Gait Biomechanics With and Without Supramalleolar Orthosis in Children with Down Syndrome

ACCEPTANCE

This dissertation, GAIT BIOMECHANICS WITH AND WITHOUT SUPRAMALLEOLAR ORTHOSIS IN CHILDREN WITH DOWN SYNDROME, 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.

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GAIT BIOMECHANICS WITH AND WITHOUT SUPRAMALLEOLAR ORTHOSIS IN CHILDREN WITH DOWN SYNDROME

by

Robert Zeid II

Under the Direction of Dr. Jerry Wu

ABSTRACT

Individuals with Down syndrome (DS) exhibit delays in motor, cognitive, language, and social development. Neural impairments lead to significant biomechanical challenges, particularly in stabilizing lower extremity joints. As a result, children with DS often develop compensatory strategies, such as co-contraction of antagonistic muscles, contributing to inefficient gait mechanics. Supramalleolar orthoses (SMOs) are commonly prescribed to provide support to the ankle above the malleoli, enhance joint stability, and improve gait. However, evidence on their effectiveness, particularly in relation to obstacle crossing mechanics and strategy selection, remains limited. Consequently, clinicians often rely on anecdotal guidance regarding the timing and necessity of SMO use. This study examined overground walking and obstacle crossing in 23 young children with DS (ages 2–6), comparing 10 daily SMO users to 13 non-users. Children were evaluated while walking barefoot and with footwear, crossing obstacles set at 10% and 30% of leg length. We assessed various crossing strategies, including successful and unsuccessful steps over the obstacle, bear crawling, walking around, or refusing to cross. Results showed that SMO users demonstrated improved overground walking mechanics when wearing their orthoses, including increased cadence, walking speed, step length, and hip and knee angular velocities. During obstacle crossing, SMO use was associated with higher rates of successful crossings and

fewer secondary strategies (e.g., walking around or refusing). Additionally, the SMO group showed improved step length and crossing velocity with SMOs on, though they relied more on frontal plane hip motion and proximal joint strategies to clear the obstacle. In conclusion, SMOs can enhance walking and obstacle crossing performance in young children with DS. However, prescription decisions should be individualized, taking into account specific characteristics such as joint laxity and hypotonia. These findings provide clinicians with data-driven insights into the functional benefits of SMOs and may inform more targeted orthotic interventions.

INDEX WORDS: Down syndrome, gait, obstacle crossing, supramalleolar orthosis, biomechanics

GAIT BIOMECHANICS WITH AND WITHOUT SUPRAMALLEOLAR ORTHOSIS IN CHILDREN WITH DOWN SYNDROME

by

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LIST OF ABBREVIATIONS

ASIS	Anterior superior iliac spine
BOTMP	Bruininks-Oseretsky Test of Motor Proficiency
DS	Down Syndrome
FO	Foot orthosis
FPA	Foot Progression Angle
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
NW	New walkers
PSIS	Posterior superior iliac spine
ROM	Range of motion
SI	Symmetry Index
SMO	Supramalleolar orthosis
TD	Typically developing

ABSTRACT

Individuals with Down syndrome (DS) display delays in motor, cognitive, language, and social development. The impairments in the central and peripheral neural systems cause significant biomechanical deficits due to the inherent need to stabilize the joints in the lower extremity, thus resulting in compensatory strategies, such as co-contracting antagonistic muscles, and inefficient gait mechanics. Supramalleolar orthosis (SMO) are orthotics that provide support to the foot and the ankle above the level of the malleoli and are a common clinical intervention to provide stability at the ankle joint and improve gait mechanics. There is limited evidence on the efficacy that SMOs provide on gait and obstacle crossing mechanics, strategy used to cross the obstacles and fall risk. Therefore, clinicians rely on anecdotal evidence for the timing of prescription and use. In this study, we assessed strategy type from all attempts, which include stepping over the obstacle successfully or unsuccessfully, bear crawling, walking around, or refusing to cross. We analyzed spatiotemporal and kinematic patterns of overground walking and obstacle crossing in young children ages 2 to 6 years old, who either use or do not use SMOs for daily walking. Twenty-three young children with DS, 10 who used SMOs for daily walking and 13 who did not use SMOs were recruited in the study. We evaluated the child's ability to walk overground and cross an obstacle height of 10% and 30% of the child's leg length, both barefoot and with their footwear. Results of the study revealed that the SMO group improved their overground walking mechanics, such as cadence, walking speed, step length, and hip and knee angular velocities, when they wore their SMOs. Supramalleolar orthotic use also improved successful obstacle crossing strategy and reduced choosing secondary strategies to cross the obstacle in the SMO group. The SMO group also presented with improvements in spatiotemporal variables, such as step length and crossing velocity, but increased the use of frontal plane hip kinematics and

increased reliance on proximal joints to clear the obstacle. The results from this study concluded that SMO use can benefit young children with Down syndrome, but the prescription may need to be individualized based on characteristics such as joint laxity and hypotonia.

Chapter 1: Literature review of gait and obstacle crossing biomechanics, and supramalleolar orthosis in children with Down syndrome

Guiding Questions

1. What are the biomechanical features of gait in children with Down syndrome?
2. What are the biomechanical features of obstacle crossing in children with Down syndrome?
3. How do SMOs impact gait biomechanics in children with Down syndrome?

Gait Characteristics in Children with Down Syndrome

Whittle describes walking as "a method of locomotion involving the use of the two legs, alternately, to provide both support and propulsion [1]." Walking requires complex neuromuscular coordination and for infants, toddlers, and children, it is a key piece for not just gross motor development, but also cognitive and social development, since walking allows the individual to explore and interact with their environment [2-4]. While walking describes the type of locomotor activity, gait refers the manner or style of walking, and is divided between stance phase and swing phase [1]. Gait analysis is an important measure to understand gait characteristics. It is particularly useful when examining motor impairments in children with developmental delays and evaluating the effectiveness of interventions in these populations [2].

Whittle defines the gait cycle as the time interval between two successive occurrences during repetitive walking, usually beginning with the initial contact of one limb, followed by the subsequent initial contact of the same limb [1]. Two notable events occur during the gait cycle, the stance phase and swing phase. The stance phase of walking occurs when the limb is placed on the ground and actively advances the body forward, usually lasting around 55% - 60% of the gait cycle in both TD children and healthy adults [5], with about 20% of that time being spent in

double support, or both legs touching the ground [1, 2, 5]. The remaining time is spent in swing phase, which is the phase where the limb is off the ground and advancing forward in preparation for the next foot contact. The stance phase can be divided up into loading response, mid-stance, terminal stance, and pre-swing. The loading response typically occurs in the first 12% of the gait cycle and begins with initial contact and concludes when the opposite leg begins its swing phase. Mid-stance occurs following loading response and ends when the feel begins to rise. Terminal stance begins when the heel begins to rise and concludes during the opposite foot's initial contact. Pre-swing concludes the stance phase and ends when at toe-off. The swing phase contains three phases, the initial swing, mid-swing, and terminal swing. Initial swing begins following pre-swing and concludes when the foot is adjacent to the stance foot of the opposite leg. Mid-swing then follows and concludes when the tibia is vertical to the ground. Finally, the terminal swing phase begins when the tibia is vertical and concludes at initial contact [1].

Toddlers and children with DS exhibit differences in gait parameters than TD individuals due to accompanying muscle hypotonia and ligamentous laxity causing foot eversion, foot flat deformity, and other structural abnormalities [6, 7]. These structural deficits and functional impairments negatively impact postural control, stability, and coordination. Therefore, there is an inherent need to utilize compensatory mechanisms, such as co-contracting antagonistic muscles, in order to safely walk and explore their environment [8, 9]. The functional impairments and subsequent structural deficits are detrimental to gait parameters. For example, it has been shown that a reduction in ankle ROM causes a reduction in plantarflexion moment and ankle power at terminal stance, resulting in lower push-off ability and making walking less efficient and impairing the child's ability to explore their environment effectively [10].

To better understand how structural deficits and functional impairments associated with DS impact walking, a gait analysis is performed to gather spatiotemporal, kinematic, kinetic, and/or muscle activation data. Patterns of this data are analyzed and graphed to observe the patterns occurring within phases of the gait cycle and compare them to a control or condition. The following sections will discuss common spatiotemporal, kinematic, kinetic, and muscle activation characteristics seen in DS gait, followed by a discussion regarding the use of SMO and its impact on gait in individuals with DS.

Spatiotemporal Characteristics

Spatiotemporal characteristics within the gait cycle consists of measures of space, time, or space relative to time. Common spatiotemporal variables calculated include the following: walking/gait velocity, the change in position over time; cadence, the number of steps over time, usually in steps per minutes; step length, the distance covered in one step, often defined by the distance in the anterior-posterior direction from the heel of one foot to the heel of the opposite foot; step width, the distance in the medial-lateral direction between the heels of each subsequent step; stride length, the distance in the anterior-posterior direction covered in one stride, i.e. from the heel of one foot to the heel of the same foot in the subsequent step [3, 11, 12]. These can be further analyzed, such as using coefficient of variation to quantify variability [12], or calculated ratios, such as Naito and colleague's duration of single leg stance ratio, which is the ratio of the duration of the stance phase minus double limb support phase over the duration of the stance phase minus the swing phase [11].

Kubo et al. (2006) examined changes of gait in TD toddlers and toddlers with DS in the anteroposterior and mediolateral directions at the onset of independent walking (i.e., visit 1) and 1 month after (i.e., visit 2). Spatiotemporal variables and displacement of center of mass in

anteroposterior and mediolateral directions were observed using 3D motion analysis during overground walking trials. Toddlers with TD walked significantly faster and displayed significantly longer stride lengths than those with DS in visit 2. Toddlers with DS demonstrated a higher stride frequency than TD during visit 1 only. Toddlers with TD demonstrated significant increases in stride frequency between visit 1 and 2, while toddlers with DS minimally improved stride frequency. Step width was similar between the two groups during visit 1. While subjects with DS presented with similar step widths during visit 2, the TD group revealed a significantly narrower step width [13].

In 63 individuals with DS aged 1-6 years who were prescribed orthotic insoles for their flat foot deformity, Naito and colleagues (2015) investigated and compared the spatiotemporal characteristics within four of the five determinants of gait maturity in TD children. The variables included walking velocity, cadence, step length, and single-support percentage. One of the determinants, the ratio of pelvic span to ankle speed, was not measured since the investigators used a sheet-type gait analyzer. A regression analysis was conducted to examine the relationship between age and each of the four gait parameters. Walking velocity and step length were positively associated with age, whereas the child becomes older by 1-month, velocity increases by 0.575 cm/s, and step length increases by 0.339 cm. There was a negative association with cadence and age, whereas the child ages by 1-month, they walk 0.648 fewer steps. There was no statistically significant relationship between age and single-support percentage. Age-related increases in walking velocity and step length, along with the decrease in cadence were also found in children with DS. However, the DS group did not present with an increase in single-support percentage compared to TD children, indicating that children with DS spend a longer time in double-limb support phase [11].

Looper et al. (2006) assessed gait variability between toddlers with DS and TD who were either new walkers (NW) recruited when they were able to take 3-6 consecutive steps or had participated in either a low-intensity or high-intensity treadmill training (TT) intervention when they were infants. The TD-NW toddlers were assessed monthly from walking onset through 6 months of walking experience, and the DS-NW were assessed at 1, 3, 4, 6, and 8 months of walking experience. The DS-TT group were assessed over 4 sessions, where the first visit occurred when the child was able to take 8-10 steps independently, then 3, 6, and 12 months following that initial visit. Step length and step width variability were assessed and calculated as the coefficient of variation. Both DS-NW and TD-NW displayed a greater variability in step length than step width at walking onset, and over time, this pattern converged in which step width variability increased as step length variability decreased. The DS-NW revealed a significantly larger difference in step length and step width variability. In the NW group, step length and step width variability converged around 4 months after the onset of walking for the TD-NW group and between 7 and 8 months for the DS-NW group. For the treadmill training groups, step length and step width variability converged after 4 months of walking experience in the high intensity group and between 5 and 6 months in the low intensity group [3].

Jung and colleagues (2017) observed gait function in children with DS and TD, which included measures of velocity, cadence, step length, stride length, and step width using a GAITRite mat. The children in each group were further divided into before school-aged (4-7 years, $N_{DS} = 9$, $N_{TD} = 9$) and school-aged (8-12 years, $N_{DS} = 7$, $N_{TD} = 11$) to compare changes seen with age. Velocity was significantly different between the two groups, with TD presenting with increased walking velocities in the group as a whole and at school-age (Total: 103.23±25.89 cm/s versus 85.8±16.0 cm/s; School-aged: 112.89±27.48 cm/s versus 80.3±19.8 cm/s,

respectively). Cadence was significantly decreased in the TD group versus the DS group, both in the group as a whole and before school-age (Total: 131.6±18.2 steps/min versus 154.8±30.1 steps/min; Before school-aged: 137.7±16.7 steps/min versus 171.2±28.3 steps/min, respectively). Compared to children with DS, TD children showed significantly longer step length (Total: 47.5±10.9 cm versus 33.6±6.7 cm; Before school-aged: 40.1±7.1 cm versus 31.8±3.7 cm; and School-aged: 53.6±9.8 cm versus 35.9±9.1 cm, respectively) and stride length (Total: 95.1±22.4 cm versus 67.4±12.1 cm; Before school-aged: 80.5±14.4 cm versus 63.8±5.9 cm; School-aged: 107.1±21.0 cm versus 72.1±16.7 cm, respectively) as a whole and with both age subgroups. Step width was significantly narrower in the TD group as a whole and in the before school-age group, compared to the DS group (Total: 8.8±2.1 cm versus 10.9±2.7 cm; Before school-age: 8.4±1.7 cm versus 11.2±2.7, respectively). The DS group also demonstrated a significant reduction in cadence in the DS school-age group versus the DS before school-age group (133.7±16.7 steps/min versus 171.2±28.3 steps/min, respectively). School-aged children with DS matched their TD peers in only two of the determinants of mature gait, cadence and step-width, indicating their delay in gait maturation [14].

Beerse et al, (2019) explored the variability of spatiotemporal gait parameters in children aged 7 – 10 years with DS and TD during two bouts of 60s treadmill walking at two different speeds and two ankle load conditions. To determine treadmill speed, the average of three 10 meter overground walking trials at the subject's preferred walking speed was calculated. The slow treadmill condition consisted of 75% of the subject's preferred walking speed, and the fast treadmill condition consisted of 100% of the preferred overground walking speed. The ankle load condition consisted of a no ankle load and 2% of the individual's body mass. Spatiotemporal variables (normalized to leg length) included normalized step length, normalized

step width, swing percentage, and double support percentage. In the DS group, normalized step length revealed a group by load interaction, where the DS group demonstrated an increase from 0.66±0.12 to 0.76±0.12 in the no load condition and 0.64±0.13 to 0.76±0.15 in the ankle load condition, and the TD group demonstrated an increase from 0.79±0.09 to 0.88±0.10 in the no load condition and 0.81±0.10 to 0.91±0.10 in the ankle load condition, when changing from slow to fast treadmill speed, respectively. Swing percentage decreased from 64.46±3.00% to 62.66±2.90% from slow speed to fast speed without load in the DS group. There was a load effect in which swing percentage decreased from 62.66±2.90% to 60.29±1.88% when changing from no load to ankle load during fast speed treadmill walking in the DS group. Despite the changes in conditions, children with DS maintained their spatiotemporal differences from their TD counterparts, though displaying trends in improvement. Children with DS displayed a decreased step length, increased step width, increased swing percentage, and increased double support time [12].

