechanism of anticipatory control of obstructed walking in relation to the perception of two different heights of an obstacle (1% of a body height and 15% of a body height) in five children with DS (aged 5-6 years) and six typically developing children (aged 4-7 years) (Virji-Babul & Brown, 2004). The kinematic outcomes of this study revealed: (1) stride length normalized to leg length was significantly shorter in children with DS; (2) step length variability was significantly greater in children with DS (Virji-Babul & Brown, 2004). When walking with an obstacle at the height of 15% of body height, step length became more variable during the first three steps before obstacle crossing in TD children, while children with DS showed an overall decrease in step length variability for these pre-obstacle steps.

Lower limb segment trajectory during obstructed walking showed that typically developing children walked smoothly from approaching the obstacle to stepping over it (Virji-

Babul & Brown, 2004). However, 4 out 5 children with DS in this study were found to stop in front of the obstacle with the height equal to 15% of body height for the duration between 0.4 seconds to 4 seconds, before stepping over it (Virji-Babul & Brown, 2004). This “stopping” strategy was not observed when children with DS negotiated the obstacle with the height equal to 1% of body height (Virji-Babul & Brown, 2004). Children with DS were able to extract some visual information about the properties of an obstacle, but not able to use that information to adjust their movement pattern (Virji-Babul & Brown, 2004). They waited till they reached the obstacle and stopped in front of the obstacle to extract relevant information to modulate obstacle crossing movement, particularly before negotiating an obstacle with a higher height (Virji-Babul & Brown, 2004). Young adults with DS may not stop before the obstacle, but walk with a significant decrease of speed at the approaching phase (Vimercati, Galli, Rigoldi, & Albertini, 2013).

1.2.4 Biomechanical pattern of walking in an environment with constraints: crossing phase

1.2.4.1 Gait pattern of walking while negotiating an obstacle

1.2.4.1.1 Kinematics of walking over an obstacle

McFadyen et al (2001) investigated walking over an obstacle with the height equal to 15% of leg length in eight TD children (aged 7-9 years) (McFadyen, Malouin, & Dumas, 2001). It was found that these children showed decreased walking velocity in both leading limb and trailing limb while walking over an obstacle; and displayed increased hip flexion and knee flexion, along with increased ankle dorsiflexion (McFadyen, Malouin, & Dumas, 2001).

The reduced velocity of ALAs may facilitate the accurate execution of modifications in locomotor patterns (Higuchi, 2013). It was reported that individuals with DS walked with a shorter yet more variable step length at the step before the obstacle, at the step during obstacle crossing, and at the step after the obstacle, compared to individuals without DS (Vimercati, Galli, Rigoldi, & Albertini, 2013). Vimercati et al (2012) stated that individuals with DS (aged 22 ± 6 years) showed a slower walking speed, a shorter step length with more variability during obstacle crossing than age-matched subjects without DS (25 ± 3 years) (Vimercati, Galli, Rigoldi, et al. 2012).

Appropriate locomotor adjustments include maintaining a spatial margin between an obstacle and the subject (Higuchi, 2013). This margin includes both horizontal spatial margin (i.e. foot placement in front of the obstacle) and a vertical spatial margin (i.e. toe clearance while stepping over the obstacle). Both margin variables are critical control parameters for locomotor adjustments in obstructed walking (Higuchi, 2013). Incorrect foot placement relative to the obstacle was also found in individuals with DS, although they were generally able to extract information about the obstacle height, and scale foot elevation to step over an obstacle (Vimercati, Galli, Rigoldi, & Albertini, 2013).

Adaptive locomotion cannot be achieved without the perception of environment in relation to human body's action capacities. The information of environmental properties relative to one's action abilities is termed body-scaled information. The body-scaled information can be used to estimate a maximum elevation height for stepping over a gap (Burton, 1992; Jiang & Mark, 1994; Snapp-Childs & Bingham, 2009). The environmental properties relative to body's action capacities, which are perceived by the central nervous system (CNS) from a distance, is considered as a pre-requisite of anticipatory locomotor adjustments (Taga, 1998). The CNS can recalibrate the perception in response to the altered action capacities (Higuchi, 2013). Additionally, visual system and visuo-motor control are also necessary for adaptive locomotion.

For example, visually guided, on-line locomotor adjustments were made in the final phase of obstacle crossing (Higuchi, 2013).

When crossing an obstacle, both TD children and children with DS were reported to be able to scale toe clearance and cross the obstacle successfully (Virji-Babul & Brown, 2004). Both groups increased their toe clearance in response to an increased obstacle height during the obstructed walking, and there was no significant difference between the two groups. Children with DS had a similar toe clearance as TD children during unobstructed walking and obstructed walking with a low obstacle. Numerically, children with DS were reported to have an averaged 5 cm margin higher than the obstacle to cross the obstacle, while typically developing children showed an averaged 7 cm margin for obstacle clearing (Virji-Babul & Brown, 2004). As for the values of maximum foot elevation, the subjects with DS walked with a lower maximum foot elevation than the subjects without DS during unobstructed ground walking, but increased the maximum height of foot elevation and reached the values in the subjects without DS when walking with an obstacle at the height of 10% of subject's height (Vimercati, Galli, Rigoldi, & Albertini, 2013; Vimercati, Galli, Rigoldi, et al. 2012). When clearing an obstacle, the subjects without DS increased hip and knee flexion to elevate the foot over the obstacle, and increased the flexion of the hip, knee, and ankle as the obstacle height increased (McFadyen, Winter, & Allard, 1994; McFadyen & Winter, 1991; Chou & Draganich, 1997; Patla & Rietdyk, 1993).

There was one study which investigated the inter-segmental coordination of the leading limb and trailing limb in ten healthy young adult subjects, and indicated that the CNS controlled fundamental harmonic phase differences in elevation angle between adjacent segments and elevation angle amplitude when walking over an obstacle (Maclellan & McFadyen, 2010). Besides, visuomotor coordination is also required for approaching and crossing an obstacle. The integration of visual input extracts information about the properties of an obstacle (height, size, location, etc.) and its location relative to the body (Pearson & Gramlich, 2010), and defines whether the current locomotor pattern appropriate for the environment (Law & Webb, 2005). The visual information is extracted at the initiation of gait to facilitate the generation of specific changes in step length and toe clearance that is dependent on the obstacle height (Patla & Vickers, 1997).

The differences in kinematic parameters for the upper limbs, trunk, and lower limbs were also found between the subjects with DS and the subjects without DS (Vimercati, Galli, Rigoldi, et al. 2012). When walking over an obstacle, the subjects with DS showed increased hip flexion and knee flexion, and more ankle dorsiflexion than the subjects without DS. Subjects with DS also displayed higher pelvic obliquity and rotation along with hip abduction, and increased hip intra-rotation than the subjects without DS during obstructed walking. Subjects with DS also elevated the arms by reducing the shoulder-arm angles and flexed the elbows so as to stabilize the center of mass and prevent possible falls when walking with an obstacle.

1.2.4.1.2 Kinetics of walking over an obstacle

McFadyen et al (2001) explored muscle moments of force at the hip, knee and ankle joints in eight TD children (aged 7-9 years), and compared those between unobstructed ground walking and obstructed ground walking (McFadyen, Malouin, & Dumas, 2001). It was reported that (1) there was a reduction in hip flexor moment and knee extensor moment at toe-off, (2) at hip joint, more extensor pattern appeared in the leading limb whereas more flexor patterns in the trailing limb during the swing phase, (3) knee flexor moment at toe-off could be identified frequently during obstructed walking, (4) there was little difference in moment of force patterns at the ankle joint across the gait cycle among walking conditions. Correspondingly, the results of muscle mechanical power pattern displayed the power bursts around toe-off, i.e. the generation burst in the power at the hip joint relevant to hip flexors at toe-off (H3), the knee extensor absorption (K3) and the knee flexor generation (K5) around toe-off. Based on the results of their study, McFadyen et al (2001) stated mid-childhood aged children had adult-like general dynamic strategies to step over an obstacle; the magnitudes of their muscle power bursts which were normalized to body mass, was lower than that of adults reported in the literature; and the usual antagonistic knee extensor power burst was found absent at the end of stance phase in children with DS during their obstructed walking (McFadyen, Malouin, & Dumas, 2001).

Salami et al (2014) investigated muscle mechanical power patterns in obstructed walking in young adult with DS (Salami, Vimercati, Rigoldi, et al. 2014). This study compared the mechanical energy parameters between subjects with DS (aged 21.6 ± 7 years) and healthy subjects (aged 25.1 ± 2.4 years) when they walked over an obstacle with the height equal to 10% of the subject's height. It was shown that subjects with DS walked with a different obstacle avoidance pattern, but there was no difference in mechanical energy recovery between the two groups.

1.2.4.2 Gait patterns of walking from level surface to stairs

This literature here generally reviews some kinematic and kinetic gait characteristics when walking from level surface to stairs in general population. Little study has been conducted with children with DS.

1.2.4.2.1 Kinematics of walking from level surface to stairs

Walking with the level changes, such as walking up the stairs, is more challenging than obstructed walking on the unvaried level surface. McFadyen and Carnahan (1997) conducted a series of walking experiments with six healthy adults. These walking conditions included unobstructed ground walking, walking over an obstacle, walking transferring from the ground to a platform, walking transferring from the ground to a three-step staircase, walking transferring from the ground to a platform with an obstacle placed one foot length before the first step, and walking transferring from the ground to a platform with an obstacle placed one foot length before the first step (McFadyen & Carnahan, 1997). It was reported that: (1) a knee strategy, i.e. an active knee flexor power generation, which was reorganized from the robust lower limbs movement patterns in unobstructed level walking, was observed when walking in the presence of an obstacle, (2) a hip strategy, i.e. an increased hip flexor power, which was augmented from the on-going hip strategy inherent in unobstructed level walking, was displayed to accommodate to a new height when simply walking from the ground to a platform or staircase, (3) both a reorganization of active knee strategy and an augmentation of hip strategy were shown to avoid an obstacle and accommodate level changes for the obstructed walking compounded with transferring to a platform or staircase.

The augmented hip strategy not only provides an adequate toe clearance in the leading limb, but also prevents the trailing foot from contacting with the surface (Niang & McFadyen, 2004). This study discussed these results in the term of an avoidance strategy and an accommodation strategy (McFadyen & Carnahan, 1997). The goal of an avoidance strategy is to step over an obstacle in the travel path. The inter-segmental dynamics of the lower limbs for an accommodation strategy is to reach out and step onto a new level in the late swing phase, bringing the lower limb to a new-end state which is required by the change of environment (e.g. stairs, type of surface), which means the augmented hip strategy for accommodation is more desirable. The combination of these two strategies is considered to ensure an adequate toe clearance for obstacle avoidance and the swinging leg for accommodation.

Rietdyk (2006) investigated the negotiation with a raised surface in nine healthy young adults (aged between 24.2 ± 2.7 years) (Rietdyk, 2006). The results of the study showed when healthy individuals walked up from the ground to a raised surface with the trailing limb, (1) overall walking speed and stride length significantly decreased while the duration for both stance and swing phases significantly increased; (2) average horizontal velocity of the head-arms-trunk (HAT) COM significantly decreased during both stance and swing phases; (3) during late stance, both horizontal foot acceleration and HAT acceleration significantly reduced, whereas vertical foot acceleration and vertical HAT acceleration significantly increased, in comparison with their unobstructed level walking condition. Kinematical outcomes revealed that, in comparison with their unobstructed level walking, healthy young adults walked with a greater extended trunk segment, a more forward thigh segment, and a farther vertical shank segment at toe-off, when they walked from the ground to a raised surface.

Sheehan & Gottschall (2011) studied the transition from unobstructed level walking to stair walking in twelve healthy young adults (aged 22 ± 2 years), and analyzed their three sagittal plane joint angles and six leg muscle activity patterns of the leg (Sheehan & Gottschall, 2011). With each time point of the transition strides compared to corresponding time points of the before-stride, the after-stride, and a theoretical mean stride, the study reported that all transition strides displayed the least number of different time points with the after-stride (34%), but not the mean-stride (51%). It is suggested that the transition stride functions not simply as an intermediate between a before-stride and an after-stride, but rather works as a unique anticipation of the upcoming stride during stair walking (Sheehan & Gottschall, 2011).

There is little study related to the stairs negotiation in individuals with DS. But one study which examined the effect of progressive resistance training on physical function in young adults with DS stated the leg strength of subjects with DS was significantly improved after the training so that they showed significantly reduced time to ascend stairs and descent stairs (Cowley, Ploutz-Snyder, Baynard, et al. 2011).

1.2.4.2.2 Kinetics of walking from level surface to stairs

Silverman et al (2014) investigated the kinetics during stair ascent and descent in thirty healthy subjects (aged 21.8 ± 4.2 years) (Silverman, Neptune, Sinitski, & Wilken, 2014). Silverman et al (2014) found that: (1) the anterior-posterior (A/P) ground reaction force (GRF) of braking peak and propulsive peak significantly reduced during stair walking than level walking, with the smaller peak A/P GRF during stair ascent than that during stair descent; (2) both medial-lateral (M/L) GRF peaks was identified the greatest during stair descent and the lowest during stair ascent, with the medium during level walking; (3) vertical GRF peak in initial stance was found to be the lowest during stair ascent and the highest during stair descent, with the medium during level walking; (4) peak vertical GRF in late stance was found to be higher during stair ascent and level walking than that during stair descent. Also, Silverman et al (2014) identified that the range of angular momentum in the frontal plane was higher during stair ascent than level walking, while in the sagittal and transverse planes lower during stair ascent and descent in comparison to level walking.

At the hip joint, Silverman et al (2014) found that (1) in the frontal plane, peak abduction moments in both early stance and late stance were lower during stair ascent than stair descent and level walking; (2) in the sagittal plane, stair walking showed both decreased peak extension moment in early stance and smaller flexion moment than those of level walking; (3) in the transverse plane, a smaller external rotation moment throughout stance phase was identified during stair descent (Silverman, Neptune, Sinitski, & Wilken, 2014). At the knee joint, it was found that (1) in the frontal plane, an abduction moment decreased in early stance and late stance during stair descent in comparison to stair ascent and level walking; (2) in sagittal plane, the peak extension moment in early stance was showed greatest during stair ascent, additionally the extension moment was found to transition to flexor moment in late stance during stair ascent and level walking; (3) in the transverse plane, the internal rotation moment was identified largest during stair ascent in early stance whereas largest during stair descent in late stance, along with the occurrence of external rotation moment during level walking in late stance. At the ankle joint, it was found that (1) in the frontal plane, the abduction moment remained throughout the stance during stair walking, particularly, with a smaller peak abduction moment in late stance during stair descent in comparison to stair ascent and level walking; (2) in the sagittal plane, stair walking showed an early plantar-flexion moment peak which was absent during level walking; (3) in the transverse plane, stair walking had a smaller internal rotation moment peak than that of level walking.

During surface accommodation, the trailing limb must support the body when the leading limb is clearing the surface, and then must also clear the surface so that the entire body is raised to a new level. It is considered that the hip, knee, and ankle muscles of the trailing limb perform more work than the leading limb during stance and swing before landing on a new level (Rietdyk, 2006). And the strategy for the trailing limb is related to the relative proximity of the surface for the leading and trailing limbs. It was found that (1) the translational energy at the hip joint increased over 300% between toe-off and when the trailing toe crossed the surface, (2) the occurrence of the largest new rotational energy generation at the trailing ankle during ankle push-off phase. This coordinates the whole body to push the body and the leading limb up onto the new level, cause the limb upwards rather than forward into the new surface, and pull hip upward to increase the elevation of the trailing limb, etc., so as to raise the entire body to the new level.

1.2.5 Motor strategy while negotiating an environment with constraints

It is postulated that individuals with DS tend to concern more about movement safety than movement efficiency (Rigoldi, Galli, Mainardi, et al. 2011; Vimercati, Galli, Rigoldi, et al. 2013). Therefore, individuals with DS usually display more “clumsy” movement and may adopt different motor strategies compared to their healthy peers (Latash, 2007; Rigoldi, Galli, Cimolin, et al. 2012). As negotiating the environment with constraints, such as crossing over an obstacle or walking up the stairs, is more challenging than over-ground walking, this provides an ideal paradigm to understand motor planning and strategy in individuals with DS.

Only two studies examined motor strategy in children with DS during obstructed walking. Wu et al (2008) investigated motor strategy in infants with DS (Wu, Ulrich, Looper, et al. 2008). Three strategies were discussed in this study: fall, crawl, and walk. It was reported that after about 10-month intervention with either a generalized, lower-intensity training protocol or an individualized, higher-intensity training protocol, infants with DS (aged about 20 months) adopted either a crawl strategy or a walk strategy to cross over an obstacle (Wu, Ulrich, Looper, et al. 2008). Further, the walk strategy became the primary motor strategy about 3 months after the intervention in those who received an individualized, high-intensity training protocol. However, both crawl and walk strategies were equally used in those who received a generalized, lower-intensity training protocol, until 9 months after the intervention.

Mulvey et al (2011) examined motor strategy adopted during obstructed walking in toddlers with DS (aged from 1 year and 2.5 months to 3 years and 4.5 months) and typically developing toddlers (aged from 11 months to 1 years and 6 months) (Mulvey, Kubo, Chang, & Ulrich, 2011). In this study, the adopted motor strategies during obstructed walking were categorized into: avoidance, errors, successful crawling, and successful walking. It stated that at 1 month of walking experience, toddlers adopted all these strategies variedly to cross the obstacle during their walking, and the difference in strategy was identified between toddlers with DS and typically developing toddlers: (1) toddlers with DS preferred to crawl over an obstacle and continued crawling after crossing the obstacle; (2) typically developing toddlers preferred to walk over an obstacle, although with errors. The study also revealed that by 3 month of walking experience, no toddler avoided the obstacle any longer; and toddlers with DS still tended to negotiate the obstacle with crawling strategy (but changed the crawling to walking immediately after crossing the obstacle); whereas typically developing toddlers tended to successfully walk over the obstacle. Mulvey et al (2011) considered that toddlers with DS used the crawling strategy which was more conservative, cautious, and safer, but also effective and successful for obstacle crossing during obstructed walking.

No study has analyzed motor strategy while walking from level surface to stairs in children with and without DS. This topic is of great importance given that the stairs are a common setting in residential, educational and recreational environments. Childhood is the critical period for children to learn new motor skills and accumulate locomotor experiences so as to adapt to the new environment or new motor tasks. The knowledge to be gained from our proposed research will advance our understanding on how biomechanically and strategically children with DS negotiate the stairs.

Our proposed research studies spatial-temporal gait pattern and motor strategy in children with and without DS while walking from level ground to stairs. We presented three staircases with different riser heights and investigated the effect of staircase riser heights on spatial-temporal gait parameters and motor strategy. Our proposed study is the first one to examine adaptive spatial-temporal gait pattern and motor strategies in children with and without DS across both the approaching and ascent phases while walking from level surface to stairs. Our proposed study provided the basic biomechanical information about the adaptive locomotion and motor strategy in children with and without DS while negotiating a constrained environment with the stairs, which allowed us to understand their anticipatory locomotor adjustments, motor function and adaptability, especially in children with DS.

References

Almeida GL, Corcos DM, Latash ML. Practice and transfer effects during fast single-joint elbow movements in individuals with Down syndrome. *Phys Ther*. 1994; 74(11):1000-12; discussion 1012-6.

Aruin AS, Almeida GL, Latash ML. Organization of a simple two-joint synergy in individuals with Down syndrome. *Am J Ment Retard.* 1996; 101(3):256-68.

Aylward EH, Habbak R, Warren AC, Pulsifer MB, Barta PE, Jerram M, Pearlson GD. Cerebellar volume in adults with Down syndrome. *Arch Neurol.* 1997; 54(2):209-12.

Berard JR, Vallis LA. Characteristics of single and double obstacle avoidance strategies: a comparison between adults and children. *Exp Brain Res.* 2006; 175(1):21-31.

Burton G. Nonvisual judgment of the crossability of path gaps. *J Exp Psychol Hum Percept Perform.* 1992; 18(3):698-713.

Capone GT. Down syndrome: advances in molecular biology and the neurosciences. *J Dev Behav Pediatr*. 2001; 22(1):40-59.

Carmeli E, Ayalon M, Barchad S, Sheklow SL, Reznick AZ.Isokinetic leg strength of institutionalized older adults with mental retardation with and without Down's syndrome. *J Strength Cond Res.* 2002; 16(2):316-20.

Carmeli E, Kessel S, Coleman R, Ayalon M. Effects of a treadmill walking program on muscle strength and balance in elderly people with Down syndrome. *J Gerontol A Biol Sci Med Sci.* 2002; 57(2):M106-10.

Caselli MA, Cohen-Sobel E, Thompson J, Adler J, Gonzalez L. Biomechanical management of children and adolescents with Down syndrome. *J Am Podiatr Med Assoc.* 1991; 81(3):119-27.

Chou LS, Draganich LF. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. J Biomech. 1997; 30(4):331-7.

Cioni M, Cocilovo A, Rossi F, Paci D, Valle MS. Analysis of ankle kinetics during walking in individuals with Down syndrome. *Am J Ment Retard* 2001; 106(5):470-8.

Cowley PM, Ploutz-Snyder LL, Baynard T, Heffernan K, Jae SY, Hsu S, Lee M, Pitetti KH, Reiman MP, Fernhall B. Physical fitness predicts functional tasks in individuals with Down syndrome. *Med Sci Sports Exerc.* 2010; 42(2):388-93.

Cowley PM, Ploutz-Snyder LL, Baynard T, Heffernan KS, Jae SY, Hsu S, Lee M, Pitetti KH, Reiman MP, Fernhall B. The effect of progressive resistance training on leg strength, aerobic capacity and functional tasks of daily living in persons with Down syndrome. *Disabil Rehabil.* 2011; 33(23-24):2229-36.

Davis I, Ounpuu S, Tyburski DJ, Gage JR. A gait analysis data collection and reduction technique. *Hum Mov Sci* 1991; 10:575-587.

Galli M, Rigoldi C, Brunner R, Virji-Babul N, Giorgio A. Joint stiffness and gait pattern evaluation in children with Down syndrome. *Gait Posture* 2008; 28(3):502-6.

Galli M, Albertini G, Tenore N, Crivellini M. Gait analysis in children with Down syndrome. *Progr Rep-Intern Rev Med Sci.* 2001; 13:21-7.

Grasso R, Assaiante C, Prévost P, Berthoz A. Development of anticipatory orienting strategies during locomotor tasks in children. *Neurosci Biobehav Rev.* 1998; 22(4):533-9.

Higuchi T. Visuomotor control of human adaptive locomotion: understanding the anticipatory nature. *Front Psychol.* 2013; 4:277.

Jernigan TL, Bellugi U. Anomalous brain morphology on magnetic resonance images in Williams syndrome and Down syndrome. *Arch Neurol.* 1990; 47(5):529-33.

Jernigan TL, Bellugi U, Sowell E, Doherty S, Hesselink JR. Cerebral morphologic distinctions between Williams and Down syndromes. *Arch Neurol.* 1993; 50(2):186-91.

Karrer R, Wojtascek Z, Davis MG. Event-related potentials and information processing in infants with and without Down syndrome. *Am J Ment Retard.* 1995; 100(2):146-59.

Kesslak JP, Nagata SF, Lott I, Nalcioglu O. Magnetic resonance imaging analysis of age-related changes in the brains of individuals with Down's syndrome. *Neurology*. 1994; 44(6):1039-45.

Koo BK, Blaser S, Harwood-Nash D, Becker LE, Murphy EG. Magnetic resonance imaging evaluation of delayed myelination in Down syndrome: a case report and review of the literature. *J Child Neurol.* 1992; 7(4):417-21.

Latash ML. Learning motor synergies by persons with Down syndrome. *J Intellect Disabil Res.* 2007; 51(Pt 12):962-71.

Law LS, Webb CY. Gait adaptation of children with cerebral palsy compared with control children when stepping over an obstacle. *Dev Med Child Neurol.* 2005; 47(5):321-8.