There are common differences in spatiotemporal gait parameters in children with DS versus TD children. Children with DS display decreased walking velocity and step and stride lengths, wider step widths, increased double support time, and step cadence. In addition to these spatiotemporal variables with walking, when challenged to a gait task, Chen et al, (2016) observed the spatiotemporal characteristics of walking and stepping over obstacles at 10, 20, and 30% of the leg lengths of children with DS and TD. In subjects with DS, step length was longer, step width was wider, and crossing speed was slower when stepping over obstacles, compared to TD. When stepping over the obstacles, the leading toe clearance was greater in children with DS, but the trailing toe clearance was similar between the two groups. The authors of this study concluded that children with DS adapt a more conservative compensatory mechanism to clear

obstacles by increasing clearing height, which can be related to a DS-related perceptual-motor problem [15].

Gait asymmetry is a notable characteristic in children with Down syndrome, with origins rooted in early motor development, influenced by accompanying impairments, such as joint laxity and hypotonia. Lim et al. (2008) reported that children with Down syndrome were found to exhibit distinctive asymmetrical gait features, including flat-footed contact, excessive abduction of the leg during swing phase, and abnormal knee and hip flexion throughout the gait cycle. The observed gait asymmetries were largely attributed to underlying muscle hypotonia, muscle weakness, ligamentous laxity, and other orthopedic abnormalities common in Down syndrome [16]. Angulo-Baroso, et al. (2008) examined the long-term effects of different treadmill training interventions on gait development in infants with Down syndrome. In this longitudinal study, new walkers with Down syndrome were assigned to various treadmill protocols, and their gait parameters were tracked over time. The authors found the results showed that both high-intensity and low-intensity treadmill interventions led to a significant reduction in foot rotation asymmetry over time in infants with Down syndrome. However, there was no significant difference in asymmetry reduction between the two training protocols. Thus, treadmill intervention appears effective in decreasing certain forms of gait asymmetry in this population, even if protocol intensity does not differentially affect the outcome.[17]. In a cross-sectional study, Valero et al. (2021) surveyed parents of 361 children with Down syndrome to examine the relationships between foot rotation asymmetry, the timing of hands-and-knees crawling, age at independent walking, and orthopedic conditions. The results indicated that children who experienced delays in crawling and later onset of walking were more likely to display foot rotation asymmetry, with each month of delayed walking onset increasing the odds

of asymmetry by 7%. Additionally, foot rotation asymmetry was significantly associated with orthopedic problems such as knee alterations and flat feet, whereas factors like gender, ethnicity, and therapy interventions showed no significant impact. These findings suggest that early motor milestone achievement and musculoskeletal health play key roles in the development of gait asymmetry in Down syndrome, highlighting the importance of early intervention and monitoring in this population. Wu & Wu (2015) discussed that gait symmetry is considered and important feature of gait and a vital indicator of gait function in both healthy and clinical populations [18]. The authors calculated gait Symmetry Index (SI) using step lengths from the right and left sides. The formula used to calculate SI was $SI = \frac{2(X_r - X_l)}{X_r + X_l} \times 100\%$, where X is the subject's right or left step length [18].

Kinematic Characteristics

Kinematic data includes the displacement and orientation of body segments and the angle of joint segments, which often involve the use of 2D or 3D motion capture with reflective markers over specific anatomical locations along the limbs [1, 19]. When analyzing joint kinematics within the gait cycle, the pelvis, hip, knee, and ankle joints are frequently measured and their patterns are observed, often in the sagittal and frontal planes of movement. Sagittal plane views are perpendicular to the subject, where one would observe movement of the right or left side of the subject, whereas the frontal plane view observes the anterior (front of the body) or posterior (back of the body) view of the subject. Despite the functional limitations associated with DS, assuming no unilateral injury or structural deficit, individuals with DS present with similar gait kinematic patterns in the hip, knee, and ankle. Therefore, peak values of the hip, knee, and ankle in the sagittal plane, as well as overall sagittal ROM of each joint are measured and compared between individuals with DS and TD.

Kinematics of the Hip

The hip joint is the most proximal joint of the lower extremity and consists of the articulation between the head of the femur and the acetabulum of the pelvis [20]. Sagittal normative ROM of the hip ranges from hip flexion, or the angle at the hip when the thigh moves towards the front of the trunk, to hip extension, or the angle at the hip when the thigh moves towards the back of the trunk. It's important to note that the hip neutral position from the sagittal view, or 0 degrees, occurs when the thigh is aligned with the trunk. Hip flexion ROM in TD individuals occurs around 123±6°, while hip extension ROM in TD individuals occurs around 7±7° [20, 21].

ROM excursion graphs in gait studies often depict hip flexion values as positive and hip extension values as negative. Frontal plane hip joint movements include hip abduction, which is when the hip moves the lower extremity away from the body, and hip adduction, which is when the hip moves the lower extremity closer to the midline of the body. At the start of the gait cycle, TD individuals begin with around 20-30° of hip flexion at initial contact [1, 20, 22-24]. The hip moves into extension to propel the body forward and reaches its peak around 50% of the gait cycle before initiating hip flexion during the swing phase [1]. Peak hip extension can range from -5° to -15° and is a contributing factor to total sagittal hip ROM and step length [22, 25]. Following peak hip extension, the hip begins to flex again, reaching peak hip flexion around 80-85% of the gait cycle [20]. Children with DS display limitations in sagittal hip ROM from their inherent increase in joint stiffness, demonstrating an increased hip flexion at initial contact, no hip flexion at terminal stance, and an overall reduction in sagittal hip ROM.

Galli and colleagues (2008) demonstrated that children (M_{age} *= 11.7 years; range = 6-15 years)* with DS did not achieve hip extension, with the hip maintaining flexion at 11.5±9.7° at

terminal stance. Overall, children with DS achieved much less total hip ROM in the sagittal plane throughout the gait cycle than TD children (27.4±7.1° versus 37.9±4.1°, respectively) [22]. Rigoldi (2011) measured the sagittal hip kinematics in children, teenagers, and adults with DS, revealing that the three groups maintained a significantly larger hip flexion at initial contact and a significant reduction in overall sagittal hip ROM than the aged matched TD group [24]. Cimolin and colleagues (2010) compared gait kinematics in 21 young adults with DS to age-matched TD controls. The authors found that the DS group had significantly more hip flexion at initial contact than the TD group (33.74±11.46° vs 27.23±9.47°). The DS group also failed to achieve hip extension, maintaining hip flexion at terminal stance compared to the TD group (1.32±9.20° vs -14.83±9.60°). Sagittal ROM was also significantly less in the DS group compared to the TD group [25].

Kinematics of the Knee

The knee joint consists of the articulation between the femur and tibia (or thigh and shank) and is primarily controlled by the quadriceps and hamstring muscle complex, to perform knee extension and knee flexion, respectively. Knee extension occurs when the angle between the thigh and shank increases, perceived as when the leg is "straightening," and knee flexion occurs when the angle between the thigh and shank decreases, perceived as when the leg is "bending." Normal ROM about the knee has been measured around -2±3° of knee hyperextension to around 144±5° of knee flexion [20, 21].

At initial contact, the knee is nearly fully extended and begins to flex as the foot continues to contact the ground. There is a peak knee flexion of approximately 15° when the foot is completely flat on the ground, within 15% of the gait cycle. At this point the knee begins to extend, reaching peak extension around 40% of the gait cycle, or when the heel begins to rise.

The knee now begins to flex again as the leg transitions into the swing phase, reaching a peak knee flexion of approximately 70°, at around mid-swing of the gait cycle [1, 20].

There is an inherent need to increase knee stiffness, particularly through stance phase as to prevent the knee from buckling. At initial contact, children with DS possess larger values of knee flexion than their TD peers (10.3±7.0° versus 6.3±4.7°, respectively) as reported by Galli and colleagues (2008). Sagittal plane knee ROM throughout the stance phase was significantly more flexed as children with DS progressed through stance phase, with knee flexion at mid-stance measured at 14.7±9.3° versus 6.5±4.2° in TD children. Additionally, the authors measure a nonsignificant reduction of knee flexion in swing phase in children with DS [22]. These patterns of reduced knee ROM are evident of overall knee stiffness by maintaining a flexed knee throughout stance phase and inherently avoiding the first knee extension excursion at midstance, has been observed in childhood and carried over to adulthood [24-26].

Kinematics of the Ankle

The articulation between the tibia and fibula of the leg forms a cavity called the mortise, in which the talus fits into, creating a hinge like joint called the talocrural joint, or more commonly, the ankle joint. The talocrural articulation has one degree of freedom of movement occurring at the sagittal plane. A neutral ankle position occurs with the foot positioned 90° from the leg. Two motions occur at the talocrural joint, ankle dorsiflexion and ankle plantarflexion, which occur in the sagittal plane. Ankle plantar flexion occurs when the foot points away from the body, with normal ROM ranging from 58±6°. It is primarily moved by the triceps surae muscle group, composed of the gastrocnemius and soleus muscle complex. Ankle dorsiflexion occurs when the foot points towards the body, with normal ROM ranging from 13±5°. It is primarily moved by contraction of the tibialis anterior muscle. In addition to the talocrural joint,

the subtalar joint is an articulation between the talus and the calcaneus, or heel bone. This joint offers more degrees of freedom, with movements including inversion/supination (the plantar aspect of the foot rotates towards the midline) and eversion/pronation of the foot (the plantar aspect of the foot rotates away from the body) occurring in the frontal plane [20, 21].

During gait, the ankle joint is a loadbearing joint that allows the body to translate forward over the foot, followed by a strong propulsion through active plantarflexion. At initial contact, the ankle around neutral position in the sagittal plane and supinated in the frontal plane. The ankle then moves towards plantarflexion and pronation during the loading response as the body pivots along the heel, which is called the first rocker. At the beginning of midstance, the ankle begins to dorsiflex as the tibia begins to translate anteriorly over the talus, which is called the second rocker. This continues until mid-terminal stance, when forward propulsion takes place and the ankle powerfully moves into plantarflexion and supination. The third rocker takes place at this time, as the ankle and midfoot pivot forward over the first metatarsal. The ankle begins to dorsiflex with continued supination during initial swing to provide foot clearance throughout the swing phase. Peak dorsiflexion in swing occurs near the end of terminal swing [1].

As with the hip and the knee joint, children with DS generate less overall sagittal ankle ROM throughout the gait cycle than their TD counterparts and is typically maintained this way throughout the lifespan [22, 24-26]. At initial contact, children with DS tend to be in a plantarflexed position of around 3-5° of ankle plantarflexion, with a reduction in the first rocker of gait [22, 25]. While the second rocker is present as the ankle moves from plantarflexion to dorsiflexion, there is a significant reduction in peak ankle plantarflexion at following propulsion, minimizing the third rocker. In individuals with DS, peak plantarflexion has been measured from 2-5° versus 8-10° achieved by TD children [22, 23, 25]. Considering the limited hip extension at

terminal stance and maintained knee flexion throughout the stance phase, it isn't surprising how limited ankle plantarflexion is achieved at push-off.

Children with DS possess an inherent need to increase lower extremity joint stiffness while walking to increase a sense of stability. This is observed when measuring hip, knee, and ankle ROM in the sagittal plane throughout the gait cycle, where children with DS present with less overall ROM in each of these joints than TD children. However, in the frontal plane, it was shown that children with DS present with larger hip ROM values than TD counterparts, likely a result of reduced ROM in the sagittal plane and underlying joint laxity [24]. At specific points within the gait cycle, such as decreased ankle plantarflexion at push-off, these reductions in ROM can impact the kinetics and overall efficiency of gait.

Supramalleolar Orthosis in Children with Down Syndrome

Although the research to support the effectiveness of SMO on gait parameters in children with DS is scarce and conflicting regarding their efficacy, clinicians commonly prescribe SMOs, which are orthotics that provide support to the foot and the ankle above the level of the malleoli and are thought to provide additional stability needed to improve overall gross motor function [8, 9]. SMO has been used by clinicians to address functional limitations, such as joint laxity, hypotonia, foot-flat deformity, and overpronation to improve gait parameters in children with DS [6-8, 27].

Looper and colleagues (2012) conducted a study on the effects of foot orthosis (FO) and SMOs on gait parameters in children with DS aged 4-7 years who were able to walk at least 50 feet independently or with an assistive device. Spatiotemporal gait parameters throughout barefoot, shoes with FOs, and shoes with SMOs conditions were measured. It was revealed that cadence was significantly decreased as cycle time significantly increased while wearing SMOs

versus FOs and barefoot or barefoot conditions. Strong correlations were found between height and cycle time ($r = 0.81$), height and single support time ($r = 0.93$), single support time and leg length ($r = 0.82$), and single support time and weight ($r = 0.92$). Additionally, there were moderate to strong correlations between hypermobility measured by the Beighton scale and cadence ($r = - 0.94$), cycle time ($r = 094$), and single support time ($r = 0.96$). Between the SMO and shoes only condition, cadence was 159.90±28.22 steps/min versus 178.09±31.56 steps/min, with a cycle time of 0.78±0.12 s versus 0.69±0.13 s, respectively. Additionally, between the SMO and shoes only condition, step length was 41.17±4.19 cm versus 40.80±6.99 cm, base of support was 10.38±2.77 cm versus 10.42±2.62 cm, and single support time was 0.33±0.03 s versus 0.32±0.04 s, respectively. The authors discussed that because of the inverse relationship between cadence and cycle time, each stride took longer to complete in the SMO group, which may be detrimental to the gait cycle. As the authors pointed out, the limitations to this pilot study is the small sample size and sampling from convenience [8]. However, the study may provide insight into how certain anthropometrics and level of hypermobility should play a role in prescribing SMOs, and that SMOs are not a “one-size fit all” for everyone with DS.

Because SMOs provide external ankle stability, this may lead to improvements in postural control in children with DS. Martin (2004) studied the effect of flexible SMOs on postural stability in 17 children with DS with an age range of 3.5 years to 8 years. -Total laxity score from six ROM measurements: bilateral knee hyperextension, elbow hyperextension, and ankle dorsiflexion. The subjects were then subdivided into the “more lax” group (total laxity score > 60°) and “less lax” group (total laxity score <60°). This study utilized clinical measures rather than biomechanical measures, such as those provided by Looper et al (2012). The standing and walking, running, and jumping dimensions of the GMFM and the BOTMP balance subtests

were used to measure change of gross motor function over time. These measures were conducted 3 times within a 10-week period: at baseline in the shoes only condition, at 2 to 3 sessions with shoes and shoes + SMO, and after 6 weeks of wearing SMOs in both shoes and shoes + SMO conditions. While balance measures improved through improving ankle stability, especially in those with more laxity based on the author's laxity measures, GMFM scores also improved, which covered walking, running, and jumping dimensions when the subjects initiated SMO use and after 6 weeks of SMO use. While it was evident that there were improvements in GMFM and BOTMP scores between shoes only and shoes + SMOs at session 2, which was the introduction of SMOs, the score differences widened further in session 3, indicating that the children were more familiarized with SMO use [6].

Regarding at what point clinicians should initiate the use of SMOs in infants with DS is another topic up for debate and highly based on expert opinion. Some clinicians choose to prescribe the orthotics as soon as the infant can pull to stand, whereas others wait until the infant begins to walk independently. Looper and Ulrich (2010) studied whether the effects of early treadmill training with SMOs versus without SMOs would lead to improvements in developmental scores. Seventeen children with DS who were recruited once they were able to pull to stand but were excluded if they were able to cruise. The SMO group (n = 10, M_{age} = 21 months) was fitted for SMOs prior to their second visit, while the control group (n = 7, M_{age} = 19 months) was fitted for SMOs once they were able to take 3 steps independently. Parents of the SMO group were instructed to have the infant wear the orthotic for 8 hours per day, 5 days per week. Both groups received treadmill training at a velocity starting at 0.2 m/s and trained 8 minutes per day, 5 days per week until the infant was able to take 3 steps independently. The SMO group wore shoes and SMOs while the control group wore shoes during the treadmill

training. Developmental testing was measured using the GMFM which included lying and rolling, sitting, crawling and kneeling, standing, and walking, running, and jumping. Scores ranged from 0 (“does not initiate”) to 4 (“completes”). Measures were obtained once per month until the treadmill intervention was terminated, followed by one other measure 1 month following onset of walking. All children improved their GMFM scores over time in a nonlinear fashion, indicating development occurs nonlinearly. The control group demonstrated significantly higher scores with large effect sizes in the GMFM total, GMFM standing, and GMFM walking, running, and jumping. The results indicate that the SMOs did not provide an advantage to accelerate gross motor development and these results may indicate that while SMOs provide external stability, this can impact motor learning of new skills in standing [7]. However, in a single-subject design by Tamminga, et al. (2012), revealed that both children included in the study improved GMFM scores with two different types of SMOs compared to shoes only [28].

The effects of SMOs have also been studied in the spastic diplegic cerebral palsy (CP) population. While this population is hypertonic and spastic rather than hypotonic, therefore possibly requiring different needs in terms of stability, these studies provide some insight into the effects that SMOs have on controlling the ankle and foot. Liu et al. (2014), used an electromagnetic motion tracking system to track motions of the tibia, calcaneus, cuboid, navicular, 1st metatarsal, and hallux in children with cerebral palsy who wore clinically prescribed orthosis, including SMOs. The authors of this study concluded that SMOs significantly constrained forefoot dorsiflexion at both loading response and terminal stance [29]. The terminal stance constraint can influence ankle kinetics at the propulsive phase of terminal stance, as well as the subsequent sagittal kinematics of the hip, knee, and ankle joint during

swing phase. Carlson and colleagues (1997) compared the effects of a fixed ankle-foot orthosis (AFO), SMO, and shoe-only condition on dynamic equinus in spastic CP. The authors proposed that because the AFOs and SMOs braces under the foot provide a longer lever arm, this would lead to enhanced ankle moments and powers, leading to a more efficient gait. As opposed to Liu and colleagues' study, this study revealed that ankle excursion was significantly longer in SMO (25.4°) versus AFO (11.9°), however, it was not significantly different than the baseline measures (24.6°). Although ankle dorsiflexion at initial contact was expectedly larger in the AFO condition (10.0°) vs SMO condition (3.3°), the SMO condition trended to more ankle dorsiflexion at initial contact than baseline shoe only measures (1.8°). Additionally, the SMO condition significantly increased maximum ankle power generation at push-off versus AFOs (1.64 W/kg versus 1.05 W/kg, respectively), and SMOs trended towards larger maximum ankle power generation at push-off versus baseline shoe-only measurements (1.64 W/kg versus 1.50 W/kg) [30].

The use of SMOs continues to be a standard practice of care for young children with DS. However, the onset of use and dosing parameters, such as duration and frequency, continues to be primarily based on expert opinion. There is limited evidence regarding the effectiveness of SMOs on gross motor development, with some studies presenting conflicting results. While Looper and colleagues (2012) discussed that the use of SMOs in children with DS was possibly detrimental to their gait based on the increased cadence and cycle time, Martin (2004) revealed that children with SMOs present with higher GMFM scores in the walking, running, and jumping dimensions than when the children wore shoes only [6, 8]. Studies with comprehensive quantitative biomechanical approaches should be conducted to further understand the effects of SMOs on gait parameters children with DS to validate their use.

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Chapter 2: Effect of Supramalleolar Orthosis on Overground Walking in Children with Down Syndrome

ABSTRACT

Individuals with Down syndrome (DS) display delays in motor, cognitive, language, and social development. The impairments in the central and peripheral neural systems cause significant biomechanical deficits due to the inherent need to stabilize the joints in the lower extremity, thus resulting in compensatory strategies, such as co-contracting antagonistic muscles, and inefficient gait mechanics. Supramalleolar orthosis (SMO) are orthotics that provide support to the foot and the ankle above the level of the malleoli and are a common clinical intervention to provide stability at the ankle joint and improve gait mechanics. There is limited evidence on the efficacy and long-term effects that SMOs provide on gait mechanics, thus clinicians rely on anecdotal evidence for the timing of prescription and use. In this study, we will assess spatiotemporal and kinematic patterns of gait in young children ages 2 to 6 years old, who either use or do not use SMOs for daily walking, to assess the differences between barefoot walking and walking with respective footwear (shoes or shoes with SMOs). Twenty-three young children with DS, 10 who used SMOs for daily walking and 13 who did not use SMOs were recruited in the study. Overground walking both barefoot and with the child's footwear was recorded using Vicon 3D motion capture. Results from this study showed that the SMO group improved their joint kinematics and spatiotemporal variables when they wore their SMOs, including improvements in cadence, walking speed, step length, and hip and knee angular velocities. The non-SMO group also demonstrated similar improvements when they wore their shoes. The results from this study provide a detailed biomechanical analysis of the effects that SMO use

have in children with DS and can lay the foundation to improve prescriptive decision making, frequency of use, and future rehabilitative strategies.

INTRODUCTION

Down syndrome (DS) is the most common genetic disorder that causes delays in motor, cognitive, language, and social development. Individuals with DS present with extensive delays in developmental skills attributed to neuromuscular manifestations such as hypotonia and impaired balance and coordination [1]. Pathological influences on motor impairments include reductions in white and grey matter volume, particularly in the brainstem, cerebellum, corpus callosum, hippocampus, frontal lobes, and parietal lobes, along with a delay in central and peripheral myelination [1-4]. Rigoldi and colleagues (2009) revealed that the extent of grey matter volume reduction in the cerebellum, particularly in the cerebellar vermis, plays a role in the severity of trunk coordination, lower extremity coordination, and gait impairment [2]. Muscle hypotonia is a cause of joint laxity [1], which causes an inherent sense of instability leading to compensatory mechanisms, such as co-contractions of antagonistic muscles, to increase joint stiffness and stability during movement [4, 5].

The acquisition of walking is important for infants to explore their environment and develop cognitive and language skills. The aforementioned impairments and compensatory mechanisms have been shown to not only cause delays in achieving motor milestones, but also in both cognitive and language skills, as infants are not adequately able to explore their environment [1, 6-8]. A systematic review by Jain, et al. (2021) revealed that independent sitting is delayed and can take up to 18 months to achieve, the probability of standing at 2 years is less than 50%, with the majority learning to stand between 3 and 4 years of age, and the ability to run and climb stairs is 18%-25% by 4 years of age and 65%-85% by 6 years of age, respectively [1]. However, in infants and children with DS, Yaumachi, et al. (2019) revealed a significant positive

correlation between motor skill acquisition and physical therapy services, which continued to strengthen with age [6].

Hypotonia and joint laxity resulting in compensatory strategies to increase joint stiffness establish specific gait characteristics found in individuals with DS. The inherent need to increase joint stiffness throughout the gait cycle is detrimental to joint kinematics, resulting in decreased overall sagittal plane range of motion (ROM) of the hip, knee, and ankle. Individuals with DS produce much less peak hip extension and ankle plantarflexion at terminal stance [9, 10]. Additionally, knee extensor strength is needed to maintain stability of the knee joint during stance phase. Individuals with DS display a much more flexed knee, with no first peak knee extensor moment in order to stabilize the knee joint, due in part to weaker knee extensor strength [9]. The reduction of ROM, particularly in the hip and the ankle impair forward propulsion, impacting both spatiotemporal and kinetic parameters. Spatiotemporal deficits in children with DS include shortened step lengths, widened step widths, decreased walking speed, and increased double support time compared to typically developing (TD) children [5, 11, 12]. Step length and step width variability has also been shown to be significantly larger in new walkers with DS versus TD new walkers [13]. Joint kinetics of the lower extremity are also greatly impaired in individuals with DS. It has been shown that ankle force production and power generation is much less at terminal stance in individuals with DS than in TD individuals, resulting in an increase in hip power generation [2, 8, 9].

Rehabilitative approaches have been utilized to improve walking ability by addressing deficits in gait parameters attributed from functional limitations and compensatory mechanisms. One of these approaches has been the introduction of supramalleolar orthosis (SMO) to address these primary complications and improve gait parameters in children with DS (figure1) [14, 15].

Clinicians commonly prescribe SMOs, which are orthotics that provide support to the foot and the ankle above the level of the malleoli and are thought to provide additional stability needed to improve overall gross motor function [14, 16]. SMOs are made of a flexible hybrid plastic and may provide stability about the ankle joint through compression [17].

Evidence regarding the efficacy SMO use in improving gait parameters is limited and conflicting, particularly the biomechanical impact that SMOs have on gait in children with DS. Looper et al. (2012) revealed no significant difference between barefoot, foot orthosis, and SMO for most gait parameters measured in children with DS aged 4 to 7 years. Furthermore, SMO use resulted in an decrease in cadence and increase in cycle time, indicating that SMOs might destabilize the gait cycle and providing the extra support may be detrimental to the gait cycle [14]. Additionally, Looper and colleagues (2010) tested SMO use in infants with DS about 20 months of age who were undergoing an early treadmill stepping intervention. The SMO group (n = 10, M_{age} = 21 months) were fitted with SMOs at the onset of training, whereas the control group (n = 7, M_{age} = 19 months) were fitted with SMOs once the intervention was terminated. Both groups received treadmill training at a velocity starting at 0.2 m/s and trained 8 minutes per day, 5 days per week until the infant was able to take 3 steps independently. Results revealed that the SMO group achieved lower gross motor function scores than the control group at walking onset. Therefore, SMO use may be detrimental to gross motor development when it is used before the infant starts walking independently [15]. On the other hand, Martin (2004) showed that the introduction of SMOs increased the scores of standing, walking, running, and jumping components of the Gross Motor Function Measure (GMFM) as well as balance scores on the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP) test in children with DS aged between 3.5 years to 10 years. These improvements carried over after 6-weeks of wearing SMOs and

widened the gap of GMFM and BOTMP scores between the shoes only condition and the shoes + SMO condition, with the latter demonstrating better scores [17]. These results suggest that SMO use in children with DS after they start walking independently may enhance locomotor development.

Currently, there is limited evidence on the biomechanical impact that SMOs have on gait in children with DS. The evidence of SMO use in DS can also be conflicting among previous studies [14, 15, 17]. The lack of evidence and conflicting results cause clinicians to rely on anecdotal evidence and expert opinion when prescribing SMOs. Traditionally, clinicians prescribe SMOs to correct abnormal alignment and provide external support as soon as the child is able to pull to stand. However, other clinicians believe that early orthotic use will limit the child's ability to develop upright locomotor skills due to limited ankle mobility [14]. In this study, we aimed to investigate the biomechanical impact of SMO use in young children with DS aged 2-6 years who were prescribed SMOs (i.e., the SMO group) versus children who were not prescribed SMOs (i.e., the non-SMO group), during overground walking. We hypothesized that compared to barefoot walking, the SMO group will improve spatiotemporal gait parameters by increasing stride length, decreasing step width, and increasing gait velocity while wearing shoes and SMOs, whereas the non-SMO group will not show any improvement in spatiotemporal gait parameters while wearing shoes. Additionally, compared to barefoot walking, the SMO group will increase hip, knee, and ankle sagittal plane ROM while wearing shoes and SMOs, whereas the non-SMO group will not show any improvement in joint kinematics. Specifically, only the SMO group will increase peak hip extension and ankle dorsiflexion during late stance phase and increase peak knee flexion during swing phase.

Figure 2-1: lateral and frontal views of supramalleolar orthosis

METHODOLOGY

Participants

Twenty-three subjects with DS with an age range of 2 to 6 years (*mean age*: 41.48±15.02 months). Of those, 10 subjects were in the SMO group who were prescribed with SMOs, and 13 subjects were in the non-SMO group who were never prescribed with SMOs. Participants must have had at least 6 months of independent walking experience. The SMO group used their SMOs at least 50% of the time during the day, which was confirmed by the subject's parents through a questionnaire. Subjects were excluded from the study if they presented with current musculoskeletal injuries of the lower extremities, uncorrected vision and hearing problems, and unresolved congenital heart defects that may cause symptoms with exertion. The subjects visited the GSU Biomechanics Lab for one visit, which lasted up to 2 hours. The study protocol was approved by the institutional review board at Georgia State University. Parental permission form was obtained from the parent of each subject prior to data collection.

Both groups were randomized by a random number generator, in which numbers ending in an odd number will begin the walking trials with their footwear, which is the SMO and shoe donned for the SMO group and shoe donned for the non-SMO group. Subjects began the walking trials barefoot if an even number was selected.

The parents were instructed to have their child wear tight fitting clothing for the data collection. Additionally, we used clips to clip the t-shirt slightly above the navel or to clip the shorts above the level of the thigh marker, to expose the ASIS (anterior superior iliac spine), PSIS (posterior superior iliac spine), and thigh markers if they were covered by the clothing. Subjects in the non-SMO group had two conditions: barefoot and with their shoes donned; and the SMO group had two conditions: barefoot and with their SMOs and shoes donned, similar to the Looper, et al. study [14].

Data Collection

We collected anthropometrics measures, including total height in mm, body mass in kg, leg length (the length measured in mm from the ASIS to the base of the medial malleoli), knee width (the width of the knee in mm, measured at the widest point), and ankle width (the width of the ankle in mm measured at the widest point between the medial and lateral malleoli). The measures were collected prior to the walking trials. To adjust for shoe height, we obtained measurements from the floor to the base of the lateral malleoli with both shoes on and off.

Additionally, we obtained bilateral ROM measures of knee hyperextension, elbow hyperextension, and ankle dorsiflexion, to explore the influence of joint laxity. The two groups were categorized as more lax, which were subjects with a total laxity score of 60° or more, or less lax, which were subjects with a total laxity score of less than 60°, as described by Martin (2004) [17]. A digital goniometer was used to obtain the joint hyperextension measures in the

elbow and knee, and ankle dorsiflexion. Knee hyperextension was measured with the subject lying supine on a treatment table with a bolster placed underneath the ankle in order to elevate the leg. Slight downward pressure was applied on the distal thigh to achieve as much knee hyperextension as possible, without discomforting the subject. The stationary arm of the goniometer was aligned with the greater trochanter of the femur, the axis was aligned on the knee joint space, and the distal arm was aligned with the lateral malleolus of the ankle. Elbow hyperextension was measured with the subject lying in supine on a treatment table. The humerus was stabilized with one hand and a slight downward pressure of the subject's forearm was applied with the opposite hand, in order to achieve as much elbow extension as possible without discomforting the subject. The stationary arm of the goniometer was aligned with the subject's greater tubercle of the humerus, the axis was aligned with the lateral humeral epicondyle, and the distal arm of the goniometer was aligned with the radial styloid process. Ankle dorsiflexion was measured with the subject lying supine on the treatment table. The stationary arm of the goniometer was aligned with the head of the fibula; the axis was aligned with the ankle joint axis, along the base of the lateral malleoli; and the distal arm was aligned with the 5th metatarsal. The foot was moved into as much ankle dorsiflexion as possible, without discomforting the subject.

A 16-marker Vicon Lower Body Plug-In Gait model was used with 14 mm spherical reflective markers attached bilaterally to the subject's ASIS, PSIS, thigh, knee, shank, ankle, heel, and 2nd metatarsal, as shown in the diagram below. A 9-camera Vicon motion capture system (Oxford, UK) was used to record the position of each marker with a sampling frequency of 100 Hz. A 6-meter walkway was used to collect the walking trials. A T-pose static calibration

was conducted to calibrate the markers with the subject standing as still as possible on one of the force plates before the walking trials.