Ledebt A, Bril B, Brenière Y. The build-up of anticipatory behaviour. An analysis of the development of gait initiation in children. *Exp Brain Res.* 1998; 120(1):9-17.

Lincoln AJ, Courchesne E, Kilman BA, Galambos R. Neuropsychological correlates of information-processing by children with Down syndrome. *Am J Ment Defic.* 1985; 89(4):403-14.

Maclellan MJ, McFadyen BJ. Segmental control for adaptive locomotor adjustments during obstacle clearance in healthy young adults. *Exp Brain Res.* 2010; 202(2):307-18.

McFadyen BJ, Carnahan H. Anticipatory locomotor adjustments for accommodating versus avoiding level changes in humans. *Exp Brain Res.* 1997; 114(3):500-6.

McFadyen BJ, Malouin F, Dumas F. Anticipatory locomotor control for obstacle avoidance in mid-childhood aged children. *Gait Posture.* 2001; 13(1):7-16.

McFadyen BJ, Winter DA, Allard F. Simulated control of unilateral, anticipatory locomotor adjustments during obstructed gait. *Biol Cybern.* 1994; 72(2):151-60.

McFadyen BJ, Winter DA. Anticipatory locomotor adjustments during obstructed human walking. *Neurosci Res Commun* 1991; 9:37–44.

Mulvey GM, Kubo M, Chang CL, Ulrich BD. New walkers with Down syndrome use cautious but effective strategies for crossing obstacles. *Res Q Exerc Sport.* 2011; 82(2):210-9.

Niang AE, McFadyen BJ. Adaptations in bilateral mechanical power patterns during obstacle avoidance reveal distinct control strategies for limb elevation versus limb progression. *Motor Control.* 2004; 8(2):160-73.

Palisano RJ, Walter SD, Russell DJ, Rosenbaum PL, Gémus M, Galuppi BE, Cunningham L. Gross motor function of children with Down syndrome: creation of motor growth curves. *Arch Phys Med Rehabil.* 2001; 82(4):494-500.

Parker AW, Bronks R. Gait of children with Down syndrome. *Arch Phys Med Rehabil.* 1980; 61(8):345-51.

Parker SE, Mai CT, Canfield MA, Rickard R, Wang Y, Meyer RE, Anderson P, Mason CA, Collins JS, Kirby RS, Correa A; National Birth Defects Prevention Network. Updated National Birth Prevalence estimates for selected birth defects in the United States, 2004-2006. *Birth Defects Res A Clin Mol Teratol.* 2010; 88(12):1008-16.

Patla AE, Rietdyk S. Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. *Gait Posture* 1993; 1:45–60.

Patla AE, Vickers JN. Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport.* 1997; 8(17):3661-5.

Pearson K, Gramlich R. Updating neural representations of objects during walking. *Ann N Y Acad Sci.* 2010; 1198:1-9.

Raz N, Torres IJ, Briggs SD, Spencer WD, Thornton AE, Loken WJ, Gunning FM, McQuain JD, Driesen NR, Acker JD. Selective neuroanatomic abnormalities in Down's syndrome and their cognitive correlates: evidence from MRI morphometry. *Neurology*.1995; 45(2):356-66.

Rietdyk S. Anticipatory locomotor adjustments of the trail limb during surface accommodation. *Gait Posture.* 2006; 23(3):268-72.

Rigoldi C, Galli M, Albertini G. Gait development during lifespan in subjects with Down syndrome. *Res Dev Disabil.* 2011; 32(1):158-63.

Rigoldi C, Galli M, Cimolin V, Camerota F, Celletti C, Tenore N, Albertini G. Gait strategy in patients with Ehlers-Danlos syndrome hypermobility type and Down syndrome. *Res Dev Disabil.* 2012; 33(5):1437-42.

Rigoldi C, Galli M, Condoluci C, Carducci F, Onorati P, Albertini G. Gait analysis and cerebral volumes in Down's syndrome. *Funct Neurol.* 2009; 24(3):147-52.

Rigoldi C, Galli M, Mainardi L, Crivellini M, Albertini G. Postural control in children, teenagers and adults with Down syndrome. *Res Dev Disabil.* 2011; 32(1):170-5.

Roizen NJ, Patterson D. Down's syndrome. *Lancet.* 2003; 361(9365):1281-9.

Salami F, Vimercati SL, Rigoldi C, Taebi A, Albertini G, Galli M. Mechanical energy assessment of adult with Down syndrome during walking with obstacle avoidance. *Res Dev Disabil.* 2014; 35(8):1856-62.

Sheehan RC, Gottschall JS. Stair walking transitions are an anticipation of the next stride. *J Electromyogr Kinesiol.* 2011; 21(3):533-41.

Shumway-Cook A, Woollacott MH. Dynamics of postural control in the child with Down syndrome. *Phys Ther.* 1985; 65(9):1315-22.

Silverman AK, Neptune RR, Sinitski EH, Wilken JM. Whole-body angular momentum during stair ascent and descent. *Gait Posture.* 2014; 39(4):1109-14.

Snapp-Childs W, Bingham GP. The affordance of barrier crossing in young children exhibits dynamic, not geometric, similarity. *Exp Brain Res.* 2009; 198(4):527-33.

Taga G. A model of the neuro-musculo-skeletal system for anticipatory adjustment of human locomotion during obstacle avoidance. *Biol Cybern.* 1998; 78(1):9-17.

Vallis LA, McFadyen BJ. Children use different anticipatory control strategies than adults to circumvent an obstacle in the travel path. *Exp Brain Res.* 2005; 167(1):119-27.

Vimercati SL, Galli M, Rigoldi C, Albertini G. Obstacle avoidance in Down syndrome. *J Electromyogr Kinesiol.* 2013; 23(2):483-9.

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G. Motor strategies and motor programs during an arm tapping task in adults with Down Syndrome. *Exp Brain Res.* 2013; 225(3):333-8.

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G. Spatiotemporal and kinematic aspects of obstacle avoidance in subjects with Down syndrome. *Funct Neurol.* 2012; 27(4):231-7.

Virji-Babul N, Brown M. Stepping over obstacles: anticipatory modifications in children with and without Down syndrome. *Exp Brain Res.* 2004; 159(4):487-90.

Wang PP, Doherty S, Hesselink JR, Bellugi U. Callosal morphology concurs with neurobehavioral and neuropathological findings in two neurodevelopmental disorders. *Arch Neurol.* 1992; 49(4):407-11.

Wiseman FK, Alford KA, Tybulewicz VL, Fisher EM. Down syndrome--recent progress and future prospects. *Hum Mol Genet.* 2009; 18(R1):R75-83.

Wu J, Ajisafe T. Kinetic patterns of treadmill walking in preadolescents with and without Down syndrome. *Gait Posture.* 2014; 39(1):241-6.

Wu J, Beerse M, Ajisafe T. Frequency domain analysis of ground reaction force in preadolescents with and without Down syndrome. *Res Dev Disabil.* 2014; 35(6):1244-51.

Wu J, Beerse M, Ajisafe T, Liang H. Walking dynamics in preadolescents with and without Down syndrome. *Phys Ther.* 2015; 95(5):740-9.

Wu J, Ulrich DA, Looper J, Tiernan CW, Angulo-Barroso RM. Strategy adoption and locomotor adjustment in obstacle clearance of newly walking toddlers with Down syndrome after different treadmill interventions. *Exp Brain Res.* 2008; 186(2):261-72.

CHAPTER 2

SPATIAL-TEMPORAL GAIT PATTERN AND MOTOR STRATEGY IN CHILDREN WITH AND WITHOUT DOWN SYNDROME WHILE WALKING FROM LEVEL SURFACE TO STAIRS

2.1 Introduction

Down syndrome (DS) is a chromosomal condition associated with a third copy of chromosome 21 (Roizen & Patterson, 2003). The three common clinical features related to neuromuscular function in individuals with DS are muscular hypotonia, ligament laxity, and motor alteration (Roizen, & Patterson, 2003; Palisano, Walter, Russell, et al. 2001; Carmeli, Ayalon, Barchad, et al. 2002; Galli, Rigoldi, Brunner, et al. 2008; Cowley, Ploutz-Snyder, Baynard, et al. 2011). Children with DS usually show lower muscular resistance to passive muscle strength (i.e., muscular hypotonia) than typically developing children. Children with DS also show significantly greater joint laxity than typically developing children (Caselli, Cohen-Sobel, Thompson, et al. 1991). In addition, motor alterations in individuals with DS results in altered co-contraction patterns of agonist and antagonist muscles, balance control deficits, postural instability, and altered movement patterns (Shumway-Cook, & Woollacott, 1985; Aruin, Almeida, Latash, 1996; Almeida, Corcos, & Latash, 1994; Rigoldi, Galli, & Albertini, 2011; Rigoldi, Galli, Mainardi, et al. 2011; Vimercati, Galli, Rigoldi, et al. 2013). Although the cause of reduced muscle strength in individuals with DS is unknown (Carmeli, Kessel, Coleman, et al. 2002; Cowley, Ploutz-Snyder, Baynard, et al. 2010), the combination of ligament laxity, reduced muscle strength and low muscle tone leads to the presence of musculo-skeletal deformities and is associated with the impairment of physical function in individuals with DS (Galli, Rigoldi, Brunner, et al. 2008; Cowley, Ploutz-Snyder, Baynard, et al. 2011).

Due to the presence of an extra chromosome 21, children with DS usually display a significantly delayed developmental trajectory in the motor domain (Palisano, Walter, Russell, et al. 2001). Children with DS often show a “Chaplinesque” gait pattern, with the features of the external rotation of hip, increased flexion and valgus of knee, and the external rotation of the tibia (Roizen & Patterson, 2003; Caselli, Cohen-Sobel, Thompson, et al. 1991). However, preadolescence has been considered as an important developmental period when children with DS display arguably their best motor skills (Ulrich, Haehl, Buzzi, et al. 2004).

Adaptive locomotion is an important motor skill that one needs to successfully negotiate an environment with constraints. Common settings of the environment with constraints include an obstacle, and a staircase, among others. While walking over an obstacle, children with DS walk with a decreased speed and a shorter stride length, and stiffer hips and less stiff ankles, compared to typically developing children (Galli, Rigoldi, Brunner, et al. 2008; Cioni, Cocilovo, Rossi, et al. 2001). Children with DS are able to scale toe clearance and cross an obstacle successfully as typically developing children, but they walk over an obstacle with a shorter stride length and greater step length variability than typically developing children (Virji-Babul & Brown, 2004). Children with DS were found to stop in front of an obstacle for a period between 0.4 second and 4 seconds before crossing the obstacle, whereas typically developing children walked smoothly when approaching an obstacle and stepping over the obstacle (Virji-Babul & Brown, 2004). In addition, individuals with DS walked with a lower maximum foot elevation than the subjects without DS during unobstructed ground walking, but increased the maximum height of foot elevation and reached the values in healthy subjects when walking with an obstacle at the height of 10% of subject's height (Vimercati, Galli, Rigoldi, & Albertini, 2013; Vimercati, Galli, Rigoldi, et al. 2012). In contrast to the number of studies which investigated gait patterns during obstacle negotiation, little study has been conducted to understand locomotor adjustments in children with and without DS while walking from level surface to stairs.

Besides gait pattern, the adoption of motor strategy provides additional information to understand adaptive locomotion. There are only two studies which investigated various motor strategies in children with DS while crossing over an obstacle. Toddlers with DS were found to use a crawling strategy which was more conservative, cautious, and safer, but also effective and successful while crossing an obstacle (Mulvey, Kubo, Chang, & Ulrich, 2011). In addition, toddlers with DS preferred to crawl over an obstacle and continued to crawl after crossing the obstacle, whereas typically developing toddlers preferred to walk over the obstacle, even with some errors (Mulvey, Kubo, Chang, & Ulrich, 2011). Another study examined the effect of treadmill intervention on motor strategy in infants with DS who received either a generalized, lower-intensity training protocol or an individualized, higher-intensity training protocol until they walked independently (Wu, Ulrich, Looper, et al. 2008). It was reported that both groups adopted either a crawling strategy or a walking strategy to cross an obstacle initially. However, a walking strategy became the primary motor strategy about 3 months after the intervention in those who received an individualized, higher-intensity training protocol. In contrast, both crawling and walking strategies were equally used in those who received a generalized, lower-intensity training protocol, until 9 months after the intervention (Wu, Ulrich, Looper, et al. 2008). However, no study has analyzed motor strategy in children with and without DS while walking from level surface to stairs.

The general hypothesis of our proposed study was that children with DS would show a different spatial-temporal gait pattern and motor strategy in comparison to typically developing children while walking from level surface to stairs. Specifically, our hypotheses on the spatial-temporal gait variables were: (1) in the last three steps during the approaching phase, children with DS would decrease their step length and velocity but increase step width, to a greater extent, than typically developing children; (2) prior to clearing the stairs, children with DS would have a longer stance time and a shorter toe-stairs horizontal distance than typically developing children; (3) in the first two steps during the ascent phase, children with DS would produce a greater step width, a lower vertical toe clearance and a slower horizontal toe velocity than typically developing children; and (4) with the increase in the riser height of a staircase, children with DS would reduce, to a greater extent, the values of the aforementioned spatial-temporal variables than typically developing children.

Our hypotheses on motor strategy were: (5) children with DS would use a higher percentage of a crawling strategy but a lower percentage of a walking strategy than typically developing children; and (6) with the increase in the riser height of staircase, children with DS would increase the percentage of a crawling strategy but reduce the percentage of a walking strategy, whereas typically developing children would probably maintain a walking strategy as their dominant strategy.

The proposed study is of great importance given that the stairs are a common setting in residential, educational and recreational environments. The knowledge to be gained from our proposed study, the spatial-temporal parameters and the motor strategy while walking from the level ground to the stairs in children with and without Down syndrome, will advance our understanding on the motor function and the environmentally related locomotion adaptations in children with DS.

2.2 Methods

2.2.1 Subjects

A total of seventeen subjects participated in this study, which included eleven typically developing children (age 7.8±1.6 years; height 130.05±9.51 cm; body mass 29.12±6.35 kg) and six children with Down syndrome (age 9.7±2.1 years; height 126.33±9.81 cm; body mass 33.70±10.68 kg). Children with Down syndrome (DS) were recruited through Down Syndrome Association of Atlanta and local parent support groups of Metro Atlanta area. Typically developing (TD) children were recruited from the local community through advertisements and personal contact. The inclusion criterion was that subjects met the age range of 5-11 years old and was able to walk 10 meter over the level floor without any assistance. The exclusion criteria were that subjects had a history of medical conditions or any known problems, such as other neurologic problems besides Down syndrome, musculoskeletal injury, or uncorrected visual problems that prevent him/her from independent locomotion. Table 1 displayed the characteristics of the subjects in TD and DS groups. The DS and TD groups were not statistically different in age, body height, body mass, and leg length. Results of the t-test were all $p > 0.05$.

Table 1 Characteristics of the analyzed subjects

Group	No.	Gender	Age (years)	Body Height (cm)	Body Mass (kg)	Average leg length (cm)
TD						
	1	M	9.3	139.0	32.0	70.55
	2	M	7.0	131.5	28.0	69.25
	3	M	8.8	141.0	37.0	74.25

4	F	5.5	119.0	23.7	59.05
5	F	9.8	135.0	26.6	69.75
6	M	8.1	131.0	31.0	69.65
7	F	9.3	140.5	33.0	75.25
8	F	5.9	122.5	27.0	65.75
9	F	5.7	111.5	19.5	60.00
10	F	9.3	134.5	40.5	76.25
11	F	7.5	125.0	22.0	66.25
Mean ± SD	-	7.8±1.6	130.05±9.51	29.12±6.35	68.73±5.66
DS					
1	F	10.3	130.5	43.0	66.10
2	M	10.7	131.0	29.0	70.50
3	M	11.8	132.0	51.0	70.50
4	F	5.3	113.0	22.0	59.0
5	F	8.8	115.0	22.0	62.25
6	F	11.0	136.5	35.2	71
Mean ± SD	-	9.7±2.1	126.33±9.81	33.70±10.68	66.56±5.03

The research protocol was approved by the Institutional Review Board (IRB) of Georgia State University. The stamped Parent Permission Forms were signed by the parent/guardian of each subject, along with the subject's verbal assent, prior to participation in this study.

2.2.2 Experimental Instrumentations

This study was conducted at the Biomechanics Laboratory of Georgia State University. The experimental equipment for this study consisted of:

1) 10-meter level walk-way: This walkway on the ground of Biomechanics Lab was used for all the walking experiments in this study (Figure 1).

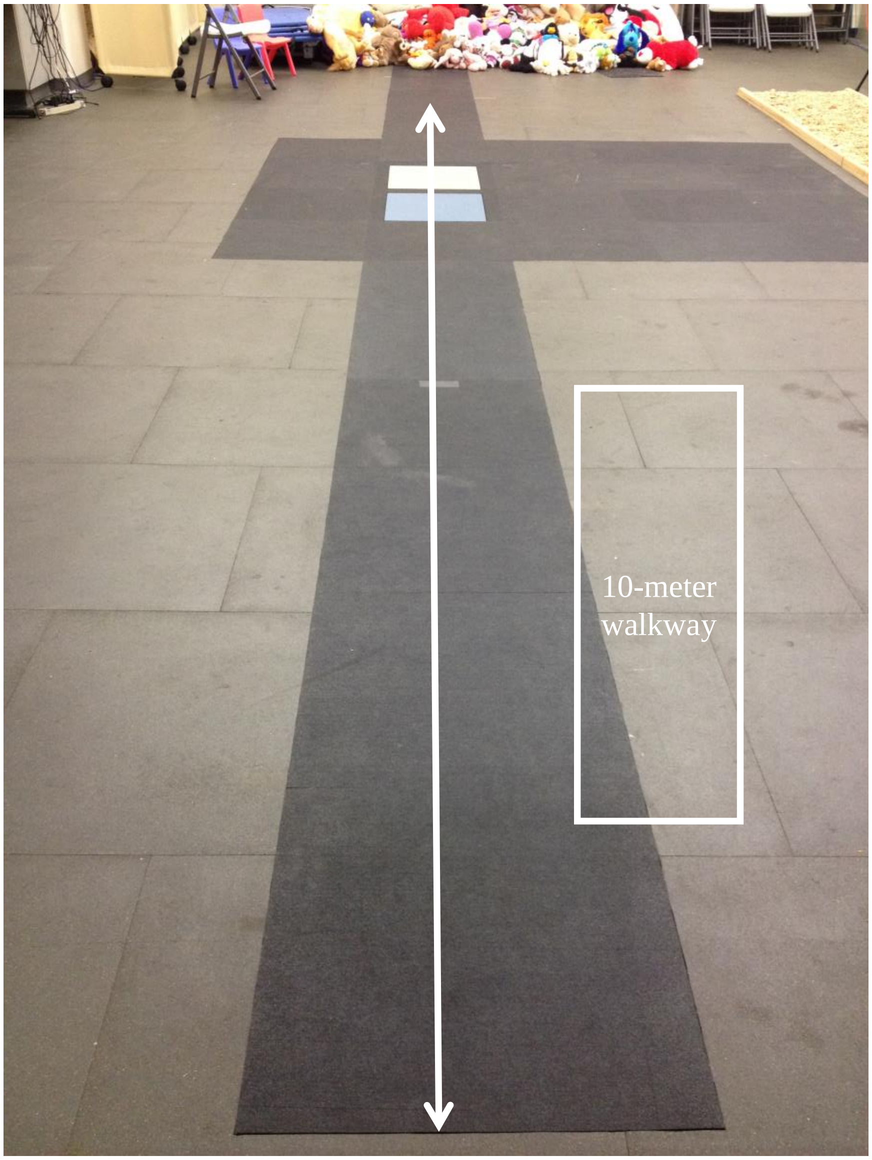


Figure 1 Lab setting: level walkway

2) Three three-step wooden staircases: Three staircases used for the walking experiments in this study were made of wood and without handrails (Figure 2). Each of the three-step staircases was made as a standard tread depth of 26 cm and a width of 86 cm (Oh-Park, Wang, & Verghese, 2011). The height of the experimental staircases was designed with

three different levels of riser height (Oh-Park, Wang, & Verghese, 2011; Chen, Ashton-Miller, Alexander, & Schultz, 1991; Spanjaard, Reeves, van Dieën, et al. 2008): a low height staircase (LS) with the raiser height of 17 cm, a medium height staircase (MS) with the riser height of 24 cm, and a high height staircase (HS) with the riser height of 31 cm. The MS condition was slightly higher than a common riser height of 20cm at residential places in the United States. The low- and high- heights of the staircases are 30% below and above the medium height, respectively. Therefore, the LS and MS conditions were slightly lower and higher, respectively, than a common riser height of 20 cm at residential places; whereas, the HS condition was markedly higher than the common riser height of 20 cm. During the walking experiments, the staircase was placed at the end of the 5-meter level walkway, 5cm away from the edge of the second force plate in the walking direction (Figure 3).

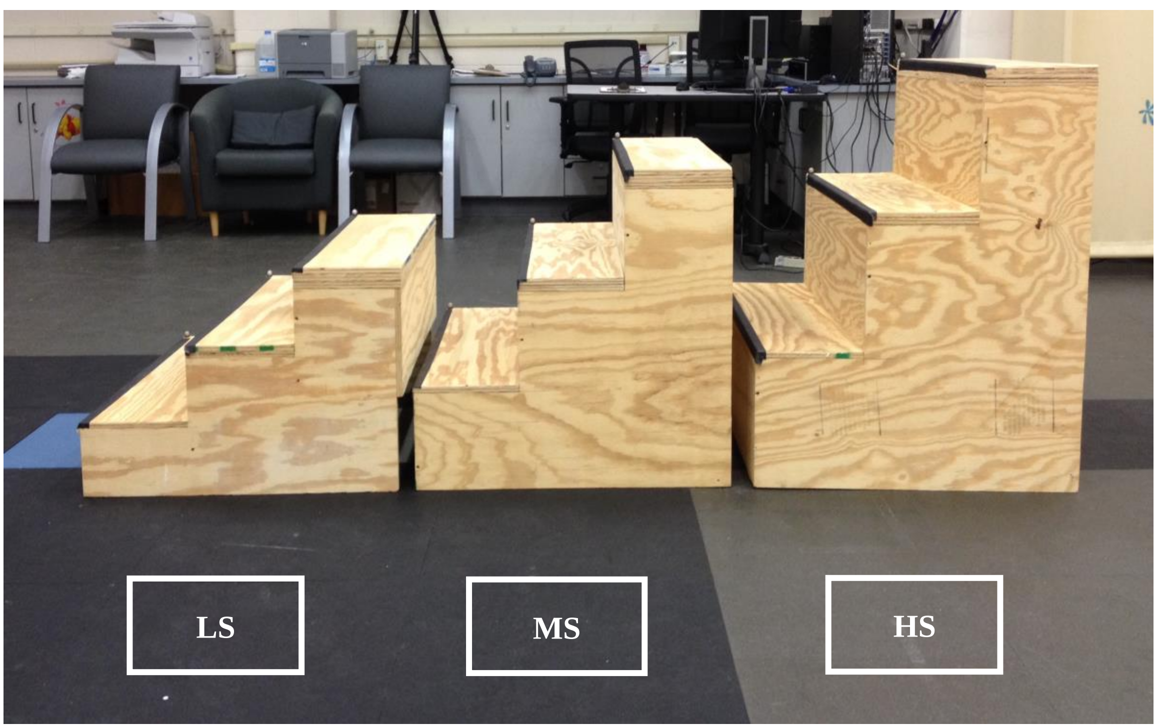


Figure 2 Lab setting: three staircases.