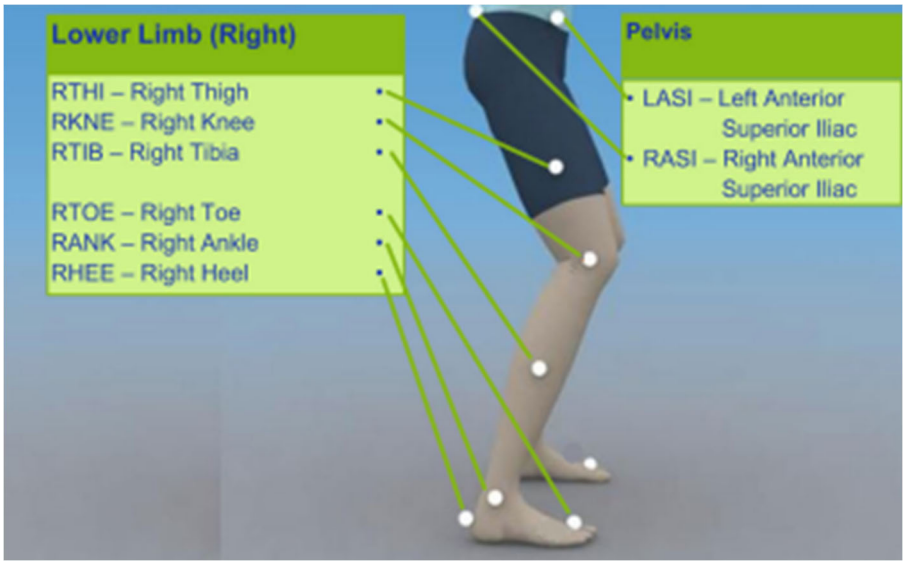

Figure 2-2: Marker placement for Vicon Lower Body Plug-In Gait Model

The subjects walked both barefoot and with their footwear at their self-selected overground walking speed. Before the walking trial was recorded, the subject was positioned at the beginning of the 6-meter walkway and was given verbal instructions to walk. The parent of the child was instructed to stand at the opposite end of the walkway to encourage the child to walk towards them, which ensured that the child walked in the straightest path possible. If the child initially refused to walk, the parent encouraged the child to walk using their smart phone or a stuffed animal. At times the parent encouraged the child to walk by holding their hand across the walkway until the child understood the activity. Successful trials included in the analysis were those which the child successfully walked the length of the walkway without handheld assistance by the researcher or parent. We would exclude trials if the subject required handheld assistance to walk along the walkway, if the subject stopped walking part of the way and sat

down, or if the subject turned around and walked back toward the starting position. We aimed to collect 5 successful trials to analyze per overground walking condition [20].

Data Analysis

R+ marker data of the overground trials was exported from the Vicon Nexus software. A 4th order zero lag Butterworth low pass filter with a cut-off frequency of 6 Hz was used to filter the kinematic data [21]. A custom Matlab ® program was used to calculate the biomechanical parameters. For spatiotemporal measures, the subject's stride length was measured by calculating the distance of the heel marker during heel strike on one leg, followed by the next heel strike of the same leg. Step width was measured as the distance between the heel markers during double-support phase of gait. Spatiotemporal variables were normalized by the subject's leg length by the following formula, $\hat{l} = \frac{l}{l_0}$, where $\hat{l}$ is the normalized step length, l is the step length, and l_0 is the subject's leg length [22]. Gait velocity was calculated as $v = m/s$, where m is the distance in meters of the right heel marker tracked by Vicon and s is the time in seconds between the first visible frame of the right heel marker to the last visible frame of the right heel marker. Velocity was normalized by the following equation, $\hat{v} = \frac{v}{\sqrt{g*l_0}}$, where $\hat{v}$ is the normalized velocity, v is the measured velocity, g is the acceleration of the Earth's gravity of 9.81 m/s^2, and l_0 is the subject's leg length [22]. With each complete gait cycle, time was normalized as a percentage and stance phase was defined as the percentage between initial contact and one frame before toe-off of the same limb. Swing phase was defined as the percentage between toe-off and one frame before initial contact of the next gait cycle of the same limb. Double support phase was calculated as the percentage between initial contact of one limb to the toe-off of the opposite limb for each leading limb.

Kinematic wave forms were also time-normalized to the duration of each gait cycle. Peak hip, knee, and ankle flexion and extension angles in the sagittal plane and the timing of these peak values, as well as the peak hip abduction and adduction values in the frontal plane, were obtained. Angular velocity was calculated using the finite difference method using the formula $\omega_i = \frac{(\theta_{i+1} - \theta_{i-1})}{2(\Delta t)}$, where ω_i is angular velocity, θ is the angle, and t is time. Angular acceleration was calculated using the formula $\alpha = \frac{(\omega_{i+1} - \omega_{i-1})}{2(\Delta t)}$, where α is the angular acceleration, ω is the angular velocity, and t is time. Peak angular velocity and acceleration values and their timing will be measured for each joint.

Symmetry Index (SI) was calculated using step lengths from the right and left sides. The formula used to calculate SI was $SI = \frac{2(X_r - X_l)}{X_r + X_l} \times 100\%$, where X is the subject's right or left step length [23]. Foot progression angle (FPA) was defined as $FPA = atan2(Y_{2M} - Y_{heel}, X_{2M} - X_{heel})$, where Y_{2M} and X_{2M} are the Y and X position of the 2nd metatarsal marker, and Y_{heel} and X_{heel} are the Y and X positions of the heel marker [24].

Statistical Analysis

Because the number of subjects in each group were unequal, a *t*-test of unequal variance was conducted on each group's age at the time of the visit in months, walking experience at the time of the visit months, leg length, laxity scores, and mean joint ROM from the goniometric measures, to detect group differences between the SMO and non-SMO groups. Paired *t*-test were conducted on the spatiotemporal and kinematic variables of the right and left limbs for each group to detect significant differences indicating asymmetries. A two-way (2 group X 2 condition) mixed ANOVA was conducted on the spatiotemporal and peak kinematic variables. The two groups were the SMO and non-SMO groups, and the two conditions were overground

walking barefoot and with their footwear (SMO group: shoes + SMO; non-SMO group: shoes only). Normality was assessed using the Shapiro-Wilk test and non-normally distributed variables were log transformed if normality was violated [11]. Statistical significance will be set at an α=0.05. All statistical analyses were conducted using SPSS (Version 29.0; IBM Corp., Armonk, NY, USA).

RESULTS

Subjects

Twenty-three young children with DS (16 male, 7 female) were recruited in this study. Ten participants were in the SMO group, and 13 participants were in the non-SMO group. Age differences (SMO: 39.60±14.31 months; non-SMO: 42.92±15.97 months, t(22)=-0.525, p=0.352) and walking experience (SMO: 22.80±14.14 months; non-SMO:23.31±13.80 months, t(22)=-0.086, p=0.896) were not significant between the two groups. While leg length was not significant (SMO: 39.52± 7.59 cm; non-SMO: 39.69±6.69 cm, t(22)=-0.057, p=0.96), there was a significant difference in joint laxity scores (SMO: 81.75±19.89°; non-SMO: 58.48±14.16°, t(22)=3.14, p=0.002) between the two groups such that the SMO group had a significantly higher joint laxity scores than the non-SMO group. Mean joint ROM, calculated as the average of summed bilateral elbow hyperextension, knee hyperextension, and ankle dorsiflexion, was significantly different between groups but violated the assumption of homogeneity of variance (Levene's test: F=4.464, p=0.047). A nonparametric Mann–Whitney U test indicated that mean joint ROM was significantly greater in the SMO group (40.88 ± 9.95°) than in the non-SMO group (31.95 ± 5.09°; p=0.015).

Table 2-1: Mean and standard deviation (SD) of participant characteristics and statistical results

	Non-SMO	SMO	T Statistic	Significance
Age (months)	42.92 (15.97)	39.6 (14.31)	$t(22)$=-0.525	p=0.352
Walking Experience (months	23.31 (13.8)	22.8 (14.14)	$t(22)$=-0.086	p=0.896
Leg Length (cm)	39.69 (6.69)	39.52 (7.59)	$t(22)$=-0.057	p=0.96
Joint Laxity Scores (deg)	58.48 (14.16)	81.75 (19.89)	$t(22)$=3.138	p=0.002

Spatiotemporal Parameters

Compared to the non-SMO group, the SMO group had a slower walking speed, increased stride time, and longer double support time in each condition. Walking speed and stride length increased when both groups wore their footwear. Additionally, the SMO group had an asymmetric FPA when barefoot, which became more symmetric with their footwear on.

A multivariate ANOVA was conducted to examine the effects of Group and Condition on the set of dependent variables. The overall model revealed significant main effects for both Group and Condition, but no significant interaction. Specifically, the analysis indicated a significant main effect of group (F_G (1,21) = 1.619, p = .035, η^2 = 0.28), suggesting that the groups differed on the combined dependent variables. There was also a significant main effect of condition (F_C(1,21) = 3.561, p < .001, η^2 = 0.461), indicating that conditions had a significant impact on the multivariate outcome. However, the group*condition interaction was not significant (F_{GC} (1,21) = 1.066, p = .389, η^2 = 0.204), suggesting that the pattern of condition effects did not differ significantly between groups.

Cadence was higher in the non-SMO group versus the SMO group. The non-SMO group cadence was similar across conditions, from 185.07±43.76 steps/min on barefoot to 176.33± 42.02 steps/min when wearing shoes. SMO group also had similar cadence across conditions,

from 159.82 ± 32.28 steps/min to 165.25 ± 38.54 steps/min. The statistical analysis revealed that there was a group effect (F_G (1,21) = 8.282, p = .005). There were no significant condition effects or group by condition interactions.

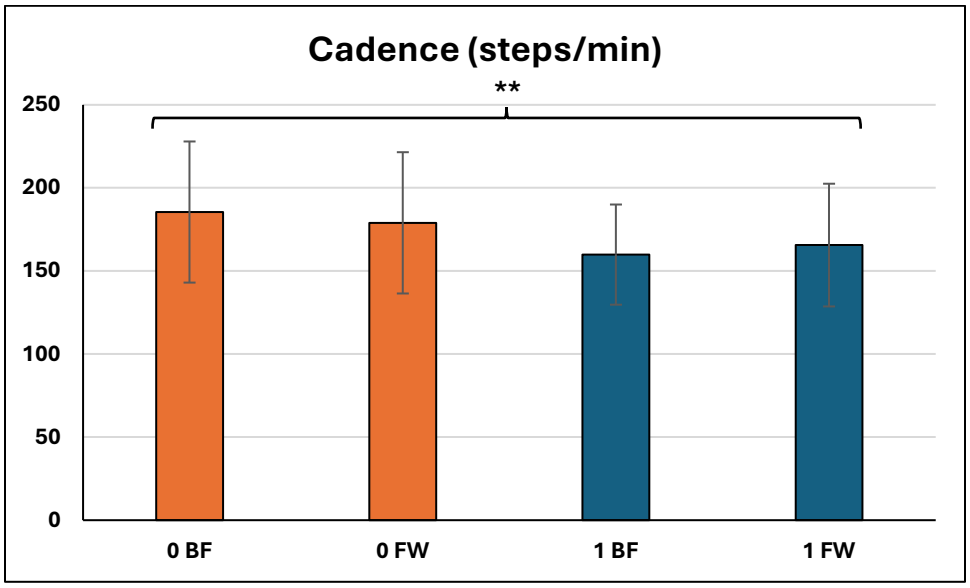

*Figure 2-3: Bar graph representing cadence (Steps/min). 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. 0 = Non-SMO, 1 = SMO, BF = Barefoot, FW = Footwear. * P < 0.05, ** p < 0.01, *** p < 0.001. Condition Effect: ╪ p < 0.05, ╪╪ p < 0.01, ╪╪╪ p < 0.001.*

Normalized walking speed was faster in the non-SMO group than the SMO group. The non-SMO group's walking speed at barefoot was 0.48 ± 0.14 m/s and increased to 0.50 ± 0.15 m/s with shoes on. Similarly, the SMO group's walking speed was 0.39 ± 0.10 m/s and increased to 0.47 ± 0.13 m/s when they walked with their SMOs on. Statistical analysis revealed a significant group effect (F_G (1,21) = 8.577, p = .004) and a condition effect (F_C (1,21) = 5.693, p = .018)

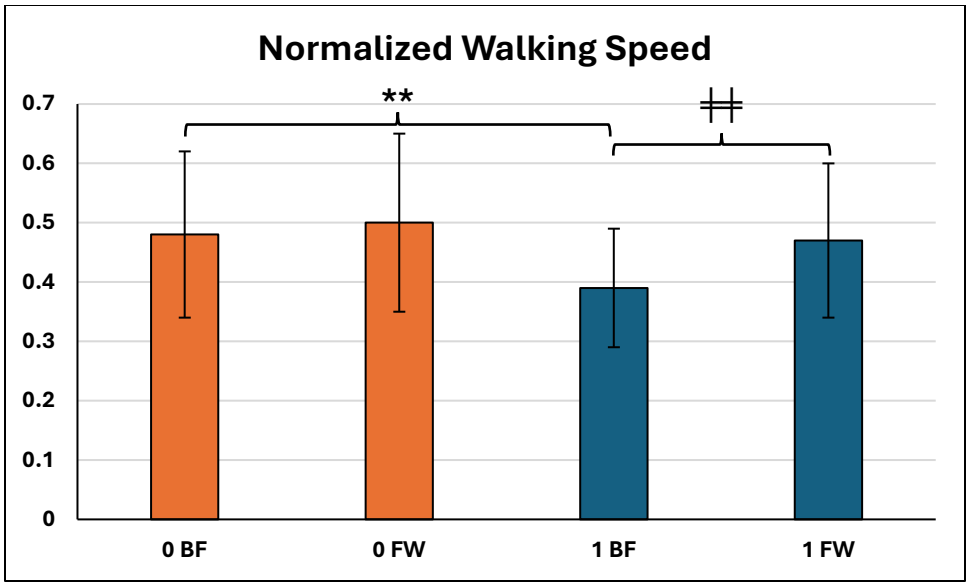

*Figure 2-4: Bar graph representing normalized walking speed (%). 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. 0 = Non-SMO, 1 = SMO, BF = Barefoot, FW = Footwear. * P < 0.05, ** p < 0.01, *** p < 0.001. Condition Effect: ╪ p < 0.05, ╪╪ p < 0.01, ╪╪╪ p < 0.001.*

Stride time was longer in the SMO group compared to the non-SMO group. In the non-SMO group, the mean stride time for the left leg was similar across conditions, with values at 0.69 ± 0.19 seconds when barefoot and 0.73 ± 0.21 seconds with shoes. In the SMO group, the left leg stride time was 0.79 ± 0.22 seconds when barefoot and was similar with SMOs on, with values at 0.77 ± 0.18 seconds. For the right leg, the non-SMO group's stride time was also similar across conditions, with values at 0.69 ± 0.18 seconds when barefoot and 0.71 ± 0.19 seconds with shoes. In the SMO group, the right leg stride time was also similar across conditions, with values at 0.78 ± 0.15 seconds when barefoot and 0.76 ± 0.17 seconds with SMOs. There was statistically significant group effect for the left leg (F_G (1,21) = 4.831, p = .029) and right leg (F_G (1,21) = 6.170, p = .014). There were no significant condition effects.