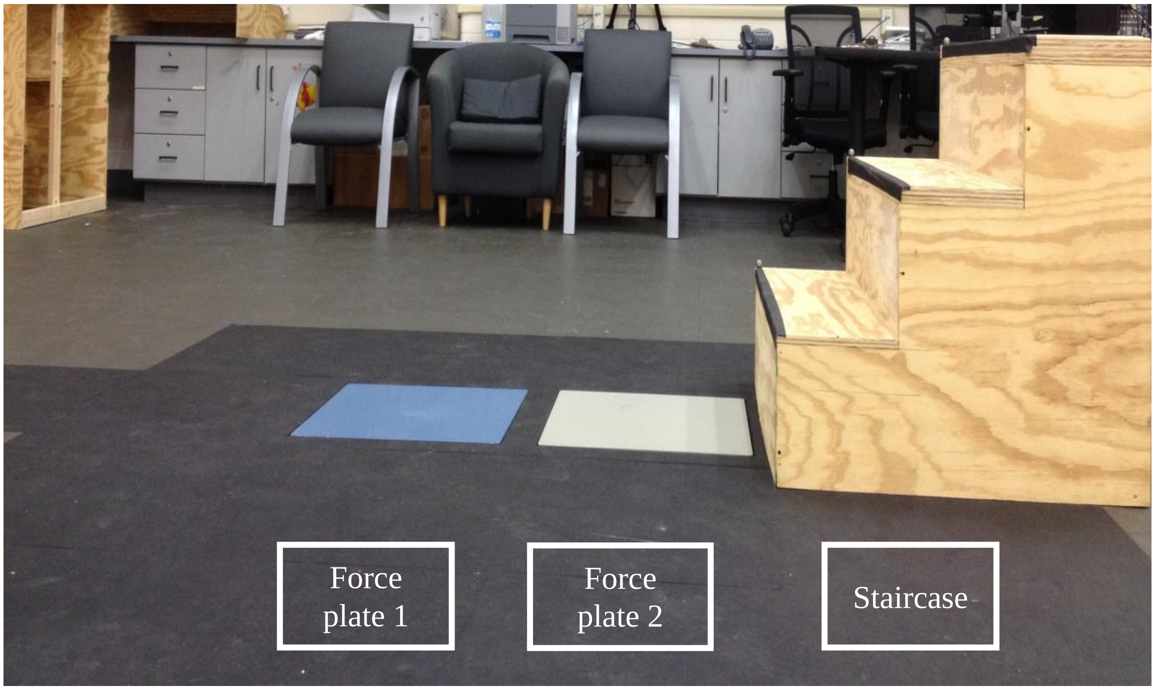


Figure 3 Lab setting: the placement of the staircase

3) Vicon Motion Capture System (Oxford Metrics Ltd., Oxford, UK): In this study, a Vicon system equipped with eight infrared cameras was used to collect three-dimensional kinematic data at the frequency of 100 Hz. We placed 35 reflective markers on the subject for data capture and used the whole body Plug-In-Gait Model of Vicon Nexus 2.3.

4) AMTI force plates (Advanced Mechanics Technology Inc., Watertown, MA): Two AMTI force plates were embedded on the ground walk-way (Figure 3), adjoined and separated by 8.9 cm, in order to identify gait events (i.e., foot-strike and foot-off). Data from both force plates were collected at a frequency of 1000 Hz and synchronized with the kinematical data by the Vicon motion capture system.

5) Vicon Nexus software (Oxford Metrics Ltd., Oxford, UK): Vicon Nexus 2.2.3 was used for the kinematic data processing.

6) MATLAB (The Mathworks, Inc., Natrick, MA): Customized MATLAB programs were developed to calculate spatial-temporal gait parameters.
7) SAS (Cary, NC): SAS statistical software was used for all the statistical analysis in this study.

2.2.3 Experimental Procedures

There were five steps for the data collection for each subject.

Step 1: Sign the Informed Consent Form

After the child and his/her parent(s) arrived at GSU Biomechanics Laboratory, the principal investigator explained this study in detail to each subject and the subject's parent, including the purpose, the procedures, associated risks and benefits, voluntary participation and withdrawal, and confidentiality of this study. The subject and the parent were free to ask any questions throughout the study. When they agreed to participate in the study, the subject's parent signed the informed consent form, and the subject gave the oral assent.

After the completion of the consent process, male subjects changed the clothes to compression shorts, and female subjects wore a bathing suit to facilitate the placement and visibility of reflective markers for data collection.

Step 2: Anthropometric Measurements

We used a scale with a height rod to measure subjects' body height (cm) and body mass (kg). Then, we used a tape measure and caliper to register subjects' anthropometric measurements, including left and right shoulder offset (cm), left and right elbow width (cm), left and right wrist width (cm), left and right hand thickness (cm), left and right knee width (cm), left and right ankle width (cm), left and right leg length (cm), and the inter-ASIS distance (cm), according to Vicon Plug-In-Gait model (Figure 4).

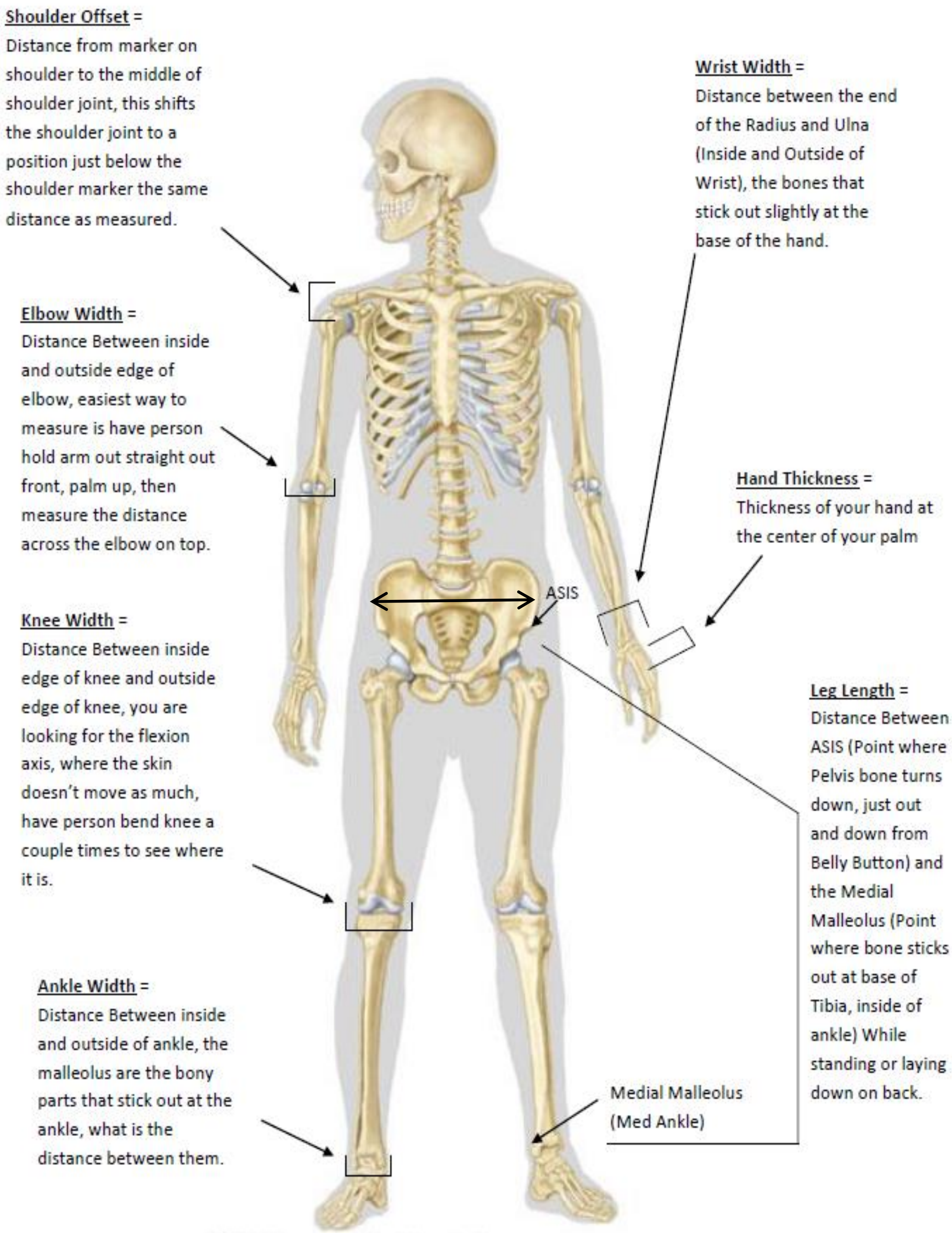


Figure 4 Plug-In-Gait Measurements

Step 3: Markers Placement

This study followed Vicon Plug-In-Gait Marker Placement Model (Figure 5) to place reflective markers (14 mm) on subjects' body.

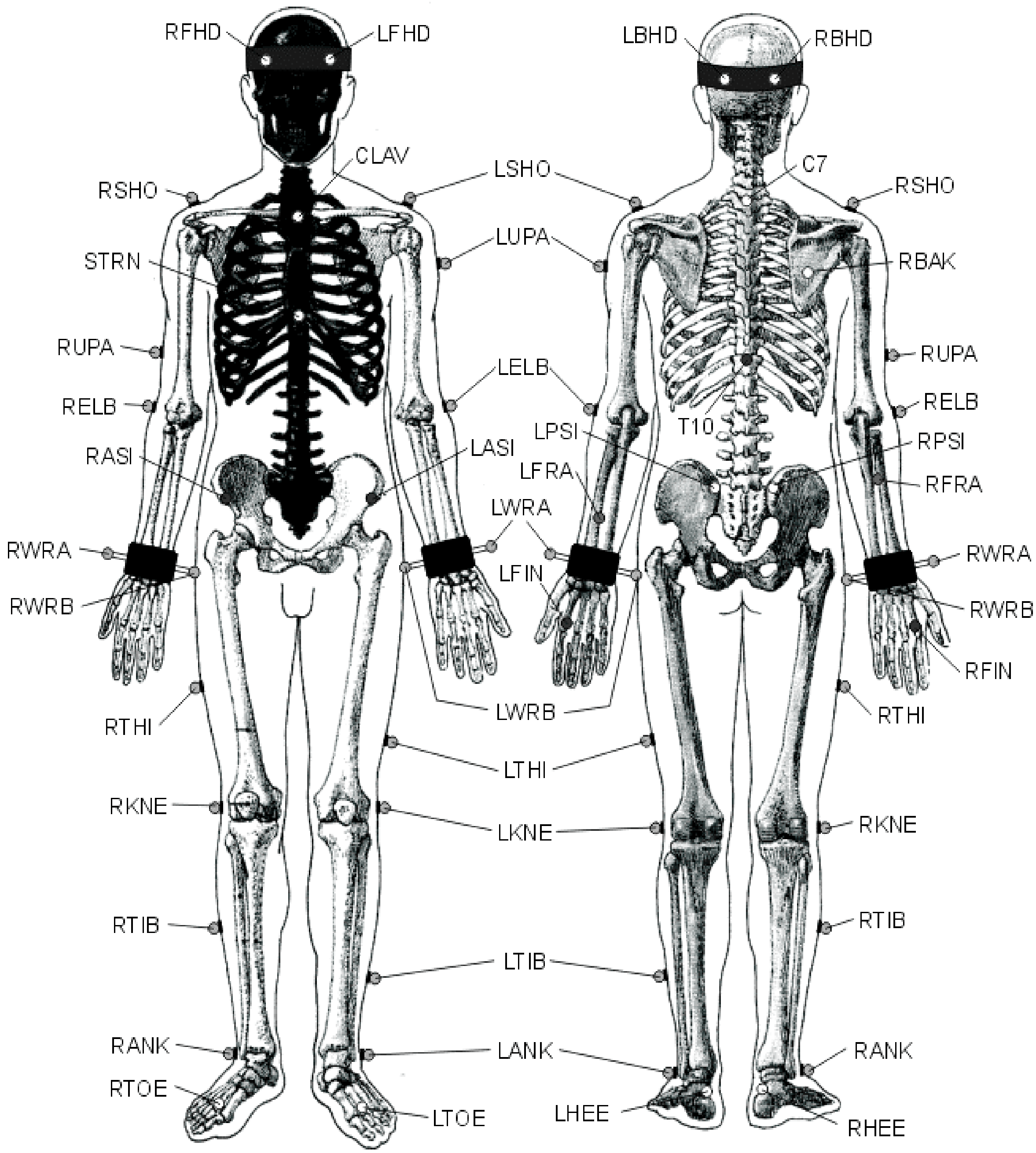


Figure 5 Plug-In-Gait Marker Placements

Firstly, we used a black eyebrow pencil to mark 25 anatomical landmarks of subject's body: 7th cervical vertebrae, 10th thoracic vertebrae, clavicle, sternum, right back, left and right shoulder marker, left and right elbow, left and right wrist marker on the thumb side, left and right wrist marker on the pinkie side, left and right finger, left and right knee, left and right shank, left and right ankle, left and right heel, left and right toe. The reflective markers were placed on these pencil-marked positions. Next, a black adhesive tape was adhered to the clothes surfaces, corresponding to subject's these 6 positions: left and right anterior superior iliac spine, left and right posterior superior iliac spine, left and right thigh. Lastly, the subject was asked to wear a head band. Four reflective markers were placed on the head band, corresponding to the locations of left and right front head, left and right back head. Therefore, a total of 35 anatomical landmarks, as indicated in Figure 3, except for left and right upper arm marker and left and right forearm marker, were placed on with reflective markers for this study.

Nine reflective markers were placed on each step of each three-step staircase to define the location of each step of the staircases.

Step 4: Data Capture

Before the data capture of the walking experiments, we completed the calibration for the Vicon system and the subject.

Each subject walked on barefoot at their preferred pace over a 5-meter unobstructed level walkway to a three-step staircase and then moved up to the staircase with their preferred strategy. Our study included three stair height conditions: LS, MS, and HS. The presentation order of three staircases was randomized across subjects.

Under each staircase condition, each subject practiced his/her walking once before the data capture. At least five valid trials were captured. A trial was deemed valid if the subject walked a few meters to the presented staircase and then moved up the stairs. The subjects were provided with verbal encouragement while ascending the stairs. After walking under one stairs height condition was completed, the subjects took an adequate rest before performing under the next stairs height condition. The total time of participation for this study was 60 minutes.

Step 5: Data Processing

Raw marker data recorded with the Vicon system were digitized in Vicon Nexus 2.2 and then exported as Excel spreadsheets for Matlab processing. Spatial-temporal gait parameters were calculated with customized Matlab programs for each walking trial. Then, the data of each dependent variable of each subject were averaged over the trials under each staircase condition.

For each subject, the type of motor strategies adopted while negotiating the stairs in each trial was analyzed, and the percentage of each motor strategies was calculated across the trials under each staircase condition.

2.2.4 Outcome Measures

The outcomes measures of this study included two parts: 1) motor strategy, 2) spatial-temporal gait pattern. The dependent variable relevant to motor strategy was the percentage of each motor strategy. The dependent variables related to the spatial-temporal parameters included step width, step length, step time, step velocity, stance time, toe-stairs horizontal distance, vertical toe clearance above the edge of stairs, and horizontal toe velocity above the edge of stairs.

In order to measure these outcomes, five steps (i.e. step -3, step -2, step -1, step 1, and step 2) (Figure 6) were identified from walking over the ground to going up he stairs for each trial. And these five steps divided the walking from level surface to stairs into two phases: (1)

walking over the ground to the front of the staircases (i.e. the approaching phase), which corresponded to steps -3, step -2, and step -1, (2) going up the staircases (i.e. the ascent phase), which corresponded to steps 1 and step 2 (Figure 6). At the ascent phase, the lower limb which walked up from the ground to the stairs first (i.e. ascending to the stairs at step 1) was defined as the leading limb, whereas the other lower limb which followed to walk up from the ground to the stairs (i.e. ascending to the stairs at step 2) was the trailing limb. Two gait events (i.e. foot-strike and foot-off) were identified in each step based on the heel and toe markers, respectively. Each step was defined by the two consecutive foot-strikes, i.e., heel-contact to heel-contact during the approaching phase and heel-contact to toe-contact during the ascent phase (Figure 6).

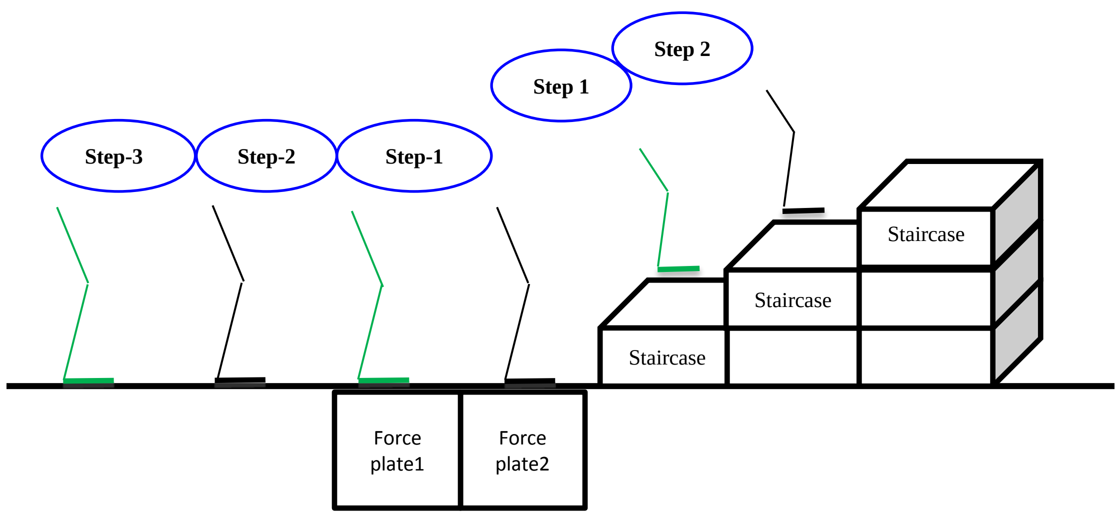


Figure 6 A schematic diagram of the five steps while walking from the level surface to stairs

2.2.4.1 Motor strategy

Based on possible motor strategies categorized in previous studies with children with DS while negotiating an obstacle (Mulvey, Kubo, Chang, & Ulrich, 2011; Wu, Ulrich, Looper, et al. 2008), our study categorized four types of motor strategy while walking from level surface to stairs: failure, crawling, step-on-step walking, and step-over-step walking (Table 2).

Generally, a strategy of failure was defined if a subject employed avoidance (i.e., refuse to go up the stairs) or made errors while walking up the stairs. A crawling strategy was defined when the subject placed his/her hands on the staircase and moved his/her feet up the stairs. Two walking strategies were defined depending on the placement of feet on each step of the staircase. A step-on-step strategy was defined such that the subjects placed both feet on each step of the staircase before going up to the next step of the staircase. A step-over-step walking strategy was defined such that the subject placed one foot on each step of the staircase; in other words, no two feet were on the same step of the staircase.

Table 2 Categories of motor strategy at the ascent phase

	Categories	Description
i.	Failure	1) Avoidance: approach to a staircase, but stop in front of the staircase or walk away from the staircase without elevate the leg from the ground upward to the stairs. 2) Errors: failed to scale toe clearance of the swinging foot with the height of staircase, when walking from level ground to stairs.
ii.	Crawling	3) Crawling: accomplish walking from level ground to stairs, with the assistance of continuously putting hand(s) on a staircase.
iii.	Step-on-step walking	4) Step-on-step walking: successfully walk from level ground to stairs by placing both feet on each step of a staircase before going up to the next step, without hand(s) on a staircase for

		assistance.
iv.	Step-over-step walking	5) Step-over-step walking: successfully walk from the ground up to stairs by placing one foot on each step of a staircase at a time, without hand(s) on a staircase for assistance.

For each subject, the percentage of each type of motor strategy in each walking condition was calculated. Then, the percentage of each type of motor strategy in each walking condition in each group was calculated, which were expected to indicate the difference of motor strategy used for walking from the level surface to stairs in children with and without Down syndrome. We focused on the last three motor strategies (i.e., crawling, step-on-step walking, and step-over-step walking) between children with and without DS, since no failure strategy was found from any subject in our study.

2.2.4.2 Spatial-temporal Gait Parameters

Spatial-temporal gait parameters in step -3, step -2, and step -1 would reveal the possible anticipatory locomotor adjustments (ALAs) during the approaching phase while walking from level surface to stairs in children with and without Down syndrome. Spatial-temporal gait parameters in step 1 and step 2 would show the biomechanical pattern of stairs negotiation during the ascent phase. All spatial-temporal gait parameters were computed from the markers' coordinates during the walking trials.

- Step width (mm): Step width was defined as the distance in medio-lateral direction between two consecutive foot-strike events of the opposite legs, which was computed as the medio-lateral distance between the heel markers at two consecutive foot-strikes events (Figure 7) (Salami, Vimercati, Rigoldi, et al. 2014). There were five data of step width in each walking trial.

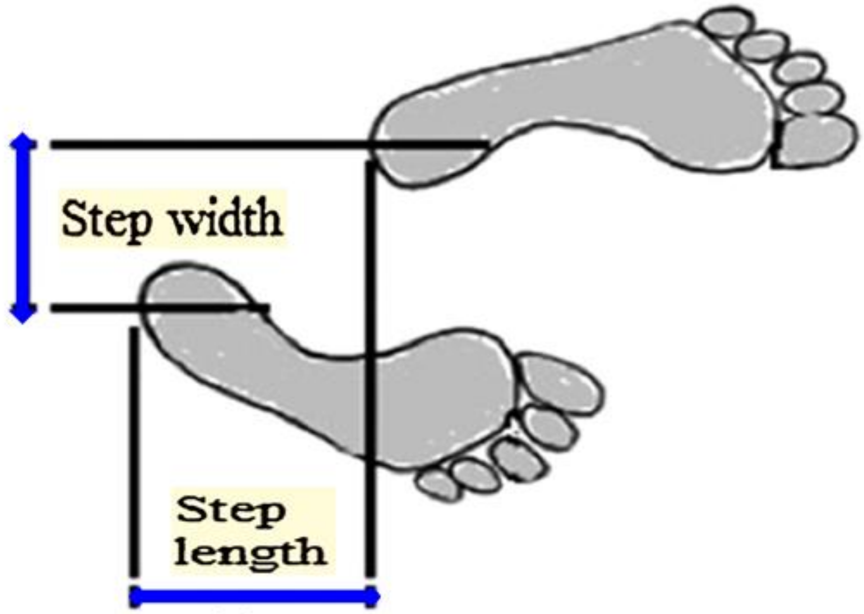


Figure 7 Definitions of step width and step length during walking

- Step length (mm): Step length was defined as the distance in antero-posterior direction between two consecutive foot-strikes of the opposite legs, which was computed as the antero-posterior distance between the heel-markers of two legs at two consecutive foot-strike events (Figure 7). There were five data of step length in each walking trial. Step length measured the presence of step adaptations (i.e. step shortening or lengthening strategy) (Chen, Ashton-Miller, Alexander, & Schultz, 1991; Weerdesteyn, Nienhuis, & Duysens, 2005).
- Step time (second): Step time was defined as the time duration between two successive foot-strike events of the opposite legs. There were five data of the step time in each walking trial.

- Step velocity (mm/s): Step velocity was calculated as step length over step time for each step. There were five data of the step velocity in each walking trial.
- Stance time (second): For each stride, stance time was measured. Stance time was defined as the time duration between foot-strike event and the subsequent foot-off event of one same leg. The stance time corresponding to step -2 indicated how long the leading limb prepared for its stairs ascending movement, whereas the stance time corresponding to step -1 displayed how long the trailing limb supported for the leading limb to walk simultaneously forward and upward from the ground to the 1^{st} step of the staircase.
- Toe-stairs horizontal distance (mm): Toe-stairs horizontal distance was defined as the antero-posterior distance from the toe of leading limb (d_1) at step 1 or trailing limb (d_2) at step 2 before they initiated the ascent walking from the level ground to the stairs to the staircase (Figure 8). Toe-stairs horizontal distance displayed the placement of two feet in front of the stairs for going up the stairs, which indicated how subjects prepared for their subsequent stairs ascending locomotion.

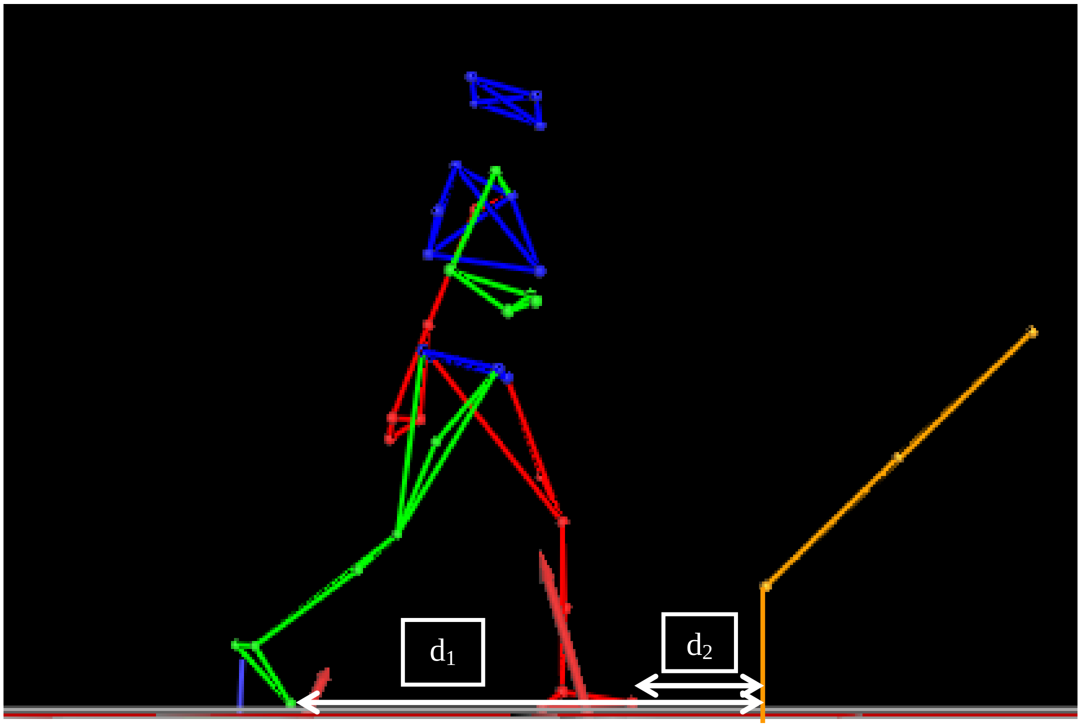
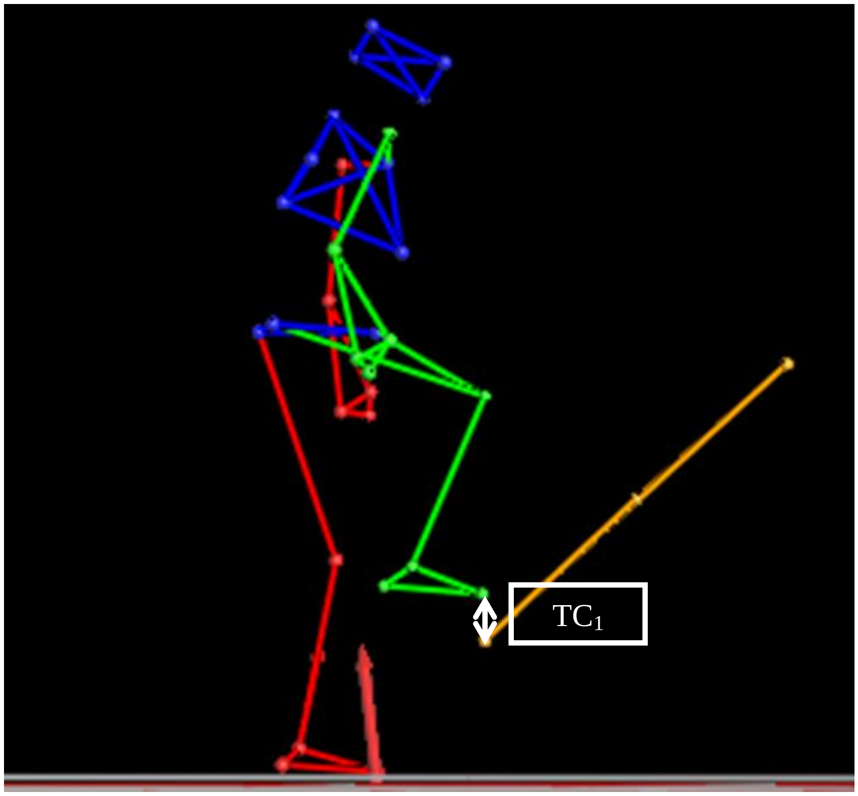


Figure 8 Toe-stairs horizontal distance from the leading limb (d_1) and the trailing limb (d_2)

- Toe clearance above the edge of stairs (mm): Toe clearance above the edge of stairs was the relative toe clearance of the ascending foot to the stairs. It was defined as the difference between the vertical height of the toe when it swung right above the outer edge of a tread of the staircase which it would step on and the vertical height of the outer edge of that step of the staircase. Toe clearance above the edge of stairs measured during step 1 (TC_1) represented that of the leading limb, and toe clearance above the edge of stairs measured during step 2 (TC_2) represented that of the leading limb (Figure 9). Toe clearance above the edge of stairs indicated the ability of subjects to estimate stairs height and the "safety" margin adopted by subject (Chou, Draganich, & Song, 1997) during walking stairs.

a)



b)

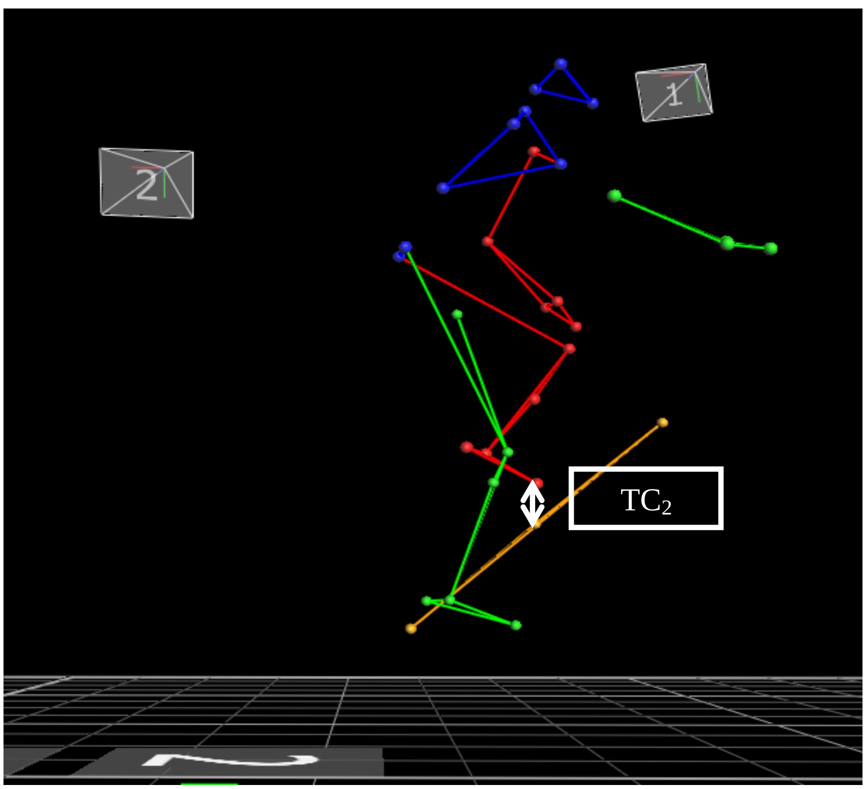


Figure 9 Toe clearance above the edge of stairs from (a) the leading limb and (b) the trailing limb.

- Horizontal toe velocity above the edge of stairs (mm/s): It was calculated as the instantaneous horizontal velocity of toe above the edge of stairs.

2.2.5 Statistical Analysis

For motor strategy, the percentages of crawling, step-on-step walking, and step-over-step walking strategy were described in each of the two groups under each of the three stairs height conditions.

For spatial-temporal variables, at the approaching phase, three-way mixed ANOVAs (2 group × 3 stairs × 3 step) with repeated measures were conducted on step width, step length, step time, step velocity, and stance time. At the ascent phase, three-way mixed ANOVAs (2 group × 3 stairs × 2 step) with repeated measures were conducted on the aforementioned spatial-temporal variables as well as toe-stairs horizontal distance, toe clearance above the edge of stairs, and horizontal toe velocity above the edge of stairs. Post Hoc analysis with Bonferroni adjustments were carried out when necessary. The significance level of this study was set at alpha $\leq$.05.

2.3 Results

2.3.1 Spatial-temporal parameters at the approaching phase

Table 3 Spatial-temporal gait parameters (Mean ± Standard deviation) at the approaching phase

Gait parameters	Stair height	Step	Group TD	Group DS	F value, significance
Step width (mm)					
	LS	-3	104.21+24.92	131.68±50.02	
		-2	68.07±23.95	132.31±34.69	Main effect of group ($F(1, 15) = 15.05$, $p = 0.0015$);
		-1	63.61±25.37	136.13±62.37	
	MS	-3	93.37±29.48	119.85±48.33	Main effect of step ($F(2, 30) = 6.11$, $p = 0.0059$);
		-2	77.68±18.30	115.22±37.33	
		-1	68.92±22.61	133.32±44.02	Interaction effect of group and step ($F(2, 30) = 12.92$, $p < 0.0001$).
	HS	-3	97.80±34.83	117.83±32.30	
		-2	68.38±21.88	116.44±27.57	
		-1	50.82±16.25	129.66±51.30	
Step length (mm)					
	LS	-3	570.82±52.10	443.30±58.42	
		-2	564.24±67.47	323.44±103.09	Main effect of group ($F(1, 15) = 62.35$, ($p < 0.0001$);
		-1	566.55±49.14	274.59±101.54	
	MS	-3	561.77±77.71	430.01±81.30	Main effect of step ($F(2, 30) = 30.41$, $p < 0.0001$);
		-2	549.36±70.16	331.95±115.25	
		-1	560.50±52.62	280.58±84.58	Interaction effect of group and step ($F(2, 30) = 26.93$, $p <$
	HS	-3	572.46±58.87	414.00±44.60	

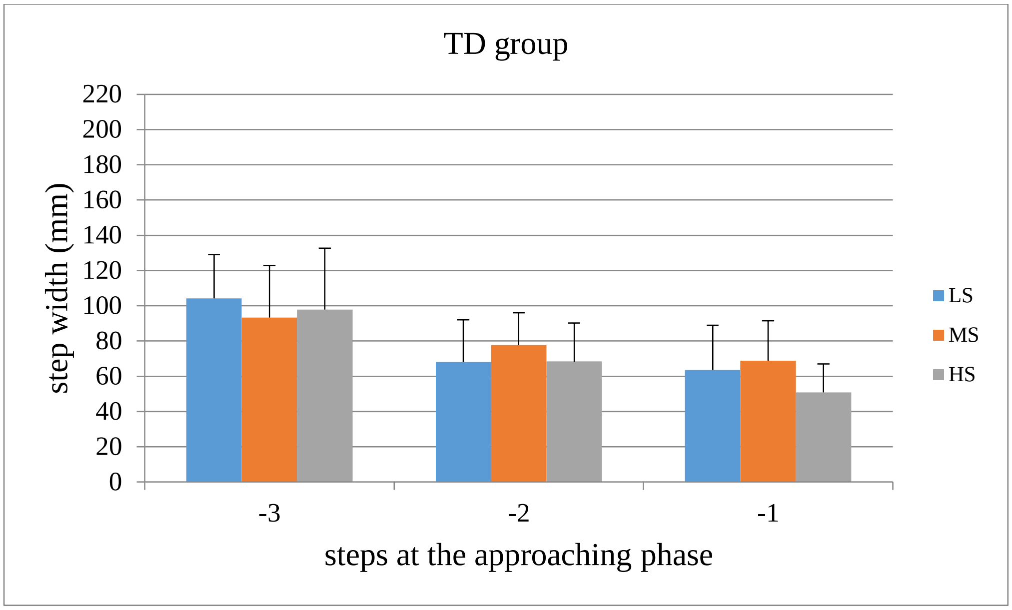
	-2	555.64±75.12	332.51±113.06	0.0001).
	-1	567.67±51.05	246.59±106.35	
Step time (second)				
LS	-3	0.43±0.03	0.42±0.04	Main effect of stair height (F (2, 30) = 4.91, p = 0.0143)
	-2	0.44±0.04	0.44±0.08	
	-1	0.44±0.04	0.43±0.06	
MS	-3	0.42±0.04	0.42±0.05	
	-2	0.43±0.05	0.41±0.07	
	-1	0.44±0.05	0.43±0.07	
HS	-3	0.44±0.05	0.43±0.06	
	-2	0.46±0.05	0.42±0.08	
	-1	0.48±0.05	0.47±0.09	
Step velocity (mm/second)				
LS	-3	1351.93±156.83	1092.60±212.11	Main effect of group (F (1, 15) = 35.08, (p < 0.0001); Main effect of step (F (2, 30) = 34.50, p < 0.0001); Stair height main effect (F (2, 30) = 4.36, p = 0.0217); Interaction effect of group and step (F (2, 30) = 18.50, p < 0.0001).
	-2	1292.75±154.59	792.26±231.43	
	-1	1313.57±170.32	645.39±268.03	
MS	-3	1337.05±151.29	1077.78±315.17	
	-2	1282.88±184.30	852.41±360.13	
	-1	1281.12±150.84	682.42±306.28	
HS	-3	1294.37±159.50	990.65±216.16	
	-2	1225.76±168.58	802.71±265.89	
	-1	1191.67±145.11	531.77±241.20	
Stance time (second)				
LS	-3	0.50±0.06	0.54±0.09	Main effect of group (F (1, 15)

	-2	0.50±0.05	0.59±0.11	= 6.89, p = 0.0191);
	-1	0.56±0.07	1.14±0.62	Main effect of step (F (2, 30) =
MS	-3	0.49±0.06	0.50±0.10	83.31, p < 0.0001);
	-2	0.50±0.06	0.52±0.11	Main effect of stair height (F (2,
	-1	0.61±0.13	1.07±0.47	30) = 6.67, p = 0.0040);
HS	-3	0.52±0.06	0.52±0.06	Interaction effect of group and
	-2	0.55±0.06	0.69±0.28	step (F (2, 30) = 35.02, p <
	-1	0.76±0.16	1.36±0.70	0.0001).

2.3.1.1 Step width at the approaching phase

Over the last three steps at the approaching phase, the DS group displayed a different pattern in step with compared to the TD group (Figure 10) (Table 3). The average step width in the DS group was 125.8 mm across the three stair heights, compared to 77.0 mm in TD group. While the TD group decreased step width from 98.5 mm at step -3, to 71.4 mm at step -2 and to 61.1 mm at step -1, the DS group maintained step width around 125 mm at all three steps. Statistical analysis revealed that there was a group by step interaction (F (2, 30) = 12.92, p < 0.0001). Post-hoc analysis reported that in the TD group, step width at both step -2 and step -1 was less than that at step -3. In contrast, in the DS group, there was no significant difference of step width among all three steps at the approaching phase. When comparing step width between the TD and DS groups, no significant difference was found at step -3, but step width was significantly greater in the DS group than the TD group at step -2 and step -1.

Both groups produced similar patterns of step width under each stair height condition in the last three steps of the approaching phase. Statistical analysis found neither a significant main effect of stairs height nor any interaction effect relevant to stair height.



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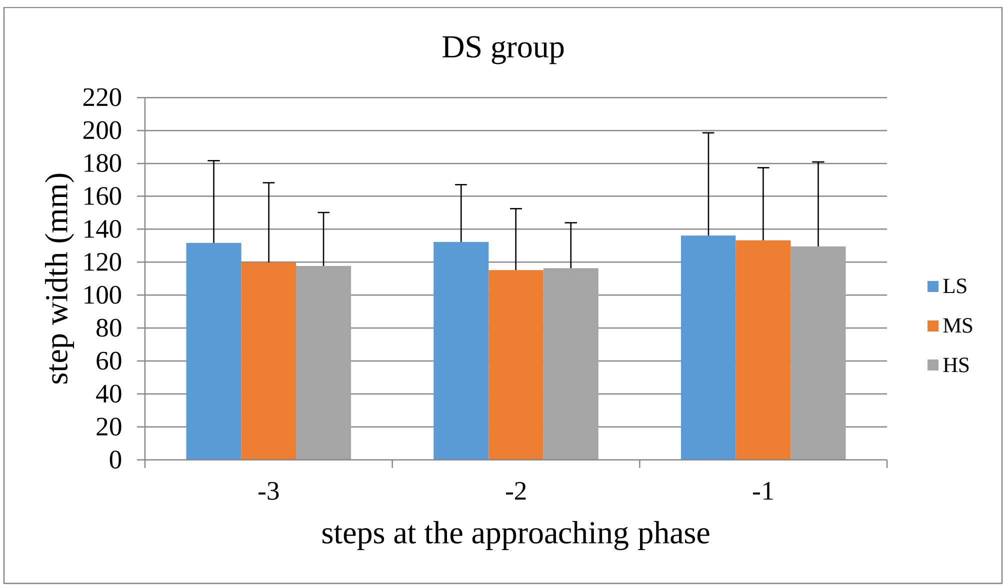


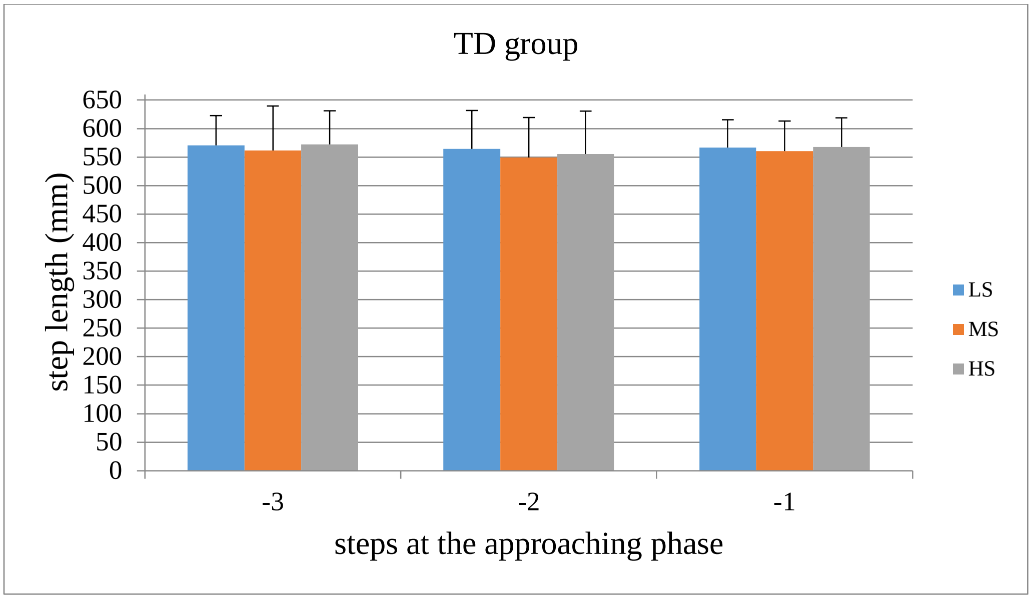
b)

Figure 10 Step width at the approaching phase in (a) TD group and (b) DS group

2.3.1.2 Step length at the approaching phase

Over the last three steps at the approaching phase, the DS group showed a different pattern in step length compared to the TD group (Figure 11) (Table 3). The average step length in the DS group was 341.9 mm across the three stair height conditions, compared to 563.2 mm in the TD group. While the TD group maintained step length around 560 mm over the last three steps at the approaching phase, the DS group decreased step length from 429.1 mm at step -3 to 329.3 mm at step -2 and to 267.3 mm at step -1. Statistical analysis revealed that there was a group by step interaction ($F (2, 30) = 26.93$, $p < 0.0001$). Post-hoc analysis reported that in the DS group, step length significantly decreased in sequence at the last three steps at the approaching phase. In contrast, in the TD group, there was no significant difference of step length among all those three steps. When comparing step length between the two groups, the DS showed a significantly shorter step length than the TD group at each of the last three steps at the approaching phase.

Both groups produced similar patterns of step length under each stairs height condition in the last three steps of the approaching phase. Statistical analysis reported neither a significant main effect of stairs height nor any interaction effect relevant to stairs height.



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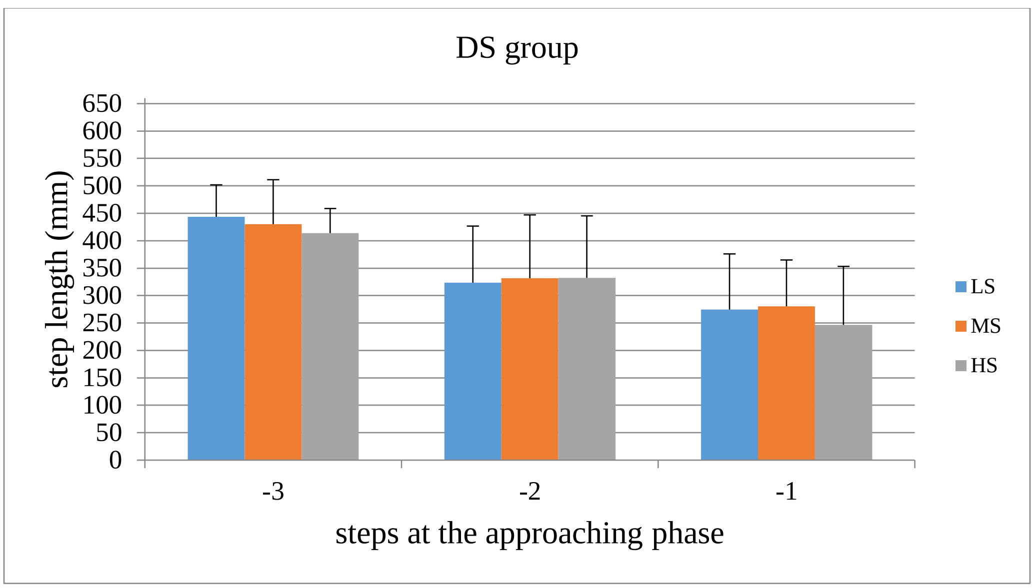

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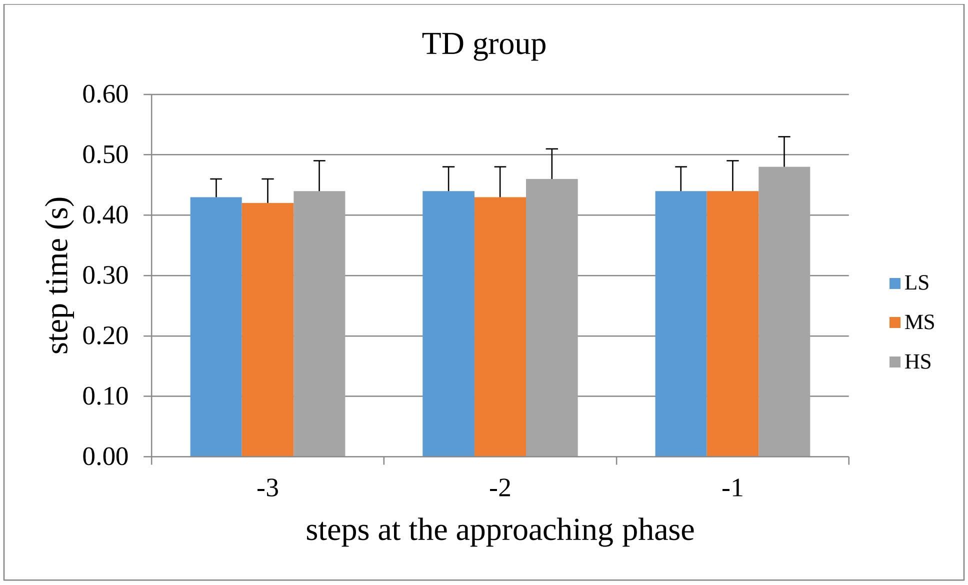
Figure 11 Step length at the approaching phase in (a) TD group and (b) DS group

2.3.1.3 Step time at the approaching phase

Both the TD and DS groups showed a similar step time across the last three steps at the approaching phase, and produced a longer step time while negotiating the highest stairs (Figure 12) (Table 3). Across the two groups, step time was 0.43 seconds under the LS condition, 0.43 seconds under the MS condition, and 0.45 seconds under the HS condition. Statistical analysis reported that there was a main effect of stairs height ($F (2, 30) = 4.94$, $p = 0.0143$). Post-hoc analysis revealed that across the two groups, step time under the HS condition was significantly longer than that under the MS condition.