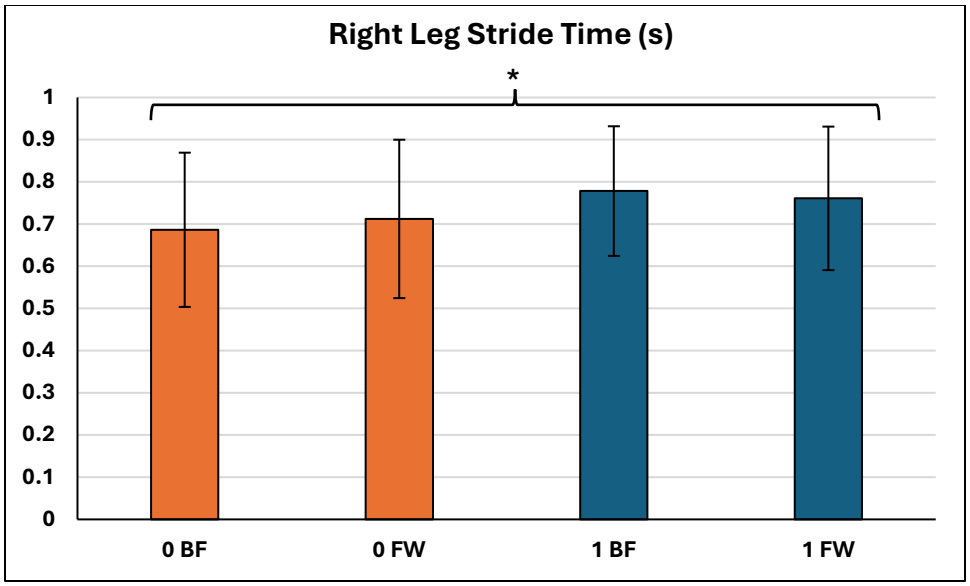

*Figure 2-5: Bar graph representing stride time (s). 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. 0 = Non-SMO, 1 = SMO, BF = Barefoot, FW = Footwear. Group Effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Condition Effect: ╪ $p < 0.05$, ╪╪ $p < 0.01$, ╪╪╪ $p < 0.001$.*

Double support time was greater in the SMO group compared to the non-SMO group. For the left leg, the non-SMO group's double support time was 0.11 ± 0.08 seconds when barefoot and increased to 0.17 ± 0.11 seconds with shoes. In the SMO group, double support time for the left leg was 0.21 ± 0.18 seconds when barefoot and 0.22 ± 0.11 seconds when wearing SMOs. For the right leg, the non-SMO group's double support time was 0.11 ± 0.08 seconds when barefoot and increased to 0.17 ± 0.10 seconds with shoes. In the SMO group, double support time for the right leg was 0.17 ± 0.09 seconds when barefoot and increased to 0.21 ± 0.10 seconds with SMOs. There was a significant group effect (F_G (1,21) = 13.893, $p < 0.001$) for the left leg and for the right leg (F_G (1,21) = 11.717, $p < 0.001$). Statistical analysis also revealed a significant condition effect for both the right leg (F_G (1,21) = 9.108, $p = .003$) and a trend towards significance for the left leg (F_G (1,21) = 3.220, $p = .075$).

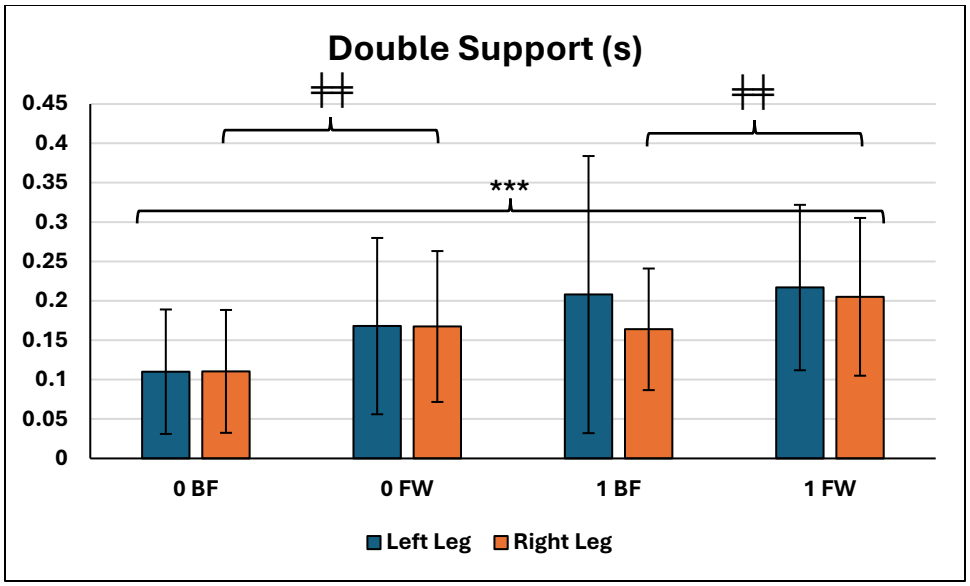

*Figure 2-6: Bar graph representing double support time (s). 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. Group Effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Condition Effect: ╪ $p < 0.05$, ╪╪ $p < 0.01$, ╪╪╪ $p < 0.001$.*

Foot off timing, expressed as a percentage of the gait cycle, was higher in the SMO group than in the non-SMO group. For the left leg, the non-SMO group's foot off occurred at 57.8% ± 5.3% of the gait cycle when barefoot and increased to 59.9% ± 5.9% with shoes. In the SMO group, left leg foot off occurred at 59.4% ± 11.9% when barefoot and increased to 63.4% ± 5.4% with SMOs. For the right leg, the non-SMO group's foot off timing was 57.4% ± 4.4% of the gait cycle when barefoot and increased to 61.0% ± 6.6% with shoes. In the SMO group, right leg foot off occurred at 59.7% ± 5.8% when barefoot and increased to 62.8% ± 5.6% with SMOs. Statistical analysis revealed a significant group effect for the left leg (F_G (1,21) = 4.592, p = .034) and right leg (F_G (1,21) = 5.237, p = .023). There were also significant condition effects for the left leg (F_C (1,21) = 6.634, p = .041) and the right leg (F_C (1,21) = 13.342, $p < 0.001$). Opposite foot contact presented with no significant changes within conditions in each group. Considering that the opposite foot contacts were relatively stable for both groups in each condition, and that the foot offs occurred later in the gait cycle when each group used their

respective footwear, this followed the trend discussed earlier in which double support time increased from barefoot walking to walking with the group's respective footwear.

Left and right stride lengths were similar in both groups, so an overall stride length was calculated. The mean stride length was generally greater in the shoe condition for both groups. In the non-SMO group, the mean stride length was 29.6 ± 4.8 cm when barefoot and increased to 32.3 ± 6.7 cm with shoes. In the SMO group, the mean stride length was 29.2 ± 6.7 cm when barefoot and increased to 33.7 ± 6.0 cm when wearing SMOs. Mean stride lengths did not present with a significant group effect, but there was a statistically significant condition effect (F_C (1,21) = 13.573, $p < 0.001$). Step width did not reveal significant differences between the group, nor a significant influence between barefoot and footwear within each group.

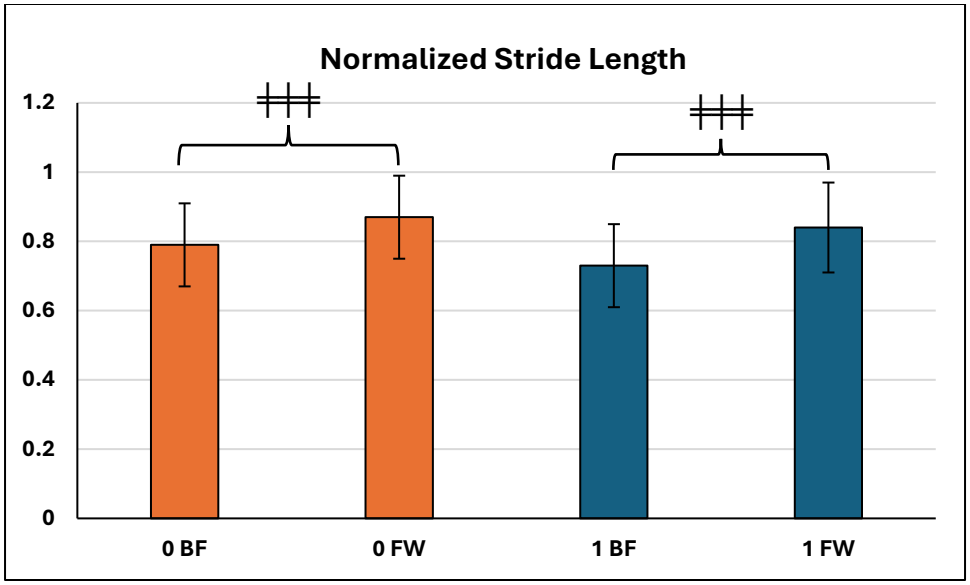

*Figure 2-7: Bar graph representing normalized step length (%). 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. Group Effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Condition Effect: ╪ $p < 0.05$, ╪╪ $p < 0.01$, ╪╪╪ $p < 0.001$.*

Symmetry index (SI) was quantified based on the subject's mean right and left step lengths, which revealed significant differences between extremities in the SMO group. The symmetry index values indicated slightly greater asymmetry in the SMO group, particularly in

the barefoot condition. In the non-SMO group, the mean symmetry index was –0.01 ± 0.16 in the barefoot condition and –0.03 ± 0.19 with shoes. In the SMO group, the mean symmetry index was 0.07 ± 0.17 when barefoot and –0.00 ± 0.18 when wearing SMOs. There was a significant group effect (F_G (1,21) = 3.926, p = .049) and a trend towards significance in the condition effect (F_C (1,21) = 3.099, p = .080).

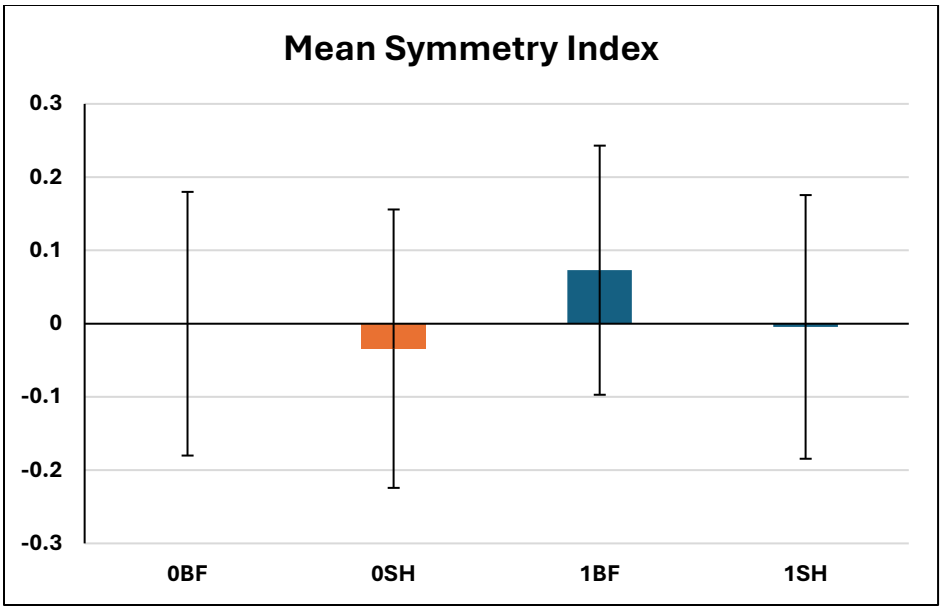

*Figure 2-8: Bar graph representing symmetry index. 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. Group Effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Condition Effect: ╪ $p < 0.05$, ╪╪ $p < 0.01$, ╪╪╪ $p < 0.001$.*

Higher FPA values reflect greater external rotation of the foot during the stance phase. In the non-SMO group, foot progression angles remained similar between the left and right feet. When barefoot, the mean progression angle was 11.4 ± 6.8° for the left foot and 12.3 ± 8.2° for the right foot. With shoes, the angles were 11.1 ± 9.9° for the left foot and 11.2 ± 8.0° for the right foot, indicating similar FPAs regardless of condition.

In contrast, the SMO group exhibited a noticeable asymmetry when barefoot, with the left foot showing a higher progression angle (16.5 ± 12.7°) compared to the right foot (9.8 ± 6.5°), indicating greater external rotation of the left foot. However, when wearing SMOs, this

asymmetry diminished. The left foot progression angle decreased to 12.1 ± 10.8°, while the right foot increased to 12.6 ± 10.1°, resulting in similar progression angles for both feet. This suggests that SMO use helped to equalize foot external rotation between sides, reducing the left–right disparity observed during barefoot walking.

Statistical analysis for the left FPA revealed a trend towards significance in the group effect (F_G (1,21) = 3.757, p = .054) and no significant condition effect. There were not significant effects for group or condition for the right FPA.

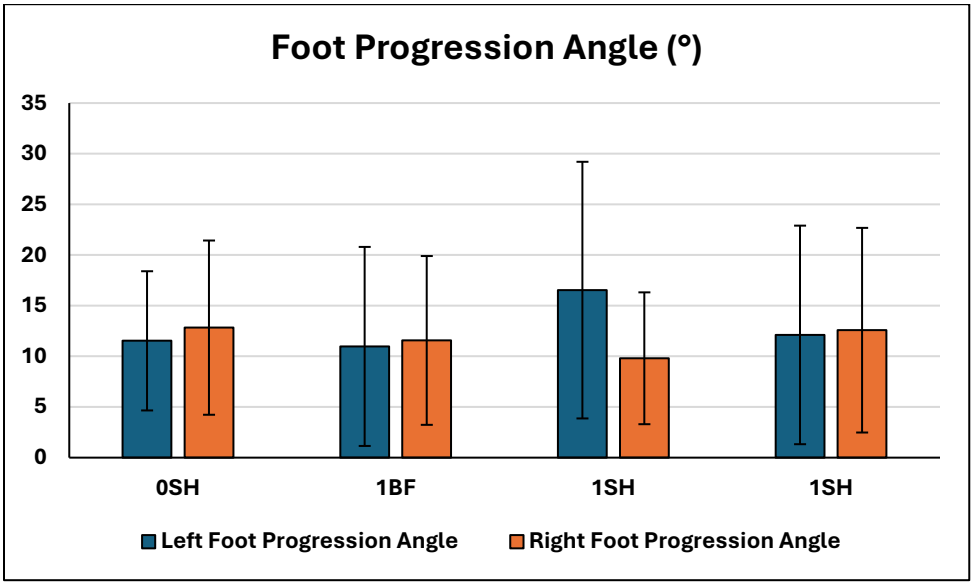

*Figure 2-9: Bar graph representing symmetry index. 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear condition. Group Effect: * p < 0.05, ** p < 0.01, *** p < 0.001. Condition Effect: ╪ p < 0.05, ╪╪ p < 0.01, ╪╪╪ p < 0.001.*

Kinematics

Kinematic analysis revealed notable changes between groups and across conditions. Peak hip and knee flexion increased when footwear was donned, while peak hip and knee extension was similar between groups and across conditions. Additionally, peak knee flexion timing occurred later in the gait cycle with footwear on. Peak hip and knee angular velocity also

increased with footwear on, and was generally higher in the non-SMO group. Additionally, there was a significant decrease in peak ankle plantarflexion during the footwear condition.

A multivariate ANOVA was conducted to examine the effects of Group and Condition on the set of dependent variables. The overall model revealed significant main effects for both Group and Condition, but no significant interaction. Specifically, the analysis indicated a significant main effect of group ($F_G(1, 21) = 5.04$, $p < .001$, partial $\eta^2 = 0.582$), suggesting that the groups differed on the combined dependent variables. There was also a significant main effect of condition ($F_C (1, 21) = 3.97$, $p < .001$, partial $\eta^2 = 0.523$), indicating that conditions had a significant impact on the multivariate outcome. However, the group by condition interaction was not significant ($F_{GC} (1, 21) = 1.10$, $p = .339$, partial $\eta^2 = 0.234$), suggesting that the pattern of condition effects did not differ significantly between groups.

Hip Joint

Peak hip extension values were similar between groups and across conditions. For the left leg, the non-SMO group's peak hip extension was –2.51 ± 3.26° when barefoot and–3.74 ± 5.71° with footwear. In the SMO group, left peak hip extension was –1.83 ± 2.93° when barefoot and –2.73 ± 5.56° with SMOs. For the right leg, the non-SMO group's peak hip extension was –2.70 ± 2.55° when barefoot and –3.10 ± 2.83° with footwear. In the SMO group, right peak hip extension was –3.9 ± 4.09° when barefoot and –3.46 ± 2.48° with SMOs. Further statistical analysis revealed no significant group or condition effects for peak hip extension values.