On average, step time in the DS group was 0.43 seconds at step -3, 0.42 second at step -2 and 0.44 seconds at step -1. The average step time in the TD group was 0.43 seconds at step -3, 0.44 seconds at step -2 and 0.45 seconds at step -1. Statistical analysis identified neither a significant main effect of group or step, nor any interaction effect on step time.

a)



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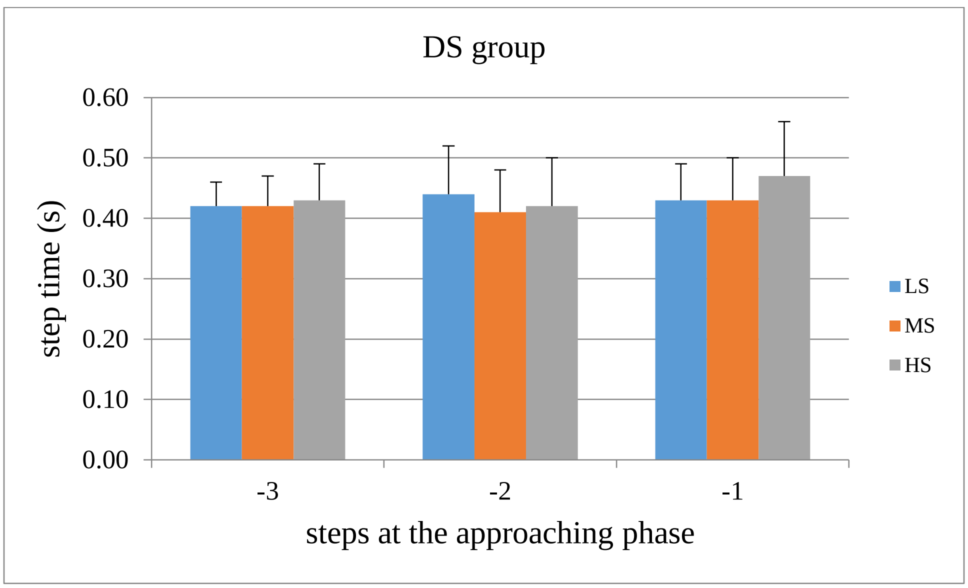
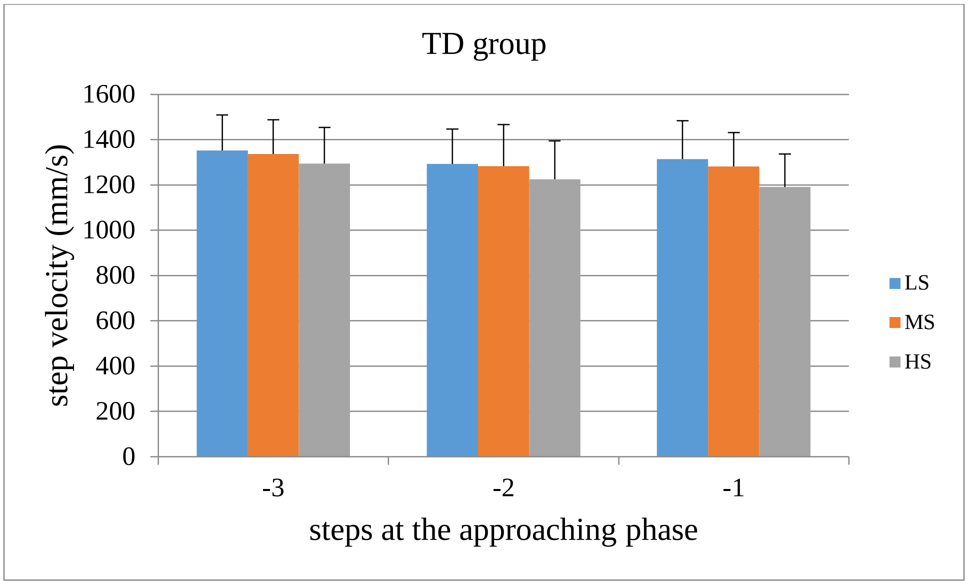


Figure 12 Step time at the approaching phase in (a) TD group and (b) DS group

2.3.1.4 Step velocity at the approaching phase

Over the last three steps at the approaching phase, the DS group displayed a different pattern in step velocity in comparison to the TD group (Figure 13) (Table 3). The average step velocity in the DS group was 829.8 mm/second across the three stair height conditions, compared to 1285.7 mm/second in the TD group. While the TD group maintained step velocity around 1285 mm/second from step -3 to step -1, the DS group showed a continuously decreased step velocity from 1053.7 mm/second at step -3 to 815.8 mm/second at step -2, and to 619.9 mm/second at step -1. Statistical analysis revealed that there was a group by step interaction on step velocity ($F(2, 30) = 18.50$, $p < 0.0001$). Post-hoc analysis reported that in the DS group, step velocity significantly decreased in sequence from step -3 to step -1. In contrast, in the TD group, there was no significant difference of step velocity among the last three steps at the approaching phase. When comparing step velocity between the two groups, the DS group produced a significantly slower step velocity than the TD group at each of the last three steps during the approaching phase.

Both groups walked at a slower velocity while negotiating the highest staircase. Across the two groups, average step velocity was 1081.4 mm/second under the LS condition, 1085.6 mm/second under the MS condition, and 1006.2 mm/second under the HS condition. Statistical analysis revealed that there was a main effect of stair height ($F(2, 30) = 4.36$, $p = 0.0217$). Post-hoc analysis reported that step velocity was significantly lower under the HS conditions than under the LS or MS conditions.



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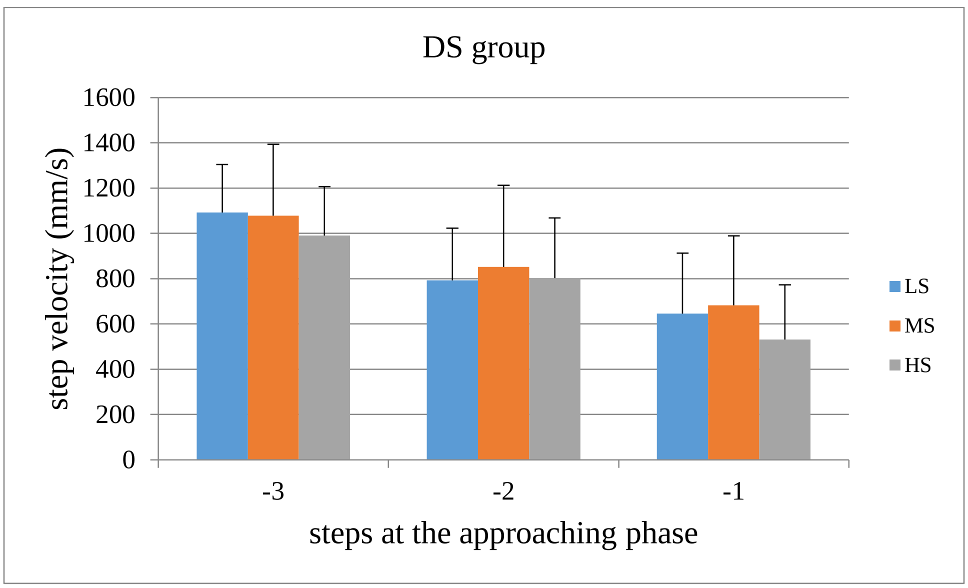


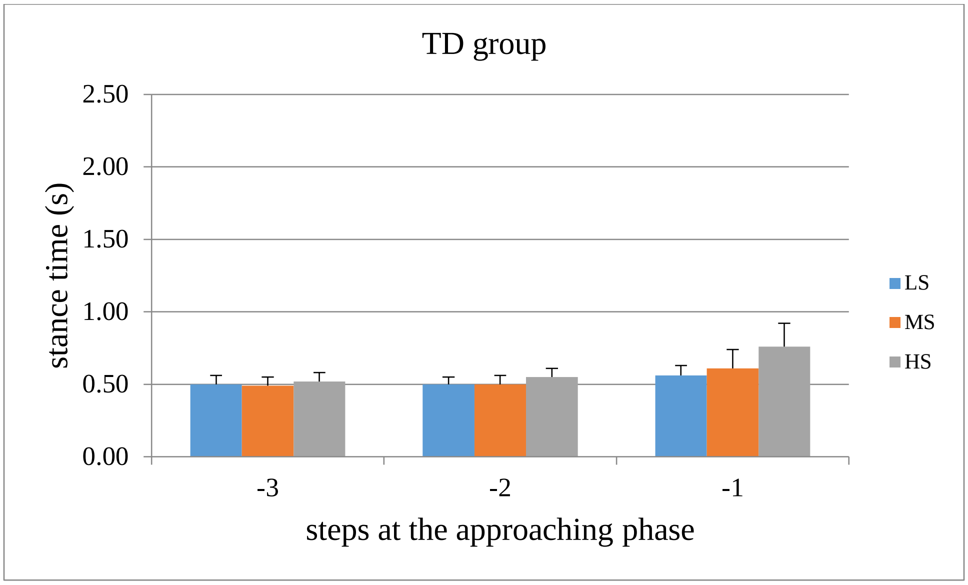
b)

Figure 13 Step velocity at the approaching phase in (a) TD group and (b) DS group

2.3.1.5 Stance time at the approaching phase

Over the last three steps at the approaching phase, the DS group displayed a different pattern in stance time in comparison to the TD group (Figure 14) (Table 3). The average stance time in the DS group was 0.77 seconds across the three stairs height conditions, compared to 0.56 seconds in the TD group. The TD group increased stance time from about 0.50 seconds at step -3 and step -2 to 0.65 seconds at step -1. In contrast, the DS group increased stance time from 0.52 seconds at step -3 to 0.60 seconds at step -2 and 1.19 seconds at step -1. Statistical analysis revealed that there was a group by step interaction ($F (2, 30) = 35.02$, $p < 0.0001$). Post-hoc analysis reported that the increase in stance time was greater in the DS group than in the TD group, although both groups increased stance time from step -2 to step -1. Between the two groups, the DS group displayed a significantly longer stance time only at step -1 than the TD group during the approaching phase.

Both groups spent a longer stance time while negotiating the highest staircase. Across the two groups, average stance time was 0.64 seconds under the LS condition, 0.62 seconds under the MS condition, and 0.73 seconds under the HS condition. Statistical analysis revealed that there was a main effect of stair height ($F (2, 30) = 6.67$, $p = 0.004$). Post-hoc analysis reported that stance time was significantly increased under the HS condition than under both the LS and MS conditions.



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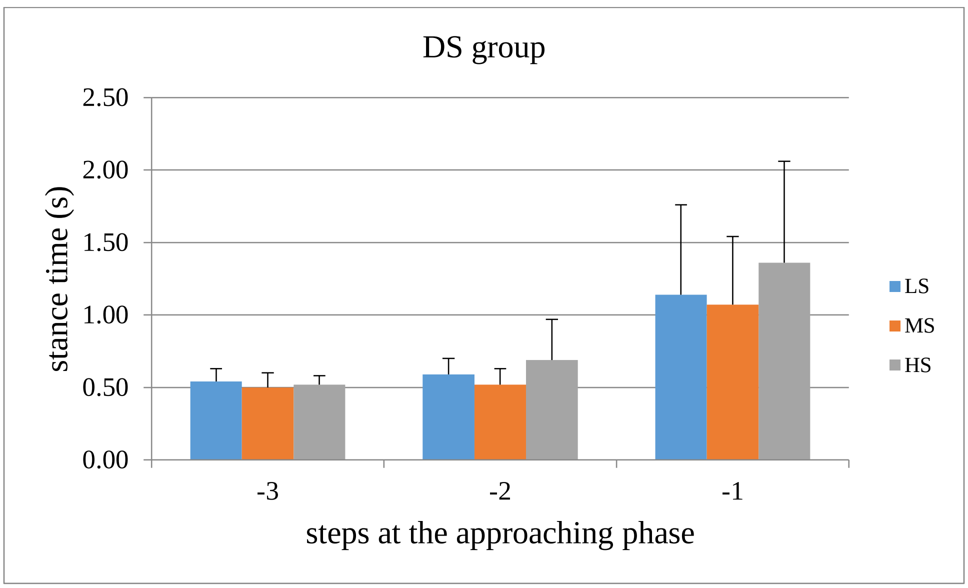

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Figure 14 Stance time at the approaching phase in (a) TD group and (b) DS group

2.3.2 Spatial-temporal parameters at the ascent phase

Table 4 Spatial-temporal gait parameters (Mean ± Standard deviation) at the ascent phase

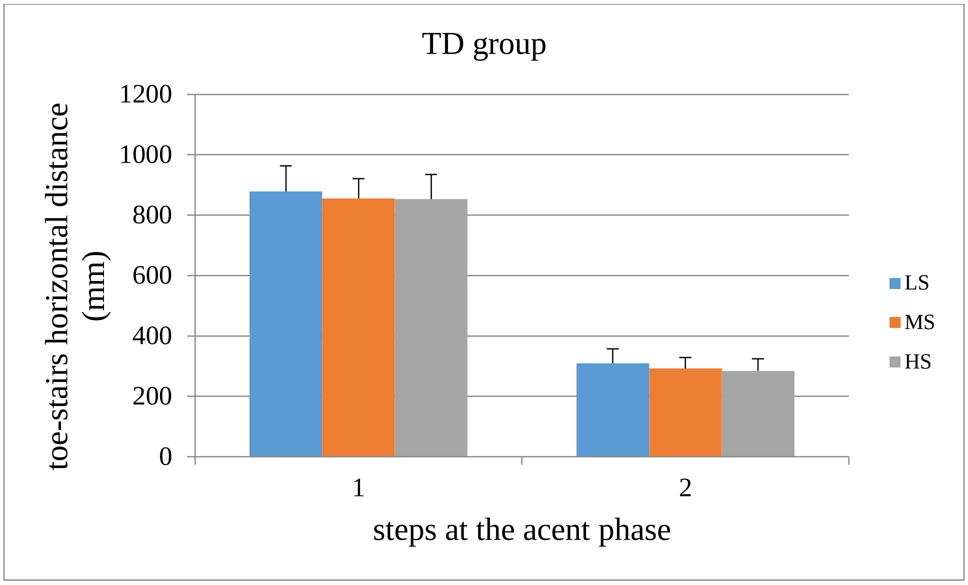
Gait parameters	Stair height	Step	Group		F value, significance
			TD	DS	
Toe-stairs horizontal distance (mm)					
	LS	1	878.45±84.90	409.43±146.39	Main effect of group (F (1, 15) = 85.88, p < 0.0001);
		2	309.16±47.49	138.19±45.37	
	MS	1	854.82±66.32	425.78±121.58	Main effect of step (F (1, 15) = 1602.10, p < 0.0001);
		2	292.36±36.16	148.71±45.43	
	HS	1	853.38±81.63	396.49±142.22	Interaction effect of group and step (F (1, 15) = 219.99, p < 0.0001).
		2	284.45±39.99	163.74±46.59	
Toe clearance above the edge of stairs (mm)					
	LS	1	86.06±17.17	118.27±14.57	Main effect of step (F (1, 15) = 26.65, p = 0.0001);
		2	90.12±17.39	96.74±11.63	
	MS	1	94.84±19.22	95.98±12.22	Main effect of stair height (F (2, 30) = 12.23, p = 0.0001);
		2	77.16±17.92	81.28±20.98	
	HS	1	101.00±28.11	78.98±20.99	Interaction effect of group and stair height (F (2, 30) = 9.31, p = 0.0007);
		2	71.84±13.22	80.55±28.36	Interaction effect of group and stair height and step (F (2, 30) = 10.57, p = 0.0003).
Horizontal toe velocity above the edge of stairs (mm/second)					

	LS	1	2496.10±377.45	1546.20±382.36	Main effect of group (F (1, 15) =
		2	2182.80±248.93	1513.01±293.41	36.50, p < 0.0001);
	MS	1	2343.65±398.65	1476.08±182.20	Main effect of step (F (1, 15) =
		2	2122.71±336.55	1466.53±291.87	10.48, p = 0.0055);
	HS	1	1877.12±196.75	1253.29±335.47	Main effect of stair height (F (2,
		2	1766.73±207.86	1110.73±313.54	30) = 38.52, p < 0.0001).
Step width (mm)					
	LS	1	82.91±26.30	153.34±60.64	Main effect of group (F (1, 15) =
		2	116.23±39.28	192.97±80.22	10.54, p = 0.0054);
	MS	1	96.03±29.76	173.35±53.09	Main effect of step (F (1, 15)
		2	136.21±34.42	200.13±64.81	=44.82, p < 0.0001);
	HS	1	102.56±42.42	196.59±58.13	Main effect of stair height (F (2,
		2	148.02±40.40	193.58±70.47	30) = 9.40, p = 0.0007).
Step length (mm)					
	LS	1	639.72±49.59	468.55±48.97	
		2	270.85±16.92	123.25±80.03	Main effect of group (F (1, 15) =
	MS	1	627.10±38.49	470.75±50.37	32.26, p < 0.0001);
		2	319.19±147.66	212.25±178.25	Main effect of step (F (1, 15) =
	HS	1	609.36±41.60	452.16±38.19	292.06, p < 0.0001).
		2	380.99±190.74	83.00±95.44	
Step time (second)					
	LS	1	0.47±0.04	0.69±0.14	Main effect of group (F (1, 15) =
		2	0.54±0.07	1.01±0.57	11.51, p = 0.0040);
	MS	1	0.50±0.09	0.62±0.09	Main effect of step (F (1, 15) =

	2	0.60±0.12	1.03±0.41	69.81, p < 0.0001);
HS	1	0.58±0.09	0.89±0.37	Main effect of stair height (F (2, 30) = 18.06, p < 0.0001);
	2	0.77±0.14	1.26±0.46	Interaction effect of group and step (F (1, 15) = 18.70, p = 0.0006).
Step velocity (mm/second)				
LS	1	1378.58±198.63	731.61±212.40	Main effect of group (F (1, 15) = 45.62, p < 0.0001);
	2	510.76±65.13	156.13±162.65	
MS	1	1293.29±218.15	789.14±180.62	Main effect of step (F (1, 15) = 443.94, p < 0.0001);
	2	532.48±197.04	221.10±239.88	
HS	1	1076.54±178.34	606.17±228.17	Main effect of stair height (F (2, 30) = 8.64, p = 0.0011);
	2	500.24±204.40	86.31±128.38	Interaction effect of group and step (F (1, 15) = 8.70, p = 0.0099).
Stance time (second)				
LS	1	0.64±0.12	1.46±1.07	
	2	0.73±0.16	1.51±1.05	Main effect of group (F (1, 15) = 7.81, p = 0.0136);
MS	1	0.74±0.19	1.60±0.70	
	2	0.85±0.20	2.00±0.70	Main effect of stair height (F (2, 30) = 14.00, p < 0.0001).
HS	1	1.05±0.33	2.13±1.36	
	2	1.27±0.46	2.29±2.28	

2.3.2.1 Toe-stairs horizontal distance

The DS group displayed different horizontal distances between the toe and the stairs before clearing the stairs, compared to the TD group (Figure 15) (Table 4). Across the three stair height conditions, average distance between the toe and the staircase in the DS group was 280.4 mm, compared to 578.8 mm in the TD group. Both groups placed the leading limb farther away from the staircase than the trailing limb. In the DS group, the distance between the toe of the leading limb and the staircase was 410.6 mm (i.e. the toe-stairs horizontal distance at step 1), whereas the distance between the toe of the trailing limb and the staircase was 150.2 mm (i.e. the toe-stairs horizontal distance at step 2). In contrast, in the TD group, the toe-stairs horizontal distance was 862.2 mm from the leading limb and 295.3 mm from the trailing limb. Statistical analysis revealed that there was a group by step interaction ($F(2, 30) = 219.99$, $p < 0.0001$). Post-hoc analysis reported the increase in this distance was greater in the TD group than in the DS group, although both groups had a longer horizontal distance from the leading limb. Comparing the two groups, the DS group produced a significantly shorter horizontal distance between the toe and the staircase than the TD group from both the leading and trailing limbs.



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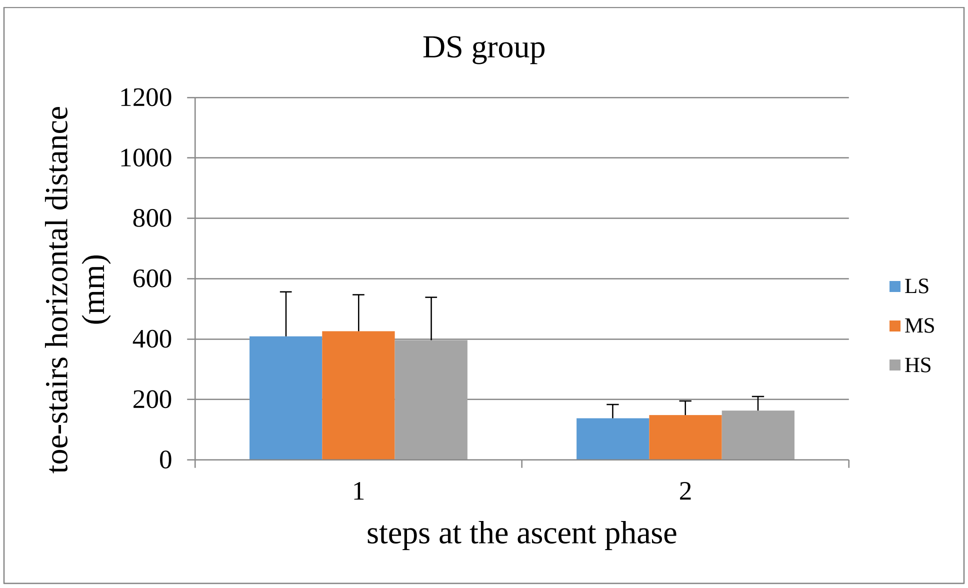


b)

Figure 15 Toe-stairs horizontal distance in (a) TD group and (b) DS group

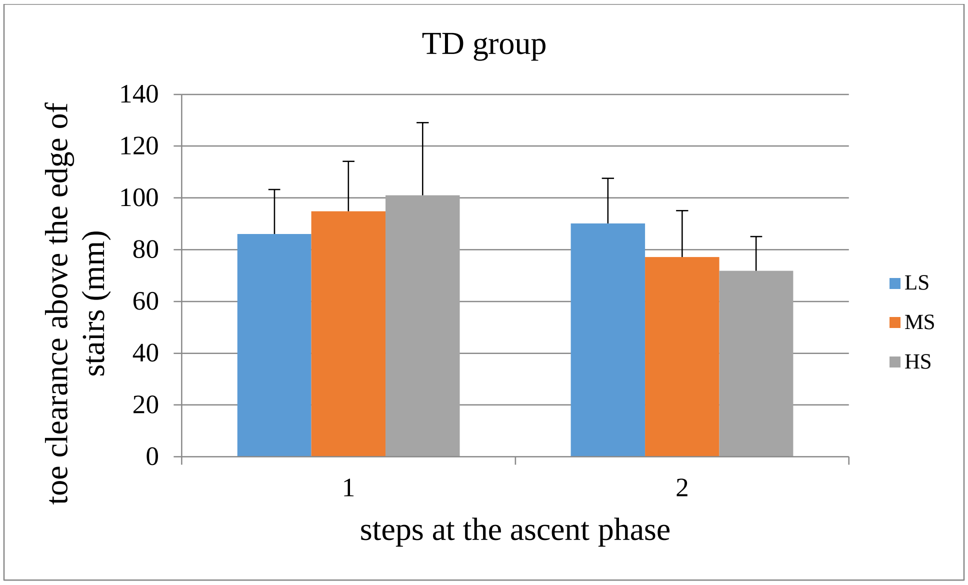
2.3.2.2 Toe clearance above the edge of stairs

The toe clearance above the edge of stairs was different between the DS group and the TD group (Figure 16) (Table 4). Statistical analysis revealed that there was a three-way interaction (group × stairs height × step) effect on toe clearance above the edge of stairs ($F(2, 30) = 10.57$, $p = 0.0003$).