Table 2-2: Mean ± SD of peak hip extension and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Hip Extension	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	-2.51 ± 3.26°	-3.74 ± 5.71°	$F_C(1,21) = 2.206$ $p = 0.139$	$F_G(1,21) = 1.363$ $p = 0.245$
SMO Left	-1.83 ± 2.93°	-2.73 ± 5.56°		
Non-SMO Right	-2.7 ± 2.55°	-3.1 ± 2.83°	$F_C(1,21) = 0.012$ $p = 0.914$	$F_G(1,21) = 2.954$ $p = 0.088$
SMO Right	-3.97 ± 4.09°	-3.46 ± 2.48°		

Peak hip flexion was generally higher in the non-SMO group compared to the SMO group. For the left leg, the non-SMO group's peak hip flexion was 27.31 ± 9.05° when barefoot and increased to 28.40 ± 11.88° with footwear. In the SMO group, left peak hip flexion was 22.58 ± 6.73° when barefoot and increased to 26.83 ± 10.49° with SMOs. For the right leg, the non-SMO group's peak hip flexion was 30.37 ± 10.50° when barefoot and increased to 35.71 ± 11.12° with footwear. In the SMO group, right peak hip flexion was 26.80 ± 8.90° when barefoot and increased to 29.57 ± 11.00° with SMOs. For left peak hip flexion, there was a significant group effect ($F_G(1, 21) = 23.812$, $p < 0.001$) and condition effect ($F_C(1, 21) = 14.469$, $p < 0.001$). Right peak hip flexion values also had a significant group effect ($F_G(1, 21) = 26.210$, $p < 0.001$) and condition effect ($F_C(1, 21) = 27.790$, $p < 0.001$).

Table 2-3: Mean ± SD of peak hip flexion and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Hip Flexion	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	27.31 ± 9.05	28.4 ± 11.88	$F_C(1, 21) = 14.469$ $p < 0.001$).	$F_G(1, 21) = 23.812$ $p < 0.001$
SMO Left	22.58 ± 6.73	26.83 ± 10.49		
Non-SMO Right	30.37 ± 10.5	35.71 ± 11.12	$F_C(1, 21) = 27.790$ $p < 0.001$	$F_G(1, 21) = 26.210$ $p < 0.001$
SMO Right	26.8 ± 8.9	29.57 ± 11		

Peak hip abduction values were generally higher in the non-SMO group compared to the SMO group. For the left leg, the non-SMO group's peak hip abduction was 9.17 ± 5.89° when barefoot and 8.73 ± 7.19° with footwear. In the SMO group, left peak hip abduction was 7.09 ± 4.17° when barefoot and 7.75 ± 5.97° with SMOs. For the right leg, the non-SMO group's peak hip abduction was 10.88 ± 10.15° when barefoot and 9.81 ± 9.72° with footwear. In the SMO group, right peak hip abduction was 6.19 ± 5.52° when barefoot and increased to 8.35 ± 5.86° with SMOs. There were no significant group or condition effects for either left or right hip abduction.

Table 2-4: Mean ± SD of peak hip abduction and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Hip Abduction	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	9.17 ± 5.89	8.73 ± 7.19	$F_C = 0.454$ $p = 0.501$	$F_G = 1.332$ $p = 0.250$
SMO Left	7.09 ± 4.17	7.75 ± 5.97		
Non-SMO Right	10.88 ± 10.15	9.81 ± 9.72	$F_C = 0.016$ $p = 0.899$	$F_G = 0.332$ $p = 0.556$
SMO Right	6.19 ± 5.52	8.35 ± 5.86		

Peak hip angular velocity was generally higher in the non-SMO group compared to the SMO group. For the left extremity, the non-SMO group's peak hip angular velocity was 125.52 ± 29.71°/s when barefoot and increased to 133.47 ± 34.19°/s with footwear. In the SMO group, left peak hip angular velocity was 100.89 ± 29.16°/s when barefoot and increased to 127.38 ± 33.81°/s with SMOs. For the right extremity, the non-SMO group's peak hip angular velocity was 136.62 ± 43.84°/s when barefoot and increased to 153.50 ± 37.51°/s with footwear. In the SMO group, right peak hip angular velocity was 117.26 ± 35.53°/s when barefoot and increased to 131.37 ± 41.55°/s with SMOs. Statistical analysis revealed that left hip angular velocity had a significant group effect ($F_G(1, 21) = 13.642$, $p < 0.001$) and condition effect ($F_C(1, 21) =$

10.875, $p = 0.001$). Right hip angular velocity values also had a significant group effect ($F_G(1, 21) = 13.490$, $p < 0.001$) and condition effect ($F_C(1, 21) = 23.177$, $p < 0.001$).

Table 2-5: Mean ± SD of peak hip angular velocity and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Hip Angular Velocity	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	125.52 ± 29.71	133.47 ± 34.19	$F_C(1, 21) = 10.875$ p = 0.001	$F_G(1, 21) = 13.642$, p < 0.001
SMO Left	100.89 ± 29.16	127.38 ± 33.81		
Non-SMO Right	136.62 ± 43.84	153.5 ± 37.51	$F_C(1, 21) = 23.177$ p < 0.001	$F_G(1, 21) = 13.490$, p < 0.001
SMO Right	117.26 ± 35.53	131.37 ± 41.55		

Knee Joint

Peak knee extension values were generally similar between groups, with some increases seen in the footwear condition. For the left extremity, the non-SMO group's peak knee extension was 7.66 ± 7.06° when barefoot and 8.56 ± 8.17° with footwear. In the SMO group, left peak knee extension was 6.52 ± 4.50° when barefoot and increased to 9.46 ± 6.01° with SMOs. For the right extremity, the non-SMO group's peak knee extension was 7.54 ± 7.55° when barefoot and 9.95 ± 8.10° with footwear. In the SMO group, right peak knee extension was 11.68 ± 10.09° when barefoot and 12.02 ± 10.22° with SMOs. Statistical analysis revealed no significant group or condition effects for right or left peak knee extension.

Table 2-6: Mean ± SD of peak knee extension and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Knee Extension	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	7.66 ± 7.06	8.56 ± 8.17	$F_C(1, 21) = 2.359$ p = 0.126	$F_G(1, 21) = 0.828$ p = 0.364
SMO Left	6.52 ± 4.5	9.46 ± 6.01		
Non-SMO Right	7.54 ± 7.55	9.95 ± 8.1	$F_C(1, 21) = 0.594$ p = 0.442	$F_G(1, 21) = 0.119$ p = 0.731
SMO Right	11.68 ± 10.09	12.02 ± 10.22		

Peak knee flexion was generally higher in the non-SMO group compared to the SMO group, and increased for both groups with footwear. For the left extremity, the non-SMO group's peak knee flexion was 70.13 ± 13.09° when barefoot and increased to 75.57 ± 13.34° with footwear. In the SMO group, left peak knee flexion was 61.18 ± 12.43° when barefoot and increased to 73.40 ± 11.61° with SMOs. For the right extremity, the non-SMO group's peak knee flexion was 70.26 ± 15.37° when barefoot and increased to 79.83 ± 14.67° with footwear. In the SMO group, right peak knee flexion was 67.48 ± 13.45° when barefoot and increased to 74.76 ± 16.54° with SMOs. Statistical analysis revealed that left peak knee flexion values had a significant group effect ($F_G(1, 21) = 17.134$, $p < 0.001$) and condition effect ($F_C(1, 21) = 20.400$, $p < 0.001$). Right peak knee flexion values also had a significant group effect ($F_G(1, 21) = 12.078$, $p < 0.001$) and condition effect ($F_C(1, 21) = 21.369$, $p < 0.001$).

Table 2-7: Mean ± SD of peak knee flexion and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Knee Flexion	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	70.13 ± 13.09	75.57 ±13.34	$F_C(1, 21) = 20.400$ $p < 0.001$	$F_G(1, 21) = 17.134$ $p < 0.001$
SMO Left	61.18 ± 12.43	73.4 ± 11.61		
Non-SMO Right	70.26 ± 15.37	79.83 ± 14.67	$F_G(1, 21) = 12.078$ $p < 0.001$	$F_C(1, 21) = 21.369$ $p < 0.001$
SMO Right	67.48 ± 13.45	74.76 ±16.54		

Peak knee flexion timing, expressed as a percentage of the gait cycle, was generally earlier in the barefoot condition and increased slightly with shoes or SMOs in both groups. For the left extremity, the non-SMO group's peak knee flexion timing was 74.46 ± 2.31% of the gait cycle when barefoot and 75.14 ± 3.03% with shoes. In the SMO group, left peak knee flexion timing was 74.91 ± 3.20% when barefoot and increased to 77.30 ± 2.92% with SMOs. For the

right extremity, the non-SMO group's peak knee flexion timing was 73.67 ± 2.57% when barefoot and 75.84 ± 3.73% with shoes. In the SMO group, right peak knee flexion timing was 75.24 ± 2.65% when barefoot and increased to 77.27 ± 3.43% with SMOs. Left peak knee flexion timing had significant group effect ($F_G(1, 21) = 8.545$, $p = 0.004$) and condition effect ($F_C(1, 21) = 11.792$, $p < 0.001$). Right peak knee flexion timing was also significant for group effect ($F_G(1, 21) = 9.183$, $p = 0.003$) and condition effect ($F_C(1, 21) = 18.097$, $p < 0.001$).

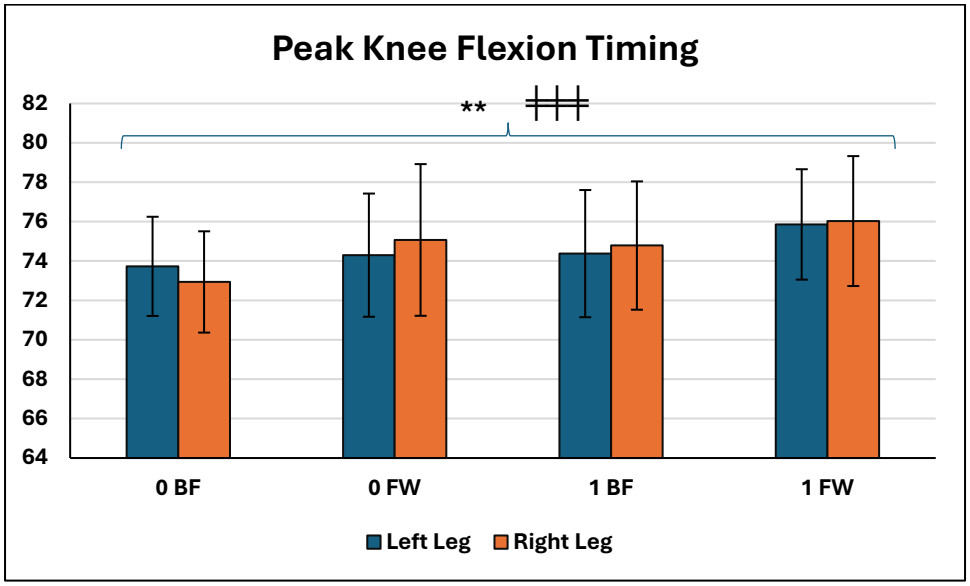

*Figure 2-10: Peak knee flexion timing (%) during the gait cycle. 0 = non-SMO group, 1 = SMO group, BF = barefoot, SH = footwear. Group Effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Condition Effect: ╪ $p < 0.05$, ╪╪ $p < 0.01$, ╪╪╪ $p < 0.001$.*

Peak knee angular velocity was generally higher in the non-SMO group compared to the SMO group in the barefoot condition and increased with footwear in both groups. For the left extremity, the non-SMO group's peak knee angular velocity was 193.07 ± 45.26°/s when barefoot and 194.27 ± 34.83°/s with footwear. In the SMO group, left peak knee angular velocity was 177.13 ± 43.08°/s when barefoot and increased to 207.34 ± 43.04°/s with SMOs. For the right extremity, the non-SMO group's peak knee angular velocity was 199.51 ± 39.45°/s when barefoot and increased to 215.81 ± 43.24°/s with footwear. In the SMO group, right peak knee

angular velocity was 187.10 ± 47.13°/s when barefoot and increased to 205.99 ± 47.58°/s with SMOs. Left peak knee angular velocity revealed only a condition effect (F_C (1, 21) = 5.753, p = 0.018) and no group effect. There was a trend towards significance for the right peak knee angular velocity group effect (F_G (1, 21) = 3.857, p = 0.051) and a significant condition effect (F_C (1, 21) = 10.902, p = 0.001).

Table 2-8: Mean ± SD of peak knee angular velocity and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Knee Angular Velocity	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	193.07 ± 45.26	194.27 ± 34.83	F_C (1, 21) = 5.753 p = 0.018	F_G (1, 21) = 2.052 p = 0.154
SMO Left	177.13 ± 43.08	207.34 ± 43.04		
Non-SMO Right	199.51 ± 39.45	215.81 ± 43.24	F_C (1, 21) = 10.902 p = 0.001	F_G (1, 21) = 3.857 p = 0.051
SMO Right	187.1 ± 47.13	205.99 ± 47.58		

Ankle Joint

Peak ankle plantar flexion values were generally more negative (greater plantar flexion) in the barefoot condition and tended to become less negative with footwear in both groups. For the left extremity, the non-SMO group's peak ankle plantar flexion was –9.25 ± 8.26° when barefoot and –7.69 ± 11.03° with footwear. In the SMO group, left peak ankle plantar flexion was –12.66 ± 7.86° when barefoot and –6.98 ± 6.46° with SMOs. For the right extremity, the non-SMO group's peak ankle plantar flexion was –13.67 ± 10.92° when barefoot and –10.03 ± 9.55° with footwear. In the SMO group, right peak ankle plantar flexion was –11.06 ± 6.69° when barefoot and –8.79 ± 6.20° with SMOs. Statistical analysis revealed significant condition effects for both peak left plantarflexion (F_C (1, 21) = 5.379, p = 0.022) and right peak plantarflexion (F_C (1, 21) = 4.040, p = 0.046). There were no significant group effects.

Table 2-9: Mean ± SD of peak ankle plantar flexion and statistical results. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis

Group Peak Ankle Plantar Flexion	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	-9.25 ± 8.26	-7.69 ± 11.03	$F_C(1, 21) = 5.379$ $p = 0.022$	$F_G(1, 21) = 0.198$ $p = 0.657$
SMO Left	-12.66 ± 7.86	-6.98 ± 6.46		
Non-SMO Right	-13.67 ± 10.92	-10.03 ± 9.55	$F_C(1, 21) = 4.040$ $p = 0.046$	$F_G(1, 21) = 0.194$ $p = 0.660$
SMO Right	-11.06 ± 6.69	-8.79 ± 6.2		

Peak ankle dorsiflexion increased with footwear and were similar between in both groups. For the left extremity, the non-SMO group's peak ankle dorsiflexion was 12.77 ± 7.07° when barefoot and increased to 18.25 ± 7.33° with footwear. In the SMO group, left peak ankle dorsiflexion was 13.00 ± 7.34° when barefoot and increased to 19.23 ± 5.97° with SMOs. For the right extremity, the non-SMO group's peak ankle dorsiflexion was 11.99 ± 8.02° when barefoot and increased to 16.32 ± 6.29° with footwear. In the SMO group, right peak ankle dorsiflexion was 14.26 ± 5.29° when barefoot and increased to 17.47 ± 4.94° with SMOs. As with ankle plantarflexion, significant condition effects were found for the left peak ankle dorsiflexion (F_C (1, 21) = 19.887, $p < 0.001$) and right peak dorsiflexion (F_C (1, 21) = 9.761, $p = 0.002$).

Table 2-10: Mean ± SD of peak ankle dorsiflexion. BF = Barefoot; FW = Footwear; SMO = supramalleolar orthosis.