Both groups produced a higher toe clearance from the leading limb (i.e., toe clearance above the edge of stairs at step 1) than from the trailing limb (i.e., toe clearance above the edge of stairs at step 2). Toe clearance from the leading limb was 95.9 mm in comparison to 82.9 mm from the trailing limb across the two groups.

Stair height affected toe clearance. Across both the leading and trailing limbs, average toe clearance above the edge of stairs in the two groups was 97.8 mm under the LS condition, 87.3 mm under the MS condition and 83.1 under the HS condition. As the stair height increased, toe clearance from the leading limb was increased in TD group, but decreased in DS group. Both TD and DS groups decreased their toe clearance from the trailing limb with the increase in stair height.

Post-hoc analysis also reported that in comparison to the TD group, the DS group displayed a higher toe clearance under the LS condition, a similar toe clearance under the MS condition, and a lower toe clearance under the HS condition from the leading limb. There was no significant toe clearance from the trailing limb between the DS and TD group under each of the three stair height conditions.



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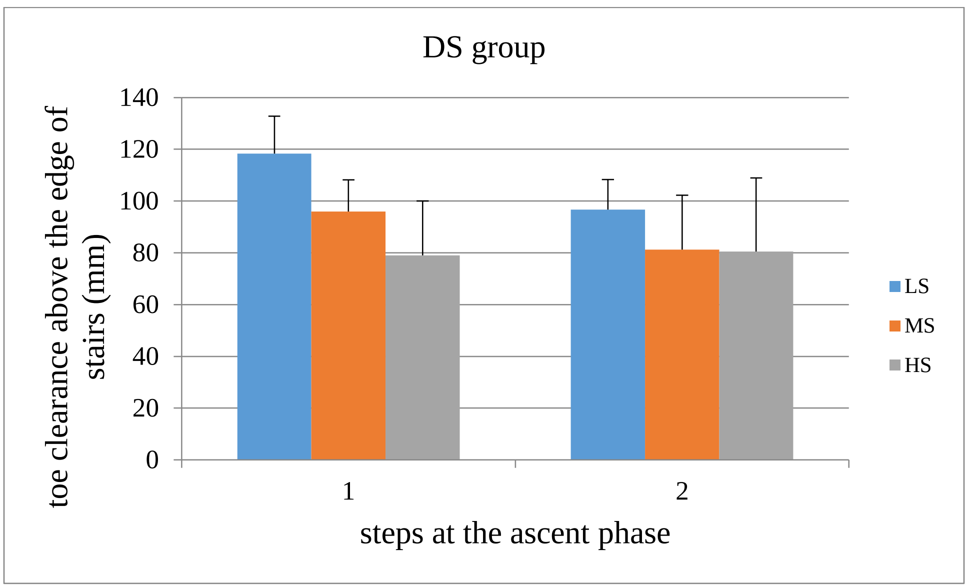


b)

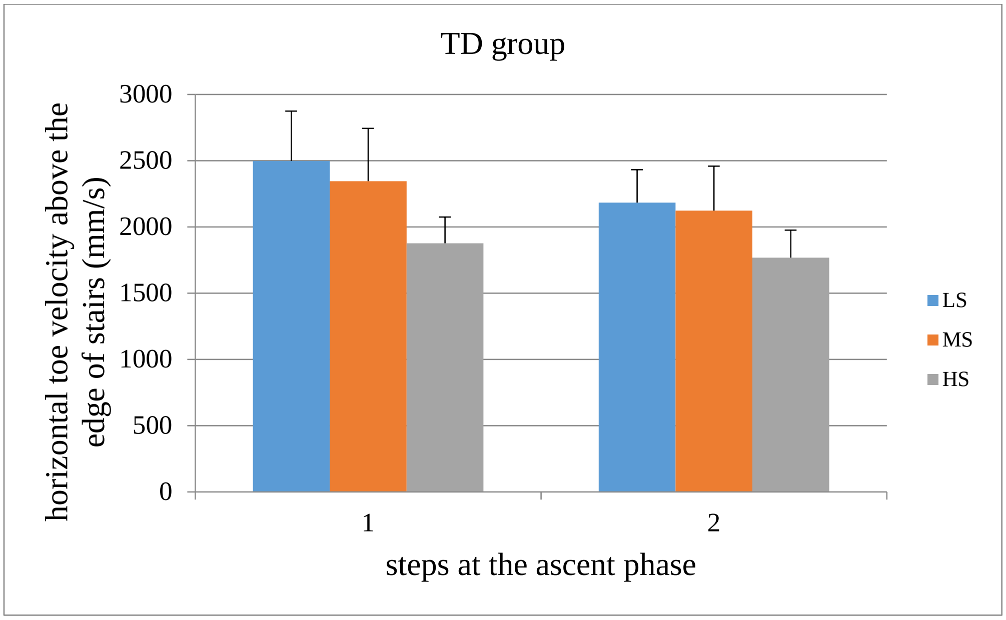
Figure 16 Toe clearance above the edge of stairs in (a) TD group and (b) DS group

2.3.2.3 Horizontal toe velocity above the edge of stairs

Overall, the DS group displayed a slower instantaneous horizontal toe velocity above the edge of stairs than the TD group (Figure 17) (Table 4). Across the three stair height conditions and the first two steps at the ascent phase, average horizontal toe velocity above the edge of stairs was 1394.3 mm/second in the DS group and 2131.5 mm/second in the TD group. Statistical analysis reported that there was a main effect of group ($F (1, 15) = 36.50$, $p < 0.0001$).

Both the DS and TD groups produced a greater horizontal toe velocity from the leading limb (i.e., at step 1) than from the trailing limb (i.e., at step 2). On average, across the two groups and the three stairs height conditions, horizontal toe velocity was 1832.1 mm/second at step 1 and 1693.8 mm/second at step 2. Statistical analysis revealed that there was a main effect of step ($F (1, 15) = 10.48$, $p = 0.0055$). This indicated children' trailing limb walked at a slower horizontal velocity than the leading limb while moving above the edge of stairs.

A similar trend was observed in both the TD and DS groups such that horizontal toe velocity decreased with the increase in stair height. Across the first two steps at the ascent phase from the two groups, average horizontal toe velocity was 1934.5 mm/second under the LS condition, 1852.2 mm/second under the MS condition, and 1502.0 mm/second under the HS condition. Statistical analysis reported that there was a main effect of stair height ($F (2, 30) = 38.52$, $p < 0.0001$). Post-hoc analysis revealed that horizontal toe velocity above the edge of stairs was lower under the HS condition than under both the MS and LS conditions.



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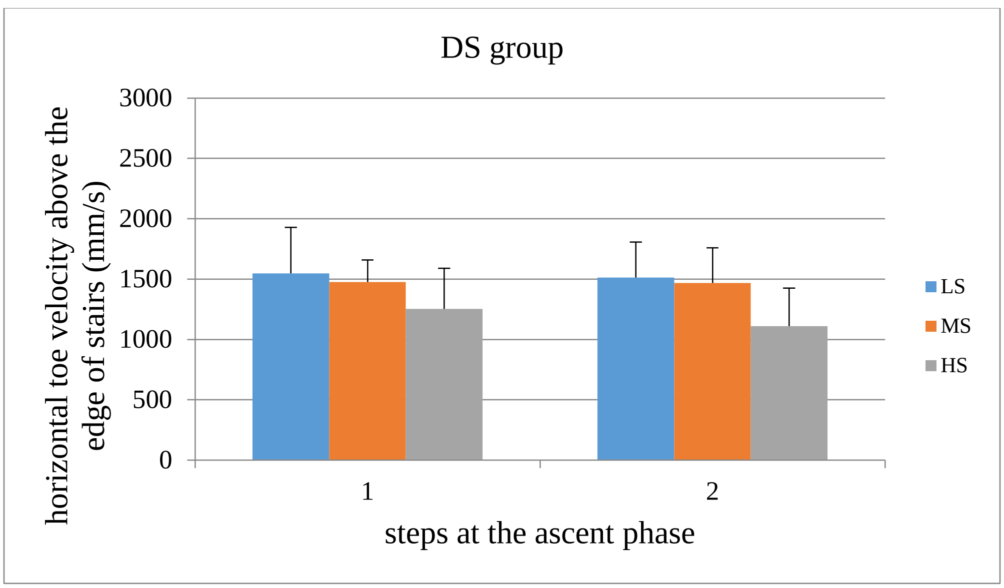


b)

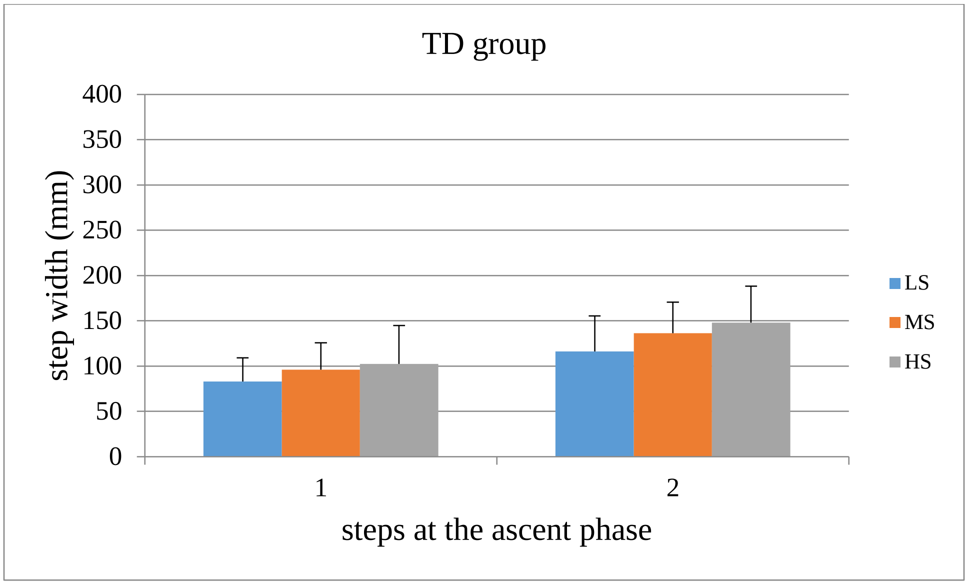
Figure 17 Horizontal toe velocity above the edge of stairs in (a) TD group and (b) DS group

2.3.2.4 Step width at the ascent phase

Overall, the DS group displayed a greater step width than the TD group at the first two steps during the ascent phase (Figure 18) (Table 4). Across the three stair height conditions and the first two steps, average step width was 185.0 mm in the DS group and 113.7 mm in the TD group. Statistical analysis reported that there was a main effect of group ($F (1, 15) = 10.54$, $p = 0.005$).

Both the DS and TD groups produced a grater step width from the trailing limb (i.e., step width at the step 2) than that from the leading limb (i.e., step width at step 1). On average, across the three stair height conditions and the two groups, step width was 134.1 mm at step 1 and 164.5 mm at step 2. Statistical analysis revealed that there was a main effect of step ($F (1, 15) = 44.82$, $p < 0.0001$). This indicated children' trailing limb produced a greater step width than the leading limb.

A similar trend was observed in both the DS and TD groups such that step width at the ascent phase increased with the increase in stair height. Across the first two steps at the ascent phase from the two groups, average step width was 136.4 mm under the LS condition, 151.4 mm under the MS condition, and 160.2 mm under the HS condition. Statistical analysis reported that there was a main effect of stairs height ($F (2, 30) = 9.40$, $p = 0.0007$). Posy-hoc analysis revealed that step width at the ascent phase was lesser under the LS condition than under the MS or HS conditions.



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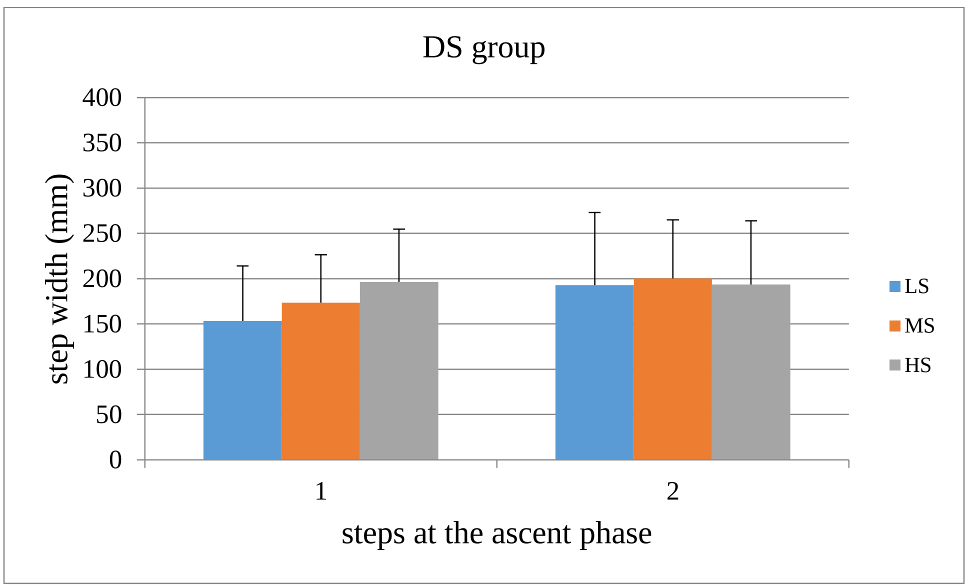


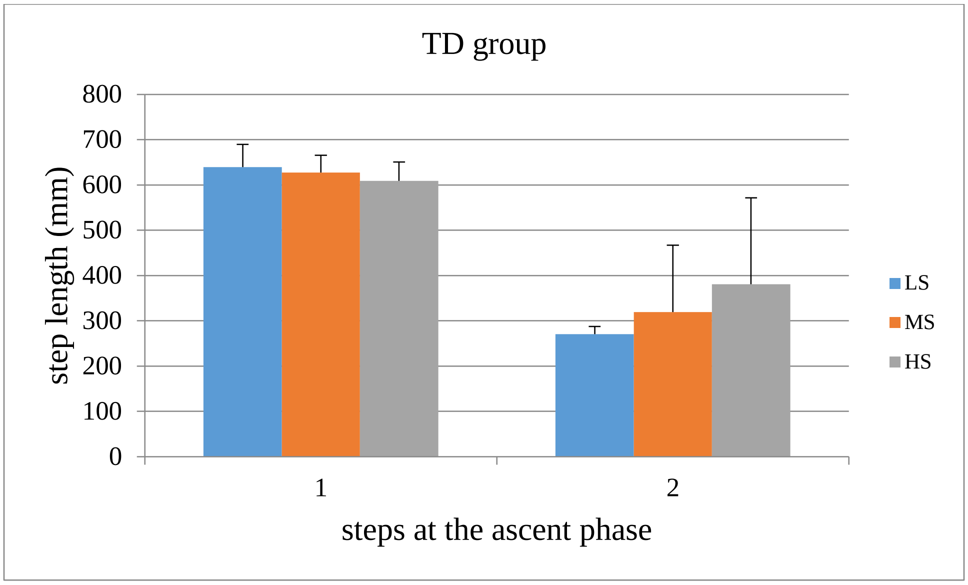
b)

Figure 18 Step width at the ascent phase in (a) TD group and (b) DS group

2.3.2.5 Step length at the ascent phase

Overall, the DS group displayed a shorter step length than the TD group (Figure 19) (Table 4). Across the first two steps of the ascent phase and the three stair height conditions, average step length was 301.7 mm in the DS group and 474.5 mm in the TD group. Statistical analysis reported that there was a main effect of group ($F(1, 15) = 32.26$, $p < 0.0001$).

Both the DS and TD groups produced a greater step length from the leading limb (i.e., step length at the step 1) than that from the trailing limb (i.e., step length at step 2). On average, across the three stair height conditions and the two groups, step length was 544.6 mm at step 1 and 231.6 mm at step 2. Statistical analysis revealed that there was a main effect of step ($F(1, 15) = 292.06$, $p < 0.0001$). This indicated children's leading limb produced a greater step length than the trailing limb. In addition, both groups produced a similar step length across the three stair height condition.



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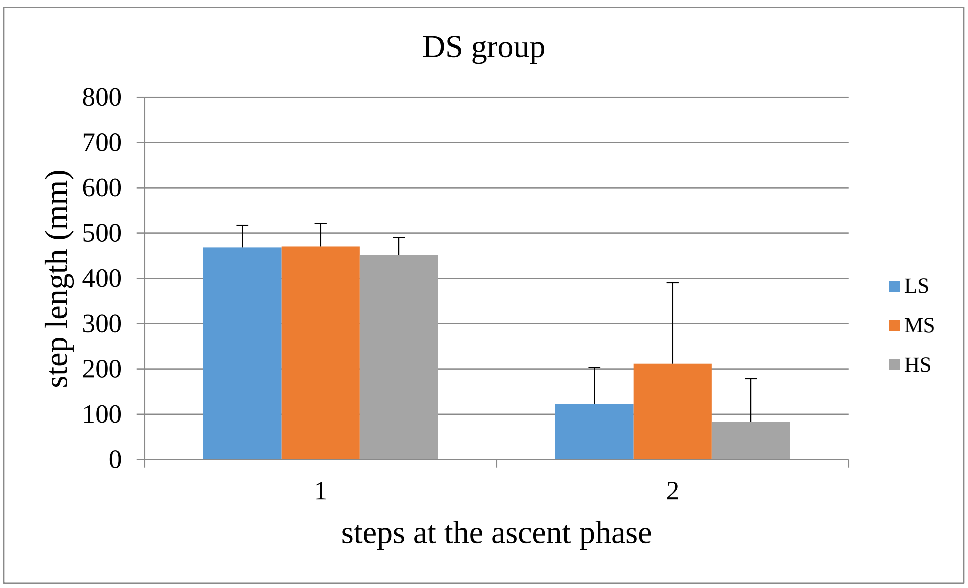


b)

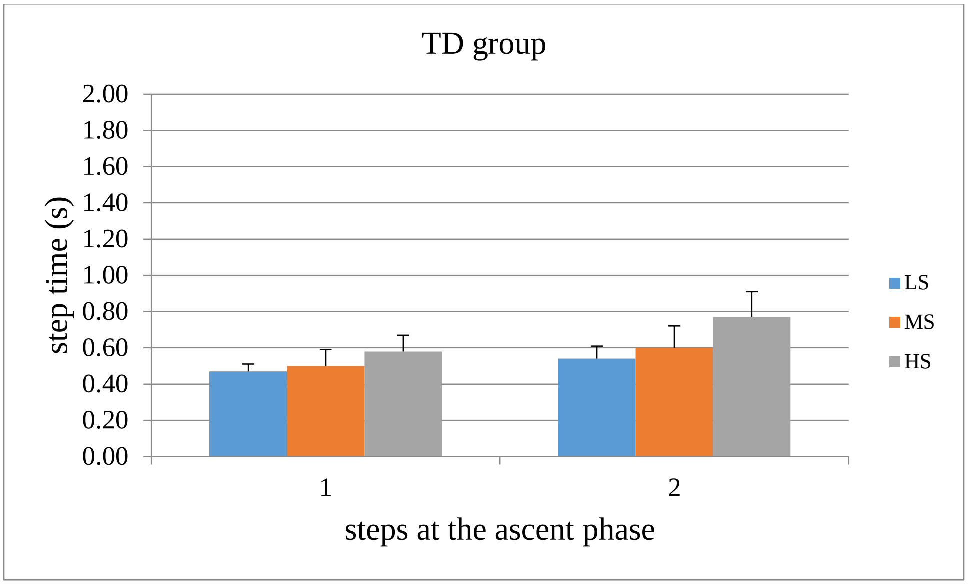
Figure 19 Step length at the ascent phase in (a) TD group and (b) DS group

2.3.2.6 Step time at the ascent phase

Over the first two steps at the ascent phase, the DS group displayed a different pattern in step time compared to the TD group (Figure 20) (Table 4). The average step time at the ascent phase in the DS group was 0.91 seconds across the three stair height conditions, compared to 0.58 seconds in the TD group. While the TD group increased step time from 0.52 seconds at step 1 to 0.64 seconds at step 2, the DS group increased step time from 0.73 seconds at step 1 to 1.10 seconds at step 2. Statistical analysis revealed that there was an interaction effect of group and step ($F (1, 15) = 18.70$, $p = 0.0006$). Post-hoc analysis reported that the DS group increased step time from step 1 to step 2 to a greater extent that the TD group. When comparing step time between the two groups, the DS group produced a significantly longer step time than the TD group at step 2 during the ascent phase.

Both groups moved with a longer step time while negotiating the highest staircase. Across the two groups, average step time was 0.68 seconds under the LS condition, 0.69 seconds under the MS condition, and 0.87 seconds under the HS condition. Statistical analysis revealed that there was a main effect of stair height ($F (2, 30) = 18.06$, $p < 0.0001$). Post-hoc analysis reported that step time at the ascent phase was significantly longer under the HS condition than under both the LS and MS conditions.

a)



b)

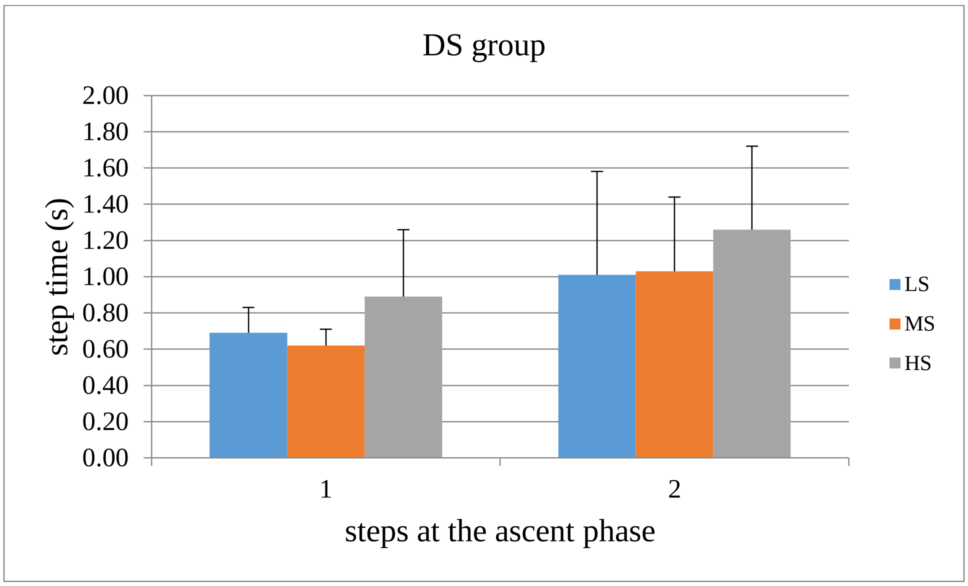
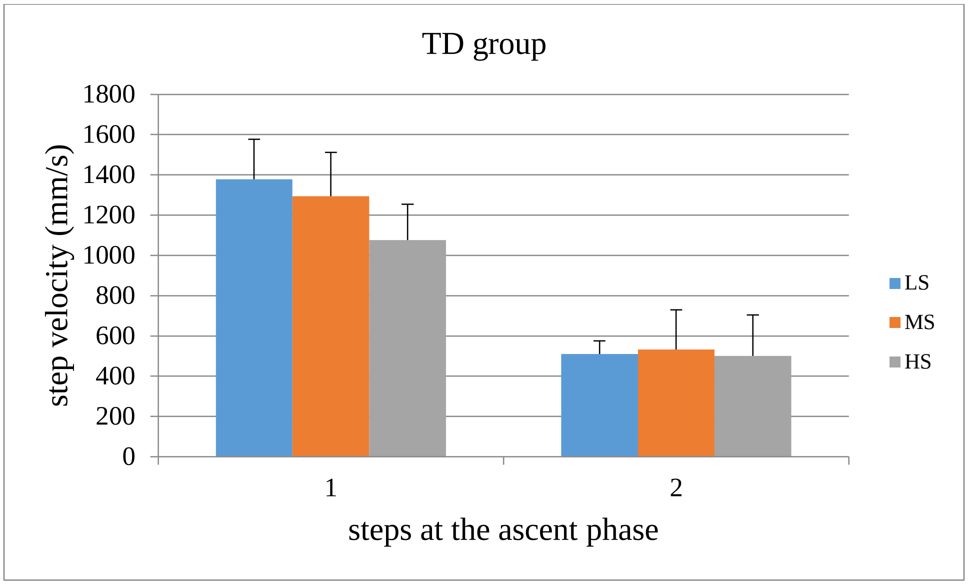


Figure 20 Step time at the ascent phase in (a) TD group and (b) DS group

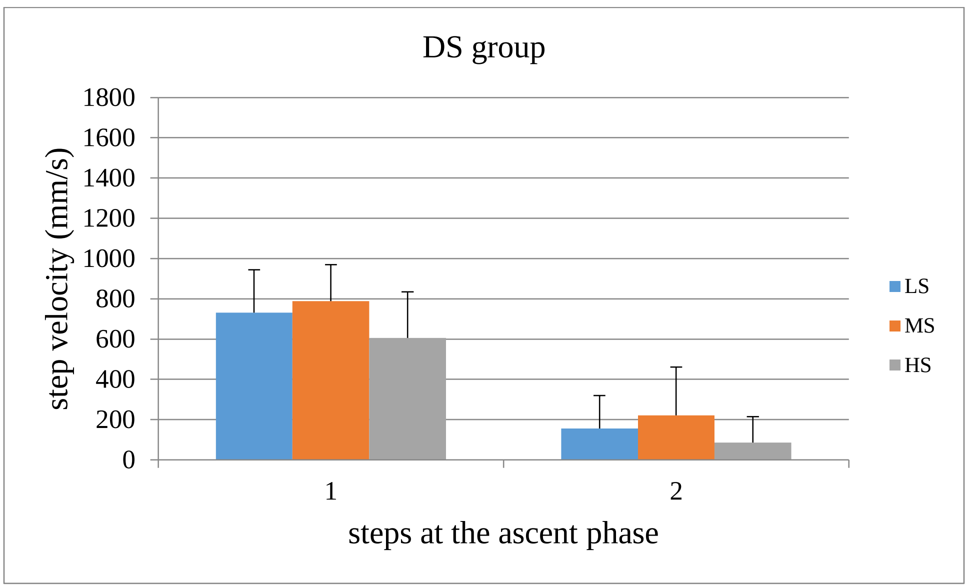
2.3.2.7 Step velocity at the ascent phase

Over the first two steps at the ascent phase, the DS group displayed a different pattern in step velocity, compared to the TD group (Figure 21) (Table 4). The average step velocity in the DS group was 431.7 mm/second across the three stair height conditions, compare to 882.0 mm/second in the TD group. While the TD group decreased step velocity from 1249.5 mm/second at step 1 to 514.5 mm/second at step 2, the DS group decreased step velocity from 709.0 mm/second at step 1 to 154.5 mm/second at step 2. Statistical analysis revealed that there was a group by step interaction (F (1, 15) = 8.70, p = 0.0099). Post-hoc analysis reported that the DS group decreased step velocity from step 1 to step 2 to a lesser extent than the TD group. When comparing step velocity between the two groups, the DS group produced a significantly slower step velocity than the TD group at each of the first two steps during the ascent phase.

Both groups moved up the stairs with a slower step velocity while negotiating the highest staircase. Across the two groups, average step velocity at the ascent phase was 694.3 mm/second under the LS condition, 709.0 mm/second under the MS condition, and 567.2 mm/second under the HS condition. Statistical analysis revealed that there was a main effect of stair height (F (2, 30) = 8.64, p = 0.0011). Post-hoc analysis reported that step velocity at the ascent phase was significantly slower under the HS condition than under both the LS and MS conditions.



a)



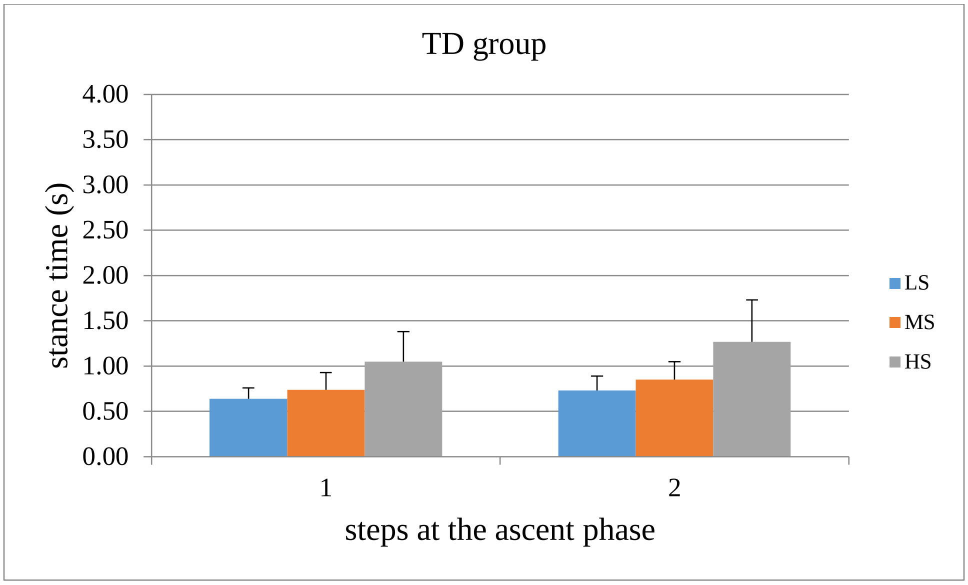
b)

Figure 21 Step velocity at the ascent phase in (a) TD group and (b) DS group

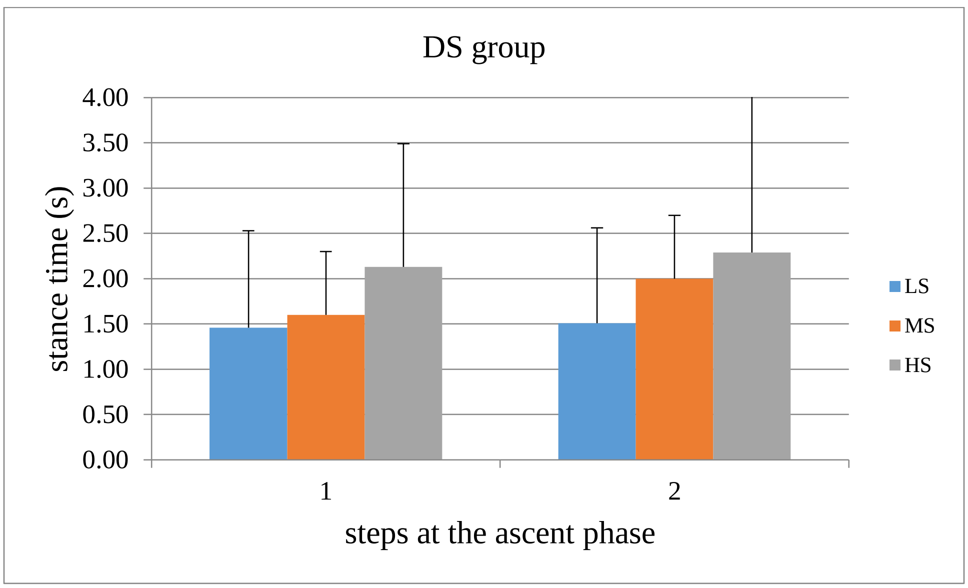
2.3.2.8 Stance time at the ascent phase

In general, the DS group produced a longer stance time than the TD group while going up the stairs (Figure 22) (Table 4). Across the three stair height conditions and the first two steps at the ascent phase, average stance time was 1.83 seconds in the DS group and 0.88 seconds in the TD group. Statistical analysis reported that there was a main effect of group ($F(1, 15) = 7.81$, $p = 0.0136$).

Both groups showed a similar trend such that stance time increased with the increase in stair height. Across the first two ascending steps and the two groups, average stance time was 1.09 seconds under the LS condition, 1.30 seconds under the MS condition, and 1.69 seconds under the HS condition. Statistical analysis reported that there was a main effect of stair height ($F(2, 30) = 14.00$, $p < 0.0001$). Post-hoc analysis revealed that stance time was found longer under the HS condition than under both the MS and LS conditions. In addition, both groups produced a similar stance time at the first two steps during the ascent phase, suggesting a similar timing between the leading and trailing limbs.



a)



b)

Figure 22 Stance time at the ascent phase in (a) TD group and (b) DS group

2.3.3 Motor strategy at the ascent phase

Table 5 Total trial number of each motor strategy under each stair height condition in TD and DS groups

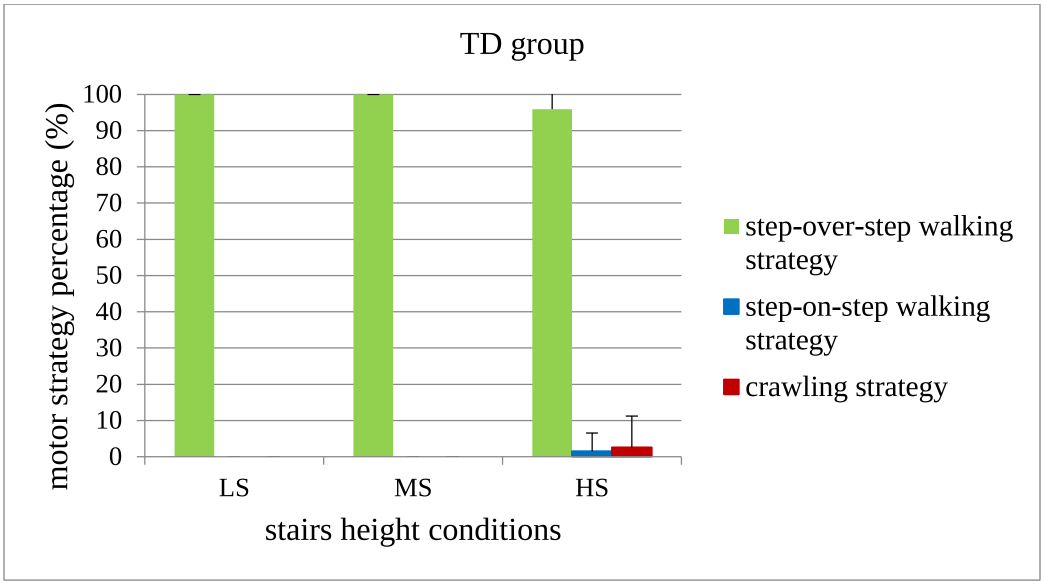
Stair height	Motor strategy	Group	
		TD (trial number)	DS (trial number)
LS			
	step-over-step walking	60	28
	step-on-step walking	0	18
	crawling	0	5
MS			
	step-over-step walking	57	4
	step-on-step walking	0	11
	crawling	0	18
HS			
	step-over-step walking	58	0
	step-on-step walking	1	0
	crawling	2	28

The motor strategy in each trial was identified in each subject. The total trial number of each motor strategy under each stair height condition in the TD and DS group was shown on Table 5.

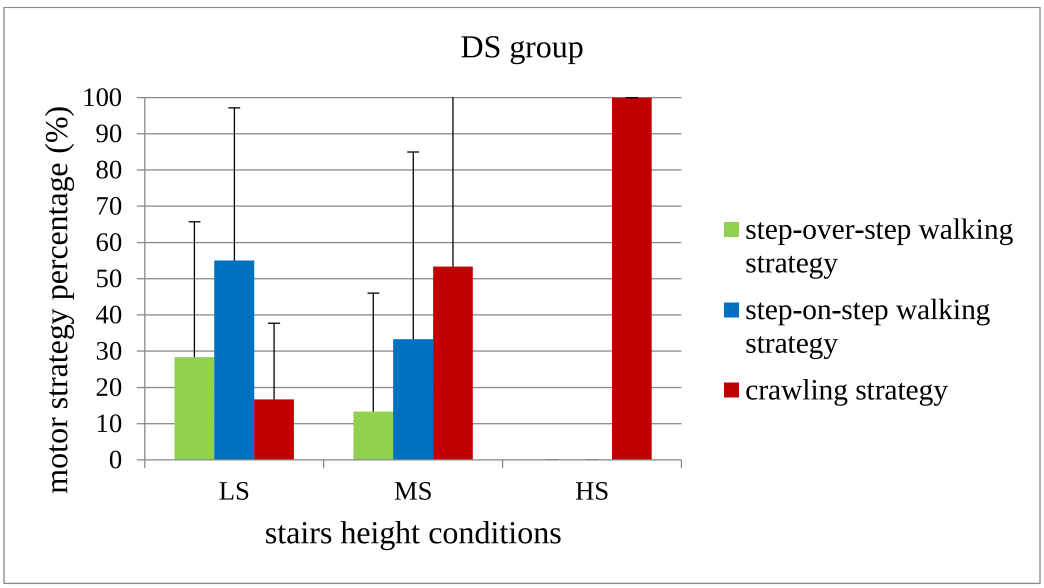
In our study, we calculated the percentage of each motor strategy under each stair height condition in each subject. Then we averaged the percentage of each motor strategy under each stair height condition for each group (Figure 23).

In the TD group, a step-over-step walking strategy was the dominant motor strategy under all the three stairs height conditions while going up the stairs (Figure 23). Specifically, it was found that (1) when walking under the LS and MS conditions, the adopted motor strategy was 100% of a step-over-step walking strategy; (2) when walking under the HS condition, 95.89% of a step-over-step walking, 1.52% of a step-on-step walking strategy, and 2.60% of a crawling strategy were observed.

In the DS group, different motor strategies adopted depended on different stairs height conditions (Figure 29). Step-over-step walking strategy was not a dominant motor strategy any more in the DS group, even under the LS condition. Alternatively, the DS group appeared to prefer either a step-on-step walking strategy or a crawling strategy while going up the stairs from the level ground. As stairs height increased, a preference was observed to adopt a crawling strategy in the DS group. Specifically, it was found that (1) under the LS condition, a step-on-step walking strategy became the dominant motor strategy (55%), a step-over-step walking strategy was the secondary strategy (28.33%), and a crawling strategy was the least adopted strategy (16.67%); (2) under the MS condition, a higher percentage of a crawling strategy was observed (53.33%), along with 33.33% of a step-on-step walking strategy, and 13.33% of a step-over-step walking strategy used; (3) under the HS condition, a crawling strategy became the only adopted motor strategy (100%).



a)



b)

Figure 23 Motor strategy percentages in (a) TD group and (b) DS group

2.4 Discussion

2.4.1 ALAs at the approaching phase in children with and without DS

2.4.1.1 ALAs in TD children while approaching a staircase

The results of our study showed that no significant differences of step length, step time, and step velocity, were found over the last three steps in the TD group while approaching a staircase. It suggested that TD children walked with a generally consistent pace and velocity in the anterior-posterior direction while approaching a staircase. This finding is similar to the ALAs reported in TD children aged 4-7 years while approaching an obstacle (Virji-Babul & Brown, 2004).

However, our finding is not consistent with the ALAs reported in another study while approaching and circumventing an obstacle (Vallis & McFadyen, 2005). Vallis & McFadyen (2005) found that TD children aged 10 years demonstrated reduced walking speed two steps prior to the obstacle and decreased step length one step while approaching an obstacle before circumventing it. Difference in the experimental settings may lead to the different ALA patterns. In order to successfully circumvent an obstacle, one needs to change the movement trajectory and avoid the direct contact with the obstacle. This may naturally cause a reduced forward velocity and distance covered in the last couple of steps before circumventing the obstacle. In contrast, going up a staircase does not require the subject to change the movement trajectory. Therefore, the subject may be able to keep walking in a straight line while manipulating the spatial-temporal variables if necessary. We postulated that TD children may be able to generate a task-specific ALA pattern while walking in an environment with different constraints.

TD children in our study still made ALAs by modulating step width and stance time while approaching a staircase. The outcomes of our study suggested that while approaching a staircase, TD children decreased their step width two steps prior to a staircase, and prolonged stance time of their trailing limb in front of the staircase. As going up the stairs requires a greater vertical movement of the lower extremity, a smaller step width may help shift the body weight from the leading limb to the trailing limb while taking the first steps of the staircase. Further, as a smaller step width generates a smaller base of support, our results indicate that TD children may have developed a compensatory strategy to reduce base of support while progressing forward and upward onto a staircase at the same time, suggesting a relatively developed balance control in the medial-lateral direction in TD children. In addition, a longer stance time at step -1 also provides a longer time to prepare the leading limb to complete both the vertical and forward movements while going up the stairs from the floor.

2.4.1.2 ALAs in children with DS while approaching a staircase

Our study indicated that while walking from the level ground to the stairs, children with DS maintained step width and step time over the last three steps of the approaching phase, but decreased step length and step velocity and increased stance time in sequence at the last three steps of the approaching phase. This finding is similar to the findings while toddlers with DS approached to an obstacle (Wu, Ulrich, Looper, et al. 2008). Wu et al. (2008) found that toddlers with DS who received either a high-intensity, individualized treadmill intervention or a low-intensity, generalized treadmill intervention, reduced walking speed, cadence and step length, and increased step width over the last three steps before crossing an obstacle. Furthermore, some similar ALAs were reported in young adults and children with DS while approaching an obstacle. For example, studies reported young adults with DS showed reduced walking speed, increased step width, decreased and more variable step length while approaching an obstacle, compared to healthy young adults (Salami, Vimercati, Rigoldi, et al. 2014; Vimercati, Galli, Rigoldi, & Albertini, 2013; Vimercati, Galli, Rigoldi, et al. 2012). Taken together, although going up a staircase is different from crossing an obstacle, it is plausible that children with DS are able to develop appropriate ALA movement patterns for moving around in an environment with constricts, starting at a young age.

Between the DS and TD groups in our study, the ALA pattern observed in the DS group is different from the aforementioned pattern in the TD group. Overall, the DS group walked with an increased step width, a decreased step length, a decreased step velocity, and an increased stance time than the TD group, but no significant difference of step time was shown between the two groups while approaching a staircase. Similar findings were reported in another study with children with DS aged 5-6 years (Virji-Babul & Brown, 2004). In their study, children with DS displayed a shorter stride length and greater step length variability than TD children while walking to an obstacle. Virji-Babul and Brown's study (2004) reported that children with DS stopped in front of the obstacle for the duration between 0.4 seconds to 4 seconds, before stepping over an obstacle with the height equal to 15% of body height (Virji-Babul & Brown, 2004). However, this "stopping" strategy was not observed in children with DS while approaching an obstacle with the height equal to 1% of body height (Virji-Babul & Brown, 2004). Young adults with DS may also not stop before an obstacle, but walk with a significant decreased speed at the approaching phase (Vimercati, Galli, Rigoldi, & Albertini, 2013). Our study didn't observe this "stopping" strategy in children with DS while approaching a staircase with either the lower riser height, the medium riser height, or the higher riser height. The possible reason for the absence of this “stopping” strategy in our study might be because children with DS in our study actually did not adopt step-over-step motor strategy for stairs negotiation, but mostly chose to use alternative motor strategy such as crawling while going up the stairs, which made it possible that they didn’t need this “stopping” strategy in front of the staircase.

Our study demonstrated that although both groups increased stance time from step -2 to step -1 at the approaching phase, the increase in stance time was greater in the DS group than in the TD group. It was suggested that although children with DS spent a similar step time as TD children at each step of the last three steps at the approaching phase, children with DS actually not only increased their step width to obtain a greater base of support, but also decreased their step length and slowed down their velocity to approach a staircase. Particularly, children with DS prolonged their stance time to a greater extent than TD children, especially at the last step of the approaching phase when the trailing limb supported the body weight while the leading limb negotiated the stairs. Another reason that children with DS greatly prolonged their stance time at the trailing limb while their leading limb was negotiating the stairs may be because they need more time to extract relevant information about the staircase to modulate the leading limb’s movement up stairs. This may be due to the fact that children with DS are able to extract visual information about the properties of the constraints in an environment to modulate movements, but may be not be able to use advance visual information about the constraints in the environment well (Virji-Babul & Brown, 2004).

Taken together, our results suggest that children with DS may display the ALAs, and such ALA patterns may emerge at a young age. However, children with DS may not be able to display the adaptive locomotion patterns comparable to their TD peers, particularly performing some more challenging motor task such as going up a staircase with a markedly greater riser height (i.e., the HS condition in our study), which may be possibly associated with their limited motor ability and coordination due to their neuromuscular characteristics.

2. 4.1.3 Effects of stairs height on ALAs in children with and without DS

The results from our study indicated that stairs height did not affect both step width and step length in both children with and without DS while approaching a staircase. However, our study observed a significantly decreased step velocity, significantly increased step time and stance time under the HS condition than under either the LS or MS condition at the approaching phase. The stairs with a riser height of 17 cm and 24 cm did not influence ALAs in children, since these two heights were slightly below and above the standard residential riser height (i.e., 20 cm). However, a staircase with a riser height of 31cm caused children to increase step time and stance time but decrease step velocity while approaching the staircase, since the HS condition, compared to the standard residential riser height, provided a 50% increase in a standard riser height and might therefore be a challenging task for both the DS and TD groups.

Similar effects of a constraint's height on spatial-temporal gait pattern were observed in individuals with and without DS while approaching an obstacle. For example, one study that compared gait patterns among unobstructed ground walking, walking over an obstacle at ground level, and walking over an obstacle at 10% of the subject's height, found that adults with DS decreased their walking speed to a greater extent when walking over an obstacle at 10% of the subject's height, whereas healthy subjects were able to walk at an unvaried speed across all conditions (Vimercati, Galli, Rigoldi, & Albertini, 2013). Another study reported that while TD children maintained smooth gait pattern at the approaching phase under obstructed walking, children with DS displayed "stopping" in front of an obstacle with the height equal to 15% of body height, but didn't display this "stopping" when approaching an obstacle with the height equal to 1% of body height (Virji-Babul & Brown, 2004).

Taken together, our results suggest that both children with and without DS are able to maintain their ALA patterns that they feel comfortable for an environment similar to their daily living and activities (i.e., the LS and MS conditions in our study). However, when presented with a constrained environment that is markedly challenging (i.e., the HS condition in our study), both children with and without DS were able to modify their ALA patterns to accommodate the challenge and complete the motor task. In our study, the stair height appears to serve as a control parameter to produce a new locomotor pattern in both children with and without DS.

2.4.2 Spatial-temporal gait pattern at the ascent phase in children with and without DS

2.4.2.1 Locomotor adjustment in TD children while moving up the stairs

While going up the stairs, the leading and trailing limbs displayed different spatial-temporal gait patterns in TD children. The results of our study at the first two steps during the ascent phase showed that TD children placed the leading limb farther away from a staircase than the trailing limb before negotiating the stairs. This finding is similar to the observation in children before crossing an obstacle (Virji-Babul & Brown, 2004). Such a foot placement may help maintain the smooth forward progression before clearing a staircase or an obstacle, and meanwhile facilitate the execution of crossing steps with a pre-planned foot movement trajectory. While going up a staircase requires one to continuously move the body up while taking each step, crossing an obstacle requires one to temporarily lift the legs up over the obstacle and place the limb back on the same surface level. Therefore, the spatial-temporal pattern of locomotor adjustments at the ascent phase of stairs negotiation cannot be compared to that observed in obstacle negotiation.