Group Peak Ankle Dorsiflexion	Barefoot (M ± SD)	Footwear (M ± SD)	Condition Effect	Group Effect
Non-SMO Left	12.77 ± 7.07	18.25 ± 7.33	$F_C(1, 21) = 19.887$ $p < 0.001$	$F_G(1, 21) = 0.000$ $p = 0.993$
SMO Left	13 ± 7.34	19.23 ± 5.97		
Non-SMO Right	11.99 ± 8.02	16.32 ± 6.29	$F_C(1, 21) = 9.761$ $p = 0.002$	$F_G(1, 21) = 0.063$ $p = 0.802$
SMO Right	14.26 ± 5.29	17.47 ± 4.94		

DISCUSSION

Originally, the hypothesis was that only the SMO group would present with significant changes in the spatiotemporal and kinematic variables measured during overground walking, while the non-SMO group would walk similarly regardless of whether they used their respective footwear or walk barefoot. The results of this study revealed that the use of SMOs can provide favorable changes in gait spatiotemporal and kinematic parameters, and shoes alone may also provide some favorable effects in children with DS with and without being prescribed with SMOs.

Characteristics of joint laxity in children with DS

Before discussing the spatiotemporal and kinematic results of this study, it is important to examine the characteristics of each group, which may explain differences observed during barefoot walking and using respective footwear for each group. Although currently there is no gold standard measure of joint laxity and hypotonia, as opposed to spasticity and hypertonia, a classification score was used based on the overall ROM scores of bilateral elbow hyperextension, knee hyperextension, and ankle dorsiflexion, as presented by Martin, et al. [17]. While subjects in each group were similar in terms of age and walking experience, their joint laxity ROM and classification differed significantly, with the SMO group presenting with higher laxity scores, indicating more flexible joints, compared to the non-SMO group. These features may cause structural abnormalities which can impact gait mechanics and cause compensatory mechanisms, such as wide base of support, increased double support time, and a reduction in joint ROM throughout the gait cycle, to safely explore their environment [14, 16]. Although these compensatory mechanisms may provide an innate sense of stability, they make walking less efficient, possibly hindering the child's ability to explore their environment [25].

Effect of SMO/shoes on spatiotemporal variables

During barefoot walking, the non-SMO group presented with a higher cadence, faster walking speed, and decreased step time compared to the SMO group, demonstrating more favorable gait mechanics [26]. However, when overground walking was assessed with each group's respective footwear, it was found that although both groups demonstrated improvements in these variables, the SMO group's reductions in cadence and step time, and an increase in walking speed approximated the non-SMO group. The use of SMOs also appeared to help improve stride length compared to shoes alone. When each group walked barefoot, the non-SMO group presented with longer step lengths. However, with each group's respective footwear donned, the SMO group surpassed the stride length values achieved by the non-SMO group, possibly reducing a more conservative compensatory mechanism of walking with the added stability of the SMOs [11, 27]. A possible mechanism for the improvement is that constraining the medial lateral ankle motion may affect stepping velocities and angular velocities. However, increasing step width and double support time is also a compensatory mechanism used to improve the base of support and increase stability during gait, which did not improve during overground walking with footwear donned. Subsequently, foot offs occurred later in the gait cycle during the footwear conditions. It's possible that with the added joint laxity in the SMO group, there may have been accompanying muscle weakness, so the added weight of the shoe + SMO may have hindered those parameters.

Effect of SMO/shoes on joint kinematics

Peak hip sagittal plane kinematics were highly asymmetric in the SMO group compared to the non-SMO group when the subjects were walking barefoot. While the SMO group generated more peak hip angle values than the non-SMO group in the right extremity, the left extremity generated much less peak hip flexion and extension values in the SMO group. Once

each group's respective footwear was donned, the differences between sides were abolished, and each group presented with similar peak hip angle values. While the added support from each group's respective footwear provided an increase both peak hip extension and hip flexion, the orthotic support improved bilateral coordination, matching joint excursions across limbs [15, 28]. The hip asymmetries observed in the sagittal plane were also observed with hip abduction. While the non-SMO group had reductions in peak hip abduction following footwear placement, the SMO group demonstrated an interesting trend, considering their hip asymmetry in the sagittal plane. When walking barefoot, the SMO group presented with more peak hip abduction on the left extremity. The reduced peak hip flexion and extension observed in the left extremity of the SMO group compared to their right may explain these differences in the frontal plane. Although hip abduction slightly increased in each extremity when SMOs were donned, there was less of a difference between each extremity's peak hip abduction, improving the symmetry of frontal plane kinematics. The SMOs seemed to provide the necessary constraint to excessive hindfoot eversion and restricting medial and lateral ankle motion, to increase sagittal plane hip ROM, peak hip joint angular velocity, and provide symmetry to hip motion.

At the knee, peak extension did not differ by group or condition. Interestingly, the peak knee extension values were more flexed during the footwear condition, despite increases in peak ROM in the more proximal and distal joints. Timing of these peaks did not differ between groups or conditions. Peak knee flexion values presented with increasing trends in both groups from barefoot to footwear conditions. However, the SMO group demonstrated a larger magnitude of peak knee flexion between the two conditions, and values were equalized with the non-SMO group during the footwear condition. These peak knee flexion values occurred later in swing phase in both groups when their respective footwear was donned. Because the peak knee

extension timing was consistent across conditions and groups, this indicates that there was a longer period of time to achieve peak knee flexion among both groups when their respective footwear was donned. Additionally, while the SMO group presented with less knee peak angular velocity compared to the non-SMO group while barefoot, SMOs allowed the group to significantly increase knee angular velocity. The findings in knee joint kinematics may suggest that orthotic support may permit a more forceful but controlled knee swing phase.

Across the ankle joint, there were no group differences in absolute peak plantarflexion or dorsiflexion. Both groups increased dorsiflexion significantly with shoes, however, peak plantar flexion values reduced for both groups during the footwear condition, with the SMO group presenting with less peak plantar flexion values than the non-SMO group. Timing of peak dorsiflexion occurred later in stance phase and appeared to be more consistent between groups when footwear was donned, allowing more ankle sagittal plane motion from initial contact to peak dorsiflexion. Consequently, peak plantarflexion timing slightly shifted later in the gait cycle as well. Although both shoes + SMOs and shoes alone provide stability, this may impact the ability to achieve more plantar flexion at push-off. However, the medial-lateral constraint provided by the SMOs may enhance the user's ability to push-off.

One feature that was seen in the SMO group compared to the non-SMO group is the improvement in symmetry for each extremity when the SMOs were donned. The SMO group in this study presented with a larger degree of asymmetry in step length, double support time, foot progression angles, knee angular velocity, and hip angular velocity during barefoot walking, compared to the non-SMO group. With the SMOs donned, it was observed that the SI values approached zero significantly in the SMO groups. Frontal plane stabilization provided by the SMOs possibly allowed the subjects to improve stability in gait, thus equalizing their gait.

Conversely, there were no significant changes in the non-SMO group, which is no surprise considering their lower joint laxity scores and more advanced spatiotemporal gait parameters compared to the SMO group. Children in the SMO group walked with shoes and SMOs for most of the day, while the non-SMO group were more familiar with barefoot walking. Thus, the lack of barefoot walking experience, particularly in the SMO group, may influence the gait differences between the two groups. The foot progression angle (FPA) also became symmetric when the SMO group donned their SMOs for overground walking. Interestingly, the SMO group displayed a larger degree of toe out in the left extremity during barefoot walking. With the SMOs providing medial-lateral stability in the ankle joint, thus allowing more sagittal plane ROM up the chain, The FPO of the left foot decreased and was not significantly different than that of the right leg. Martin (2004) describes the compression SMOs provide promotes midline positioning and thought to subsequently promote joint receptor function [17]. Additionally, this same observation was seen in a study by Selby-Silverstein and Palisano (2001), where children with DS ages 3-6 years of age demonstrated a decrease in transverse plane foot angle when walking overground with foot orthoses [28].

Limitations and future directions

This study is not without limitations. While to our knowledge, this is the first study to use 3D motion capture to analyze the effects that SMOs have on overground walking in young children with DS, we did not collect kinetic or muscle activity data. This data may provide a more robust explanation on the effects of SMOs on overground walking, such as the effects of ankle plantarflexion force at push-off or co-contractions that may occur between the quadriceps and hamstrings during stance phase and throughout swing phase of gait. Some subjects were also sensitive to the placement and removal of the reflective markers, making the randomization

process difficult. If there was overstimulation from the initial anthropometric measures and marker placement, we would begin to collect in the barefoot condition, right after the anthropometric measures. Often, we were able to redirect the child, with the assistance of their parent, by using distraction methods such as giving them a stuffed animal or the parent would show them a video in between trials.

Another limitation is that we did not collect overground walking trials with shoes alone for the SMO group or using SMOs in the non-SMO group. Due to the cost and differences in the size of the foot per child, we were not able to provide custom made SMOs to the non-SMO groups. Conversely, because the SMO group used SMOs during most of the waking day, their shoes were fitted slightly larger to accommodate the SMOs. Therefore, the shoes would be too loose to collect trials without the SMOs on, which may alter gait biomechanics. We also did not account for the type of shoe that the control group had, such as those that fit below or above the level of the malleoli. Gait asymmetry was observed in some variables; however, we did not assess the relationship between leg dominance and asymmetry. Joint laxity may have a confounding effect on the groups and influence their gait biomechanics. Thus, we may consider subgrouping individuals with similar joint laxity scores or conducting an ANCOVA with joint laxity score as a covariate to adjust for the influence that joint laxity may have on gait biomechanics. Finally, we had a modest sample size for this study. Ongoing recruitment will help solidify the trends and significances we observed in this study.

Conclusion

In conclusion, this study supports the use of SMOs in children with DS. Significant and favorable changes in gait biomechanics were observed from barefoot walking to walking with SMOs. Additionally, there were observable trends towards gait symmetry when SMOs were

being used compared to barefoot. Based on the goniometric measures, the SMO group presented with a higher degree of hypermobility and joint laxity compared to the non-SMO group. Additionally, the non-SMO group had more optimal gait mechanics than the SMO group when walking barefoot. While the non-SMO group displayed some favorable changes in their gait mechanics with their shoes on, the SMO group's improvement in gait mechanics while using SMOs closely matched the non-SMO group when they used shoes alone. Therefore, the use of SMOs can improve overground walking mechanics, especially those who have a higher degree of hypermobility. Conversely, SMOs may not be needed for every child with DS. Rather, clinicians may consider conducting clinical test for hypermobility and postural alignment to determine the appropriateness of SMO prescription.

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Chapter 3: Effect of Supramalleolar Orthosis on Obstacle Negotiation in Children with Down Syndrome

ABSTRACT

Individuals with Down syndrome (DS) display delays in motor, cognitive, language, and social development. The impairments in the central and peripheral neural systems cause significant biomechanical deficits due to the inherent need to stabilize the joints in the lower extremity, thus resulting in compensatory strategies, such as co-contracting antagonistic muscles, and inefficient gait mechanics. Supramalleolar orthosis (SMO) are orthotics that provide support to the foot and the ankle above the level of the malleoli and are a common clinical intervention to provide stability at the ankle joint and improve gait mechanics. There is limited evidence on the efficacy that SMOs provide on gait and obstacle crossing mechanics, strategy used to cross the obstacles and fall risk. Therefore, clinicians rely on anecdotal evidence for the timing of prescription and use. In this study, we investigated obstacle negotiation in young children with DS ages 2 to 6 years old, who either used or have not used SMOs for daily walking, to assess the differences in obstacle crossing between barefoot versus external support (shoes only or shoes with SMOs). We presented an obstacle height of 10% and 30% of the child's leg length, both barefoot and with their external support. We first assessed motor strategies from all attempts, which included stepping over the obstacle successfully or unsuccessfully, bear crawling, walking around, or refusing to cross. We analyzed spatiotemporal and kinematic patterns of the trials where participants successfully crossed the obstacle . We hypothesized that with external support, the SMO group will present with a higher frequency of stepping over the obstacle as their primary choice of strategy. Additionally, the SMO group would present with significant

improvements in spatiotemporal and kinematic variables than the non-SMO group during the preparatory phase and crossing phase of obstacle crossing. Results of the study revealed that SMO use improved the percentage of successful obstacle crossing strategy and reduced the percentage of secondary strategies to cross the obstacle in the SMO group. The non-SMO group demonstrated reduced use of secondary strategies and increased use of the primary strategy to cross with footwear. However, their primary strategy success rate was similar across conditions for both heights. The non-SMO group also presented improvements in spatiotemporal variables, such as step length and crossing velocity, but increased the use of frontal plane hip kinematics and increased reliance on proximal joints to clear the obstacle. The results from this study concluded that SMO use can benefit young children with DS, but the prescription may need to be individualized based on characteristics such as joint laxity and hypotonia.

INTRODUCTION

Down syndrome (DS) is the most common genetic disorder that causes delays in motor, cognitive, language, and social development. Individuals with DS present with extensive delays in developmental skills attributed to neuromuscular manifestations such as hypotonia and impaired balance and coordination [1].

Rehabilitative approaches have been utilized to improve walking ability by addressing deficits in gait parameters attributed to functional limitations and compensatory mechanisms. One of these approaches has been the introduction of supramalleolar orthosis (SMO) to address these primary complications and improve gait parameters in children with DS [2, 3]. Clinicians commonly prescribe SMOs, which are orthotics that provide support to the foot and the ankle above the level of the malleoli and are thought to provide additional stability needed to improve overall gross motor function [2, 4]. SMOs are made of a flexible hybrid plastic and may provide stability about the ankle joint through compression [5].

Evidence regarding the efficacy SMO use in improving gait parameters is limited and conflicting, particularly the biomechanical impact that SMOs have on gait in children with DS. Looper et al. (2012) revealed no significant difference between barefoot, foot orthosis, and SMO for most gait parameters measured in children with DS aged 4 to 7 years. Furthermore, SMO use resulted in an decrease in cadence and increase in cycle time, indicating that SMOs might destabilize the gait cycle and providing the extra support may be detrimental to the gait cycle [2]. Additionally, Looper and colleagues (2010) tested SMO use in infants with DS about 20 months of age who were undergoing an early treadmill stepping intervention. The SMO group (n = 10, M_{age} = 21 months) were fitted with SMOs at the onset of training, whereas the control group (n = 7, M_{age} = 19 months) were fitted with SMOs once the intervention was terminated. Both groups

received treadmill training at a velocity starting at 0.2 m/s and trained 8 minutes per day, 5 days per week until the infant was able to take 3 steps independently. Results revealed that the SMO group achieved lower gross motor function scores than the control group at walking onset. Therefore, SMO use may be detrimental to gross motor development when it is used before the infant starts walking independently [3]. On the other hand, Martin (2004) showed that the introduction of SMOs increased the scores of standing, walking, running, and jumping components of the Gross Motor Function Measure (GMFM) as well as balance scores on the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP) test in children with DS aged between 3.5 years to 10 years. These improvements carried over after 6-weeks of wearing SMOs and widened the gap of GMFM and BOTMP scores between the shoes only condition and the shoes + SMO condition, with the latter demonstrating better scores [5]. These results suggest that SMO use in children with DS after they start walking independently may enhance locomotor development.

Walking in uncontrolled environments may require the task to cross over obstacles, requiring motor and perceptual skill. Children with DS may find this task difficult, owing to perceptual and motor deficits, which are required to make the coordinated adjustments of the swing leg to clear the obstacle, while at the same time maintaining balance from the stance limb, thus preventing falls [6]. Chen and colleagues (2016) studied the spatiotemporal and kinematic strategies of 15 children with DS with a mean age of 7-9 years compared to 15 age-matched typically developing controls. Each group crossed obstacle heights of 10%, 20%, and 30% of the subject's leg length. Compared to the control group, children with DS presented with a more cautious crossing strategy, such as slower crossing speeds over the obstacle, wider step widths and lengths, and increased obstacle clearance height of both limbs [6]. This study did not specify

SMO use, and to our knowledge, there are no studies observing the impact that SMOs would have on obstacle crossing.

The evidence of SMO use in DS can also be conflicting among previous studies [2, 3, 5]. Traditionally, clinicians prescribe SMOs to correct abnormal alignment and provide external support as soon as the child is able to pull to stand. However, other clinicians believe that early orthotic use will limit the child's ability to develop upright locomotor skills due to limited ankle mobility [2]. The lack of evidence and conflicting results cause clinicians to rely on anecdotal evidence and expert opinion when prescribing SMOs. In this study, we investigated the biomechanical impact of SMO use in children with DS who were prescribed SMOs (i.e., the SMO group) versus children who were not prescribed SMOs (i.e., the non-SMO group), during obstacle crossing at a height of 10% and 30% of the child's leg length. We hypothesized that the SMO group will increase the frequency of stepping over the obstacle as a strategy to cross the obstacle, decrease proximal joint kinematics and kinematics along the frontal plane, and improve spatiotemporal parameters, whereas the non-SMO group would not demonstrate improvements in obstacle crossing with their shoes only.

METHODOLOGY

Participants

We recruited 10 children with DS who have been prescribed supramalleolar orthosis (SMO) and 13 children with DS who were not prescribed SMOs, with an age range of 2 to 6 years. A priori power analysis (G*Power, Dösseldorf) with sufficient power (>0.80) and moderate effect size (d=0.60) could be obtained with 12 subjects in each group [2]. Due to potential loss of data and the subject's inability to complete all tests, we aim to recruit 15 subjects per group. Participants had at least 6 months of independent walking experience. To be

allocated to the SMO group, the children must have worn their SMOs at least 50% of the time they are walking during the day, which was confirmed by the subject's parents through a questionnaire. Subjects were excluded from the study if they presented with current musculoskeletal injuries of the lower extremities, uncorrected vision and hearing problems, and unresolved congenital heart defects that may cause symptoms with exertion. The subjects visited the GSU Biomechanics Lab one time for approximately 2 hours. Parental permission form was obtained from the parent of each subject before data collection began. The study protocol was approved by Georgia State University's internal review board.

Data Collection

Both groups were randomized by a random number generator, in which numbers ending in an odd number began the walking trials with the group's respective footwear (SMO and shoe donned for the SMO group and shoe only donned for the non-SMO group), and the numbers ending in an even number will begin the walking trials barefoot. We minimized fatiguing or overstimulating the child by beginning the next activity with the condition that ended the previous activity. The sequence appeared as AB|BA, starting with the first obstacle height, and finally the second obstacle height (see figure 1).

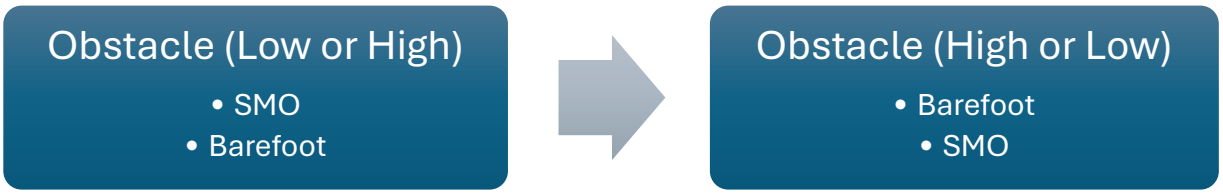


Figure 3-1: Trial sequence example for the SMO group randomized to start the trials barefoot.

The parents were instructed to have their child wear tight fitting clothing for the duration of the data collection. We also clipped the subject's shirt and/or shorts in order to expose the reflective markers. Subjects in the non-SMO group had two conditions: barefoot and with their

shoes, and the SMO group had two conditions: barefoot and with their SMOs and shoes donned, similar to the Looper, et al. study [2]. Anthropometrics measures, including total height in mm, body mass in kg, leg length (the length measured in mm from the ASIS (anterior superior iliac spine) to the base of the medial malleoli), knee width (the width of the knee in mm, measured at the widest point), and ankle width (the width of the ankle in mm measured at the widest point between the medial and lateral malleoli), were measured prior to walking trials. To adjust for shoe height, we obtained measurements from the floor to the base of the lateral malleoli with both shoes on and off.

Additionally, we obtained bilateral ROM measures of knee hyperextension, elbow hyperextension, and ankle dorsiflexion, to explore the influence of joint laxity. The two groups were categorized as either more lax, or those with a total laxity score of 60° or more, or less lax, or those with a total laxity score of less than 60°, as described by Martin (2004) [5]. We used a digital goniometer to obtain the joint ROM measures. Knee hyperextension was measured with the subject lying supine on a treatment table with a bolster placed underneath the ankle in order to elevate the leg or the examiner supporting the leg off of the mat by the ankle. The examiner applied a slight downward pressure on the thigh and shank to achieve as much knee hyperextension as possible, without discomforting the subject. The stationary arm of the goniometer was aligned with the greater trochanter of the femur, the axis was aligned along the knee joint space, and the distal arm was aligned with the lateral malleolus of the ankle. For elbow hyperextension, the subject laid supine on a treatment table. The examiner stabilized the humerus with one hand and applied a slight downward pressure of the subject's wrist with the opposite hand, in order to achieve as much elbow extension as possible without discomforting the subject. The stationary arm of the goniometer was aligned to the subject's greater tubercle,

the axis was aligned with the lateral humeral epicondyle, and the distal arm of the goniometer was aligned with the radial styloid process. Ankle dorsiflexion was measured with the subject lying supine on the treatment table. The stationary arm of the goniometer was aligned with the head of the fibula, the axis was aligned with the ankle joint axis, along the base of the lateral malleoli, and the distal arm was aligned with the 5th metatarsal. The examiner moved the foot into as much ankle dorsiflexion as possible, without discomforting the subject.

A 16-marker Vicon Lower Body Plug-In Gait model was used with 14 mm spherical reflective markers attached bilaterally to the subject's ASIS, posterior-superior iliac spine (PSIS), thigh, knee, shank, ankle, heel, and 2nd metatarsal. A 9-camera Vicon motion capture system (Oxford, UK) was used to record the position of each marker with a sampling frequency of 100 Hz. A 6-meter walkway was used to collect the walking trials. A T-pose calibration was conducted to calibrate the markers while the subjects stood as still as possible on one of the force plates before the trials. We obtained a second calibration with the subject's respective footwear donned.

In this study, the subject's crossed an obstacle set at either a "low" height of 10% of their leg length, or a "high" height of 30% of their leg length. The obstacle heights were randomized so that half of the subjects started by crossing an obstacle set at a "low" height, followed by the "high" height, and the other half used a reversed order. These two obstacle heights presented biomechanical changes when crossing the obstacle but not so high that children were unable to clear the obstacle [6]. The obstacle consisted of a 5 ft long x 2 in diameter rod encased in foam and painted with a bright color in order to provide visual contrast to be able to see the obstacle. The rod was supported on each side by a height adjuster. The obstacle was placed in the middle of the 6m walkway, and the subjects were instructed to walk across the walkway at their selected

walking speed and to step over the obstacle. The subjects attempted each height at each condition, barefoot and with shoes or shoes and SMOs donned.

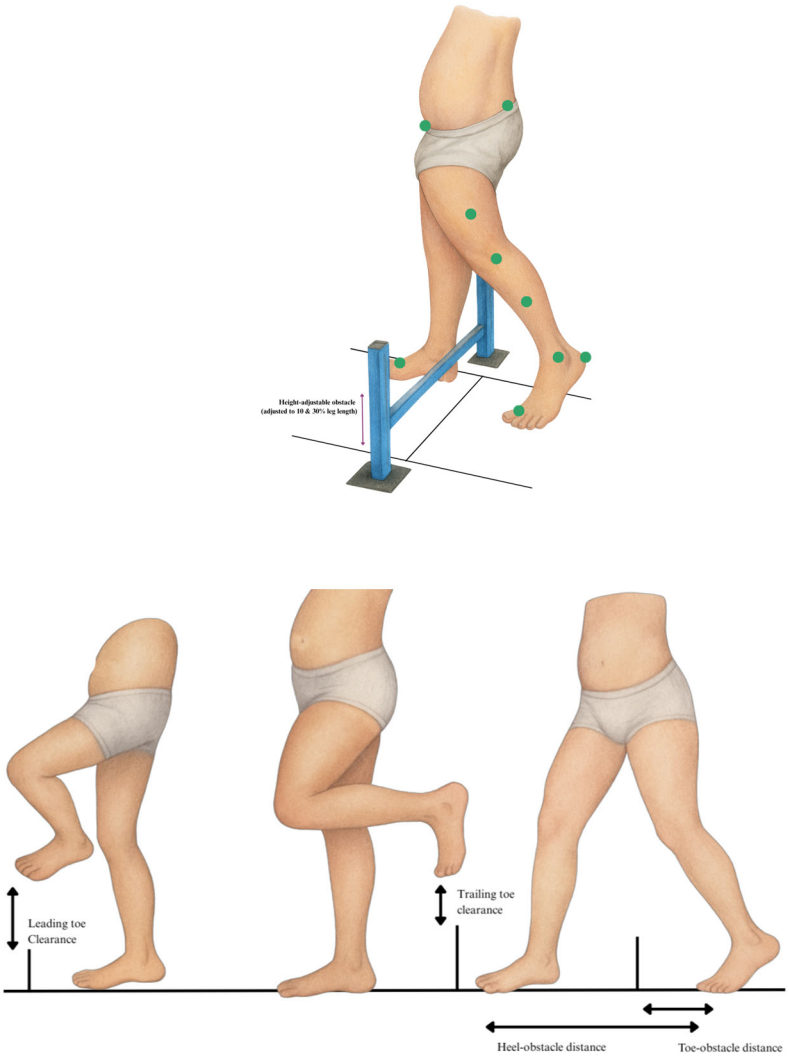


Figure 3-2: Obstacle crossing and obstacle crossing spatiotemporal parameters.

Because some subjects presented with gait limitations and had difficulty crossing obstacles, we documented the strategy that the subject used for each trial attempt and the percentage of each strategy chosen by each group was calculated. Strategies included (a)

stepping over the obstacle (successful or unsuccessful, such as a fall), (b) bear crawling over the obstacle, (c) walking around the obstacle, or (d) refusing to cross the obstacle. A successful step-over attempt was when the subject stepped over the obstacle with both limbs without hitting the obstacle and continued to walk. An unsuccessful step-over attempt was when the subject attempted to step over the obstacle but was unable to clear the obstacle with either limb or tripped over the obstacle during the crossing attempt. Crawling over the obstacle was when the subject transitioned to a quadruped position before crossing the obstacle and used both their upper extremity and lower extremity to cross the obstacle. Walking around the obstacle occurred when the subject avoided crossing the obstacle by deviating away from the obstacle but continued to walk forward without changing directions. Refusing to cross the obstacle occurred when the subject avoided the obstacle during the approach by changing directions to walk away from the obstacle or refusing to walk towards the obstacle. The percentage of each strategy from the total number of attempts per obstacle height and condition were calculated.

We analyzed two phases during obstacle crossing: the preparatory phase, or the stance phase of the crossing attempt; and the obstacle crossing phase for the stepping-over strategy only. The preparatory phase was defined as the initial foot contact to the toe-off event when the step is taken to initiate the obstacle crossing, for both legs. During the preparatory phase, the toe-marker to obstacle distance measured in centimeters. The preparatory phase timing was measured as the time between heel strike and toe-off of the leading and trailing limbs when crossing the obstacle, measured in seconds. The leading limb is defined as the limb that crossed the obstacle first and the trail limb is defined as the limb the crossed the obstacle last. The timing represents the time to prepare to cross the obstacle, which requires a degree of processing and selection of motor pattern to cross safely.

During the obstacle crossing phase, we measured the spatiotemporal and kinematic variables of successful crossing trials, where the subject stepped over the obstacle.

Data Analysis

Raw marker data of the obstacle crossing trials were exported from the Vicon Nexus software. A 4th order zero lag Butterworth low pass filter with a cut-off frequency of 6 Hz was used to filter the kinematic data [7]. We used a custom Matlab ® program to calculate biomechanical parameters. Preparatory phase spatiotemporal variables and obstacle crossing spatiotemporal variables and sagittal plane kinematics of the hip, knee, and ankle were measured during obstacle clearance of 10% and 30% obstacle height normalized to the subject's leg length. Normalization procedures for step length was calculated by the following formula, $\hat{l} = \frac{l}{l_0}$, where $\hat{l}$ is the normalized step length, l, is the step length, and l_0 is the subject's leg length [8]. Gait velocity was calculated as $v = m/s$, where m is the distance in meters of the right heel marker tracked by Vicon and s is the time in seconds between the first visible frame of the right heel marker to the last visible frame of the right heel marker. Whole body crossing velocity was normalized by the following equation, $\hat{v} = \frac{v}{\sqrt{g*l_0}}$, where $\hat{v}$ is the normalized velocity, v is the measured velocity, g is the acceleration of the Earth's gravity of 9.81 m/s^2, and l_0 is the subject's leg length [8].

Spatiotemporal variables of interest include leading toe clearance when the toe is above the obstacle, and foot placement before and after crossing; trailing toe clearance when the toe is above the obstacle, and foot placement before and after crossing; and whole body crossing speed were measured. Leading toe clearance is the vertical distance between the obstacle and the toe marker of the leading limb when the toe marker is above the obstacle; leading foot placement after crossing the obstacle is the horizontal distance between the obstacle and the heel marker of

the leading foot after initial contact; trailing toe clearance is the vertical distance between the obstacle and the toe marker of the trailing limb when the toe marker is above the obstacle; trailing foot placement after crossing the obstacle is the horizontal distance between the obstacle and the heel marker of the leading foot after initial contact; and whole body crossing speed is the instantaneous velocity when the mid-point of the inter-ASIS line is directly over the obstacle [6]. Joint kinematics include sagittal plane hip, knee, and ankle angles and frontal plane hip angles when the lead and trail limb toe markers are directly over the obstacle.

Statistical Analysis

Paired *t*-tests were conducted to detect any group differences between the SMO and non-SMO groups in each of subject's anthropometric measures. The effects of SMO use on all variables were conducted using a three-way (2 group x 2 condition x 2 obstacle height) mixed ANOVA. For all statistical analyses, a Bonferroni post-hoc analysis was conducted when necessary. Normality was assessed using the Shapiro-Wilk test and non-normally distributed variables were log-transformed if normality was violated [9]. A statistical significance was set at an $\alpha=0.05$. All statistical analyses were performed using SPSS (Version 29.0; IBM Corp., Armonk, NY, USA).

RESULTS

Subjects

Twenty-three young children with DS (16 male, 7 female) were recruited in this study. Ten participants were in the SMO group, and 13 participants were in the non-SMO group. Age differences (SMO: 39.60±14.31 months; non-SMO: 42.92±15.97 months, $t(22)=-0.525$, $p=0.352$) and walking experience (SMO: 22.80±14.14 months; non-SMO:23.31±13.80 months, $t(22)=-0.086$, $p=0.896$) were not significant between the two groups. While leg length was not

significant (SMO: 39.52± 7.59 cm; non-SMO: 39.69±6.69 cm, t(22)=-0.057, p=0.96), there was a significant difference in joint laxity scores (SMO: 81.75±19.89°; non-SMO: 58.48±14.16°, t(22)=3.14, p=0.002) between the two groups such that the SMO group had a significantly higher joint laxity scores than the non-SMO group. Mean joint ROM, calculated as the average of summed bilateral elbow hyperextension, knee hyperextension, and ankle dorsiflexion, was significantly different between groups but violated the assumption of homogeneity of variance (Levene's test: F=4.464, p=0.047). A nonparametric Mann–Whitney U test indicated that mean joint ROM was significantly greater in the SMO group (40.88 ± 9.95°) than in the non-SMO group (31.95 ± 5.09°; p=0.015).

Table 3-1: Mean and standard deviation (SD) of participant characteristics and statistical results

	Non-SMO	**SMO**	**T Statistic**	**Significance**
Age (months)	42.92 (15.97)	39.6 (14.31)	*t(22)*=-0.525	*p*=0.352
Walking