Spatial margin variables were critical control parameters for locomotor adjustments while negotiating an obstacle (Higuchi, 2013). Similarly, both the horizontal spatial margin (i.e. a foot placement in front of a staircase) and the vertical spatial margin (i.e. a toe clearance while going up the stairs) also played an important role in the negotiation of the stairs. Between the leading and trailing limbs while going up a staircase, the leading limb displayed a higher toe clearance, a greater horizontal toe velocity above the edge of stairs, and a greater step length than the trailing limb. In contrast, the trailing limb showed a greater step width, a longer step time, and a slower step velocity than the leading limb. However, no significant difference of stance time was observed between the leading and trailing limbs.

In general, while going up the stairs, the leading limb needs to negotiate one riser height but the trailing limb needs to clear two times of the riser height. In other words, the leading limb may travel with a longer horizontal distance and a lower vertical distance before landing on the first step of the staircase. In contrast, the trailing limb may travel with a shorter horizontal distance but a higher vertical distance before landing on the second step of the staircase. By pulling up the whole body for a higher vertical displacement, the trailing limb may require better balance support and a longer process time to cautiously execute the ascending step, which results in a greater step width, a longer step time, and a slower step velocity compared to the leading limb. Meanwhile, the trailing limb may be restricted by the horizontal layout of the staircase and the maximal flexion at the hip and knee joints while taking the ascending step, which leads to a shorter step length and a lower toe clearance, particularly under the HS condition.

During the accommodation to a raised surface, the trailing limb must support the body when the leading limb was clearing the surface, and then must also clear the surface so that the entire body was raised to a new level. It was considered that the trailing limb performed more work than the leading limb during stance and swing before going up a new level ((Rietdyk, 2006). When walking from the ground to a raised surface, even healthy young adults increased both stance and swing phases and decreased stride length and walking speed ((Rietdyk, 2006).

2.4.2.2 Locomotor adjustment in children with DS while moving up the stairs

When comparing the spatial-temporal gait parameters between the TD and DS groups at the first two steps while going up the stairs, many differences were identified in our study.

Our study found that overall the DS group displayed a shorter horizontal distance between the toe and the stairs than the TD group from both the leading and trailing limbs. In the DS group, the horizontal distance between the staircase and the toe of the leading and trailing limbs was 410.6 mm and 150.2 mm, respectively. In contrast, in the TD group, the toe-stairs horizontal distance was 862.2 mm from the leading limb and 295.3 mm from the trailing limb. In other words, compared to the DS group, the TD group placed their leading and trailing limbs about two times farther away from a staircase. This would potentially cause a shorter step length for both the leading and trailing limbs in the DS group while going up the stairs. A closer foot placement to the stairs in the DS group may be due to a slower visual information processing, a slower motor planning, or a lack of confidence in negotiating the constraints of the environment associated with weak neuromuscular control and coordination in this population.

Scaling foot elevation has been shown to be one critical locomotor adjustment while accommodating to the constraint of an environment, which cannot be achieved without the perception of environment relation to human body's action capacities. While approaching an object, the central nervous system (CNS) perceives the body-scaled information from a distance (Taga, 1998), and recalibrates the perception in response to the altered action capacities (Higuchi, 2013). The integration of extracted visual input about the properties of the constraint (height, size, location, etc.) and its location relative to the body (Pearson & Gramlich, 2010), facilitates to define the current locomotor pattern appropriate for the environment (Law & Webb, 2005). Previous studies reported that both TD children and children with DS are able to scale adequate foot elevation to step over an obstacle (Vimercati, Galli, Rigoldi, & Albertini, 2013; Virji-Babul & Brown, 2004). In our study, no significant difference of toe clearance above the edge of stairs (i.e., the vertical spatial margin) was found between the TD and DS groups under the MS condition. This finding suggested that children with DS were able to extract information about the stairs height (slightly higher than the standard residential riser height), and scale adequate toe clearance to step onto the stairs as successfully as TD children, although children with DS might have adopted some alternative motor strategies (such as crawling).

The DS group displayed a different toe clearance pattern to the TD group while negotiating a staircase with a slower riser height (i.e., the LS condition) or a higher riser height (i.e., the HS condition). Under the LS condition, the DS group produced a toe clearance about 30 mm higher than the TD group from the leading limb, but showed a similar toe clearance from the trailing limb as the TD group. This suggests that the DS group might have overshot the movement trajectory of their leading limb but made an appropriate adjustment from their trailing limb. This "overshooting" pattern may be due to the inaccurate perception of the height of the stairs, inappropriate motor planning, or an intentionally increased upward movement of the leading limb to ensure a safe vertical margin in the DS group.

The "overshooting" pattern from the leading limb under the LS condition became reversed to an "undershooting" pattern under the HS condition in the DS group. Under the HS condition, the DS group produced a toe clearance about 20 mm lower than the TD group from the leading limb, but showed a similar toe clearance as the TD group from the trailing limb. As the riser height of the HS condition is about 50% higher than the riser height of standard residential stairs, this challenging condition caused the DS group to predominantly use a crawling strategy for the stairs negotiation. While using both hands and feet to clear the stairs, the DS group might have limited the range of motion at the hip and knee joints when negotiating the stairs.

In our study, we also found that although children with DS produced a slower instantaneous horizontal toe velocity than TD children when the swinging foot was above the edge of stairs. The outcomes of our study showed that across the three stairs height conditions and the first two steps at the ascent phase, the average horizontal toe velocity above the edge of stairs was 1394.3 mm/second in the DS group and 2131.5 mm/second in the TD group. In the DS group, a slower horizontal toe velocity might have been associated with a safer and more cautious movement strategy (i.e., crawling strategy), which aimed to avoid any accidental tripping on the stairs. Since the overall goal was to go up the stairs, increasing horizontal toe velocity became secondary so as to ensure the safety and success of clearing the stairs.

Our study indicated that overall children with DS displayed a greater step width but a shorter step length than TD children while negotiating the stairs. Additionally, our study indicated that both children with and without DS decreased step velocity at the first steps during the ascent phase, but the decrease in step velocity was lesser in children with DS than TD children. Similarly, a shorter yet more variable step length and a slower walking speed were also observed in both young adults with DS and TD children during obstacle crossing (Vimercati, Galli, Rigoldi, & Albertini, 2013; Vimercati, Galli, Rigoldi, et al. 2012; McFadyen, Malouin, & Dumas, 2001). Decreased walking speed was also shown in healthy young adults while walking up from the ground to a raised surface (Rietdyk, 2006). The reduced velocity may facilitate the accurate execution of modifications in locomotor patterns (Higuchi, 2013).

Our study also indicated that overall, children with DS displayed a longer step time and a prolonged stance time than TD children while negotiating a staircase. Specifically, children with DS produced a longer step time than TD children from the trailing limb, but not from the leading limb. In addition, both TD children and children with DS increased step time at the first two steps during the ascent phase, but the increase in step time was greater in children with DS than TD children. These results suggest that the DS group needed a longer preparation time before taking the first ascent step and a slower but more cautious movement strategy at the ascent phase. This pattern might be associated with less developed neuromuscular system in the DS group as well as the nature of a slower crawling movement.

2.4.2.3 Effect of stairs height on spatial-temporal gait pattern at the ascent phase

Our study indicated that stair height did not affect a toe-stairs horizontal distance in children with and without DS while negotiating a staircase. Although the DS group produced one half of the distance than the TD group from both the leading and trailing limbs, foot placement was consistent in both groups with the increase in stairs height.

Stair height did not affect step length at the ascent phase, either. This observation is not in agreement with the change in step length while crossing an obstacle in the literature. This difference can be explained by the different task paradigms between stairs negotiation and obstacle crossing, since a higher obstacle may naturally change the movement trajectory of the foot and cause the corresponding change in step length (Patla & Vickers, 1997).

As discussed earlier, toe clearance from the leading limb increased with the increase in the stair height in TD children but decreased in children with DS; whereas toe clearance from the trailing limb decreased in both children with and without DS. Further, children with DS had a decreased toe clearance from the trailing limb under both the MS and HS conditions, compared to LS condition. Under the LS condition, children with DS produced higher toe clearances from both the leading and trailing limb than the TD group. The height of the constraint with an obstacle or a staircase displayed a similar effect trend. Studies reported that when crossing an obstacle, TD children and children with DS increased toe elevation (from the leading limb) in response to the increased obstacle height (Virji-Babul & Brown, 2004: McFadyen, Winter, & Allard, 1994; McFadyen & Winter, 1991; Chou & Draganich, 1997; Patla & Rietdyk, 1993; Patla & Vickers, 1997).

Our study also indicated that instantaneous horizontal toe velocity above the edge of stairs and step velocity decreased, whereas step width, step time, and stance time increased with the increase in stairs height in children with and without DS. Specifically, a decreased horizontal toe velocity above the edge of stairs, a slower step velocity, an increased step time, and a longer stance time were observed under the HS condition, compared to those under both the LS and MS conditions. A greater step width was observed under both the MS and HS conditions, compared to those under the LS condition. Our results suggested that the spatial-temporal pattern might not be markedly changed in children with and without DS when negotiating the stairs with a riser height slightly above or below the riser height of the standard residential stair, until the stairs with a more challenging higher riser height were presented. This may be due to the fact that children with and without DS have accumulated abundant experience from negotiating the riser height of the standard residential stairs during their daily life and activities, but have limited exposure to a new stair condition with drastically higher riser height.

2.4.3 Motor strategy in children with and without DS at the ascent phase

Our study indicated that a step-over-step walking strategy was the dominant motor strategy adopted by TD children under all the three stairs height conditions while going up the stairs. Although in our study, a step-on-step walking strategy and even a crawling strategy were observed under the HS condition in TD children, each of these two motor strategies occurred just once in one subject. In general, TD children were able to negotiate the constraint of a staircase in an environment, despite the increase of stairs height.

Children with DS displayed a variety of motor strategies while going up a staircase, including a step-over-step walking strategy, a step-on-step walking strategy, and a crawling strategy. Stair height played an important role in the selection of motor strategy to accommodate a staircase in children with DS. As the stair height increased, children with DS displayed a lesser preference to adopt a step-over-step walking strategy, but a greater preference to adopt a step-on-step walking strategy and a crawling strategy. The dominant motor strategy was a step-on-step walking strategy under the LS conditions, but a crawling strategy under both the MS and HS conditions in the DS group. And the crawling strategy was the only motor strategy adopted in children with DS while going up a staircase with a high height. Our study indicated that children with DS were able to negotiate the constraint of a staircase in an environment by adopting alternative motor strategies such as a crawling strategy and a step-on-step walking strategy. It might be because individuals with DS tend to be more concerned about movement safety than movement efficiency (Rigoldi, Galli, Mainardi, et al. 2011; Vimercati, Galli, Rigoldi, et al. 2013); hence, they may adopt alternative motor strategies to complete the motor task (Latash, 2007; Rigoldi, Galli, Cimolin, et al. 2012).

Similar findings were observed in individuals with DS while negotiating a constrained environment such as an obstacle. Mulvey et al (2011) found that toddlers with DS used a crawling strategy which was more conservative, cautious, and safer, but also effective and successful to cross an obstacle (Mulvey, Kubo, Chang, & Ulrich, 2011). At 1 month of walking experience, toddlers with DS preferred to crawl over an obstacle and continued crawling after crossing the obstacle, whereas TD toddlers preferred to walk over an obstacle, although with errors; by 3 month of walking experience, toddlers with DS still tended to negotiate an obstacle with crawling strategy (but changed the crawling to walking immediately after crossing the obstacle), whereas TD toddlers tended to successfully walk over an obstacle. Infants with DS were also found to adopt both crawling and walking strategies to cross an obstacle (Wu, Ulrich, Looper, et al. 2008), whereas infants with DS who received an individualized, high-intensity training protocol used a walking strategy as the primary strategy in clearing an obstacle about 6 months earlier than those who received a generalized, lower-intensity training protocol (Wu, Ulrich, Looper, et al. 2008). Taken together, it was concluded that both infants and children with DS prefer to select a safer motor strategy alternative to walking when presented with a challenging constrained environment. However, an effective locomotor training program can markedly improve adaptive locomotion ability in children with DS.

2.4.4 Limitations of the Study and Future Research Direction

There were some limitations in this study.

The first limitation was the sample size. As there might be different levels of developmental delay in the physical, cognitive, and mental domains in children with DS, our small sample size of subjects with DS in this study may not represent the motor pattern in the whole population of children with DS. We acknowledge that children older than 7 years of age may have better motor capacity than those young than 7 years of age. Even though the age range of the subjects in our study was between 5 and 11 years, we had only 1 child with DS and 3 TD children aged 5 years. The majority of our subjects with and without DS were between 7 and 11 years. Therefore, our subjects may represent a good sample of this narrower age range with better motor ability. Future studies are warranted to increase the subject number of children with and without DS, particularly between 5 and 7 years of age, to explore the potential developmental differences in adaptive locomotion.

The second limitation was the staircases used for the walking experiments in this study. The height of staircase used in this study was not specifically proportional to each subject's body/leg length. A staircase setting is different from an obstacle setting in that it is easy to change the height of an obstacle to the proportion of each subject's height. In practice, it is almost impossible to make three staircases with different riser heights for every subject. Even though we used three staircases with fixed riser heights, a similar body height between children with and without DS in our study allowed us to compare motor strategy and general locomotor pattern between the two groups while transitioning from the level surface to the stairs. Future studies may want to provide additional staircases with even lower and higher riser heights. A lower riser height would allow us to understand when children with DS would use a walking strategy as their dominant strategy and what their locomotor pattern looks like. A higher riser height would allow us to remove the ceiling effect for TD children and explore their motor capacity and alternative strategies while confronting a challenging environment. In addition, future studies may be warranted to compare staircases with and without handrails to investigate the effect of handrails on motor strategy and locomotor pattern between children with and without DS while going up the stairs.

The third limitation was that the walking gait of recruited subjects was collected in the laboratory environment, which may be different from their natural walking environment in their daily life and activities. In our study, there were two force plates embedded in the walkway. Even though we told the subjects they should not target their feet on those two force plates, children might still have targeted their feet while approaching the stairs. This might change the natural waking pattern, to a certain extent, in both children with and without DS. Future studies may want to eliminate the visual difference between the surface of force plate area and the surface of walkway area which leads to subjects targeting their feet on the force plates. As children will not try to land feet on the force plates while approaching a staircase, it may facilitate the display of natural locomotion pattern in children with and without DS.

2.4.5 Summary and Conclusions

At the approaching phase:

1) TD children walked with a similar step length, step time, and step velocity over the last three steps while approaching a staircase. However, TD children decreased their step width two steps prior to a staircase, and prolonged stance time of their trailing limbs in front of the staircase. It was suggested that TD children were able to make task-specific ALAs in accordance with different environments during the locomotion.

2) Children with DS maintained step width and step time over the last three steps of the approaching phase, but decreased step length and step velocity and increased stance time in sequence at the last three steps during the approaching phase. When compared to TD children, the DS group walked with an increased step width, a decreased step length, a decreased step velocity, and an increased stance time. Children with DS were able to make some ALAs although it was less advanced in comparison to TD children.
3) The stair riser heights which were slightly different from the standard residential stairs riser height did not affect both step width and step length in children with and without DS while approaching a staircase. However, the constraint of a staircase with a riser height of 31cm caused children with and without DS to increase step time and stance time but decrease step velocity while approaching the staircase.

At the ascent phase:

4) While going up the stairs, both children with and without DS displayed a decreased toe-stairs horizontal distance, a decreased toe clearance above the edge of stairs, a decreased horizontal toe velocity, a decreased step length, a decreased step velocity, an increased step width, and an increased step time, from the trailing limb than from the leading limb. This suggests a similar coordination between the leading and trailing limbs in both groups.
5) Overall, children with DS displayed a decreased toe-stairs horizontal distance, a decreased horizontal toe velocity, a decreased step length, a decreased step velocity, an increased step width, an increased step time, an increased stance time than TD children at the first two steps during the ascent phase. While making relevant locomotor adjustments

during the ascent phase, children with DS are not able to produce the spatial-temporal patterns similar to TD children.

6) Similar to the approaching phase, stair riser heights which were slightly different from the standard residential stairs riser height did not affect foot placement and step length in children with and without DS. A markedly higher stair riser height elicited locomotor adjustment in children with and without DS, particularly in children with DS. Further, a lower stair riser height caused an "overshooting" movement pattern and a higher stair riser height resulted in an "undershooting" movement pattern from the leading limb in children with DS.
7) TD children used a step-over-step walking strategy as the dominant motor strategy under all the three stairs riser height conditions. In contrast, children with DS preferred a more conservative crawling strategy while going up a higher staircase. Children with DS were able to use their available resources related to locomotion and select an appropriate motor strategy while negotiating a staircase.

References

Almeida GL, Corcos DM, Latash ML. Practice and transfer effects during fast single-joint elbow movements in individuals with Down syndrome. *Phys Ther.* 1994; 74(11):1000-12; discussion 1012-6.

Aruin AS, Almeida GL, Latash ML. Organization of a simple two-joint synergy in individuals with Down syndrome. *Am J Ment Retard.* 1996; 101(3):256-68.

Carmeli E, Ayalon M, Barchad S, Sheklow SL, Reznick AZ.Isokinetic leg strength of institutionalized older adults with mental retardation with and without Down's syndrome. *J Strength Cond Res.* 2002; 16(2):316-20.

Carmeli E, Kessel S, Coleman R, Ayalon M. Effects of a treadmill walking program on muscle strength and balance in elderly people with Down syndrome. *J Gerontol A Biol Sci Med Sci.* 2002; 57(2):M106-10.

Caselli MA, Cohen-Sobel E, Thompson J, Adler J, Gonzalez L. Biomechanical management of children and adolescents with Down syndrome. *J Am Podiatr Med Assoc.* 1991; 81(3):119-27.

Chen HC, Ashton-Miller JA, Alexander NB, Schultz AB. Stepping over obstacles: gait patterns of healthy young and old adults. *J Gerontol.* 1991; 46(6):M196-203.

Chou LS, Draganich LF. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. *J Biomech.* 1997; 30(4):331-7.

Cioni M, Cocilovo A, Rossi F, Paci D, Valle MS. Analysis of ankle kinetics during walking in individuals with Down syndrome. *Am J Ment Retard* 2001; 106(5):470-8.

Cowley PM, Ploutz-Snyder LL, Baynard T, Heffernan K, Jae SY, Hsu S, Lee M, Pitetti KH, Reiman MP, Fernhall B. Physical fitness predicts functional tasks in individuals with Down syndrome. *Med Sci Sports Exerc.* 2010; 42(2):388-93.

Cowley PM, Ploutz-Snyder LL, Baynard T, Heffernan KS, Jae SY, Hsu S, Lee M, Pitetti KH, Reiman MP, Fernhall B. The effect of progressive resistance training on leg strength, aerobic capacity and functional tasks of daily living in persons with Down syndrome. *Disabil Rehabil.* 2011; 33(23-24):2229-36.

Galli M, Rigoldi C, Brunner R, Virji-Babul N, Giorgio A. Joint stiffness and gait pattern evaluation in children with Down syndrome. *Gait Posture* 2008; 28(3):502-6.

Higuchi T. Visuomotor control of human adaptive locomotion: understanding the anticipatory nature. *Front Psychol.* 2013; 4:277.

Latash ML. Learning motor synergies by persons with Down syndrome. *J Intellect Disabil Res.* 2007; 51(Pt 12):962-71.

Law LS, Webb CY. Gait adaptation of children with cerebral palsy compared with control children when stepping over an obstacle. *Dev Med Child Neurol.* 2005; 47(5):321-8.

McFadyen BJ, Malouin F, Dumas F. Anticipatory locomotor control for obstacle avoidance in mid-childhood aged children. *Gait Posture.* 2001; 13(1):7-16.

McFadyen BJ, Winter DA, Allard F. Simulated control of unilateral, anticipatory locomotor adjustments during obstructed gait. *Biol Cybern.* 1994; 72(2):151-60.

McFadyen BJ, Winter DA. Anticipatory locomotor adjustments during obstructed human walking. *Neurosci Res Commun* 1991; 9:37–44.

Mulvey GM, Kubo M, Chang CL, Ulrich BD. New walkers with Down syndrome use cautious but effective strategies for crossing obstacles. *Res Q Exerc Sport*. 2011; 82(2):210-9.

Oh-Park M, Wang C, Verghese J. Stair negotiation time in community-dwelling older adults: normative values and association with functional decline. *Arch Phys Med Rehabil.* 2011; 92(12):2006-11.

Palisano RJ, Walter SD, Russell DJ, Rosenbaum PL, Gémus M, Galuppi BE, Cunningham L. Gross motor function of children with down syndrome: creation of motor growth curves. *Arch Phys Med Rehabil.* 2001; 82(4):494-500.

Patla AE, Rietdyk S. Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. *Gait Posture* 1993; 1:45–60.

Patla AE, Vickers JN. Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport.* 1997; 8(17):3661-5.

Pearson K, Gramlich R. Updating neural representations of objects during walking. *Ann N Y Acad Sci.* 2010; 1198:1-9.

Rietdyk S. Anticipatory locomotor adjustments of the trail limb during surface accommodation. *Gait Posture.* 2006; 23(3):268-72.

Rigoldi C, Galli M, Albertini G. Gait development during lifespan in subjects with Down syndrome. *Res Dev Disabil.* 2011; 32(1):158-63.

Rigoldi C, Galli M, Mainardi L, Crivellini M, Albertini G. Postural control in children, teenagers and adults with Down syndrome. *Res Dev Disabil.* 2011; 32(1):170-5.

Roizen NJ, Patterson D. Down's syndrome. *Lancet.* 2003; 361(9365):1281-9.

Salami F, Vimercati SL, Rigoldi C, Taebi A, Albertini G, Galli M. Mechanical energy assessment of adult with Down syndrome during walking with obstacle avoidance. *Res Dev Disabil*. 2014; 35(8):1856-62.

Shumway-Cook A, Woollacott MH. Dynamics of postural control in the child with Down syndrome. *Phys Ther*. 1985; 65(9):1315-22.

Spanjaard M, Reeves ND, van Dieën JH, Baltzopoulos V, Maganaris CN. Influence of step-height and body mass on gastrocnemius muscle fascicle behavior during stair ascent. *J Biomech.* 2008; 41(5):937-44.

Taga G. A model of the neuro-musculo-skeletal system for anticipatory adjustment of human locomotion during obstacle avoidance. *Biol Cybern.* 1998; 78(1):9-17.

Ulrich BD, Haehl V, Buzzi UH, Kubo M, Holt KG. Modeling dynamic resource utilization in populations with unique constraints: preadolescents with and without Down syndrome. *Hum Mov Sci.* 2004; 23(2):133-56.

Vallis LA, McFadyen BJ. Children use different anticipatory control strategies than adults to circumvent an obstacle in the travel path. *Exp Brain Res.* 2005; 167(1):119-27.

Vimercati SL, Galli M, Rigoldi C, Albertini G. Obstacle avoidance in Down syndrome. *J Electromyogr Kinesiol.* 2013; 23(2):483-9.

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G. Motor strategies and motor programs during an arm tapping task in adults with Down Syndrome. *Exp Brain Res.* 2013; 225(3):333-8.

Vimercati SL, Galli M, Rigoldi C, Ancillao A, Albertini G. Spatiotemporal and kinematic aspects of obstacle avoidance in subjects with Down syndrome. *Funct Neurol.* 2012; 27(4):231-7.

Virji-Babul N, Brown M. Stepping over obstacles: anticipatory modifications in children with and without Down syndrome. *Exp Brain Res.* 2004; 159(4):487-90.

Weerdesteyn V, Nienhuis B, Duysens J. Advancing age progressively affects obstacle avoidance skills in the elderly. *Hum Mov Sci.* 2005; 24(5-6):865-80.

Wu J, Beerse M, Ajisafe T. Frequency domain analysis of ground reaction force in preadolescents with and without Down syndrome. *Res Dev Disabil.* 2014; 35(6):1244-51.

Wu J, Ulrich DA, Looper J, Tiernan CW, Angulo-Barroso RM. Strategy adoption and locomotor adjustment in obstacle clearance of newly walking toddlers with Down syndrome after different treadmill interventions. *Exp Brain Res.* 2008; 186(2):261-72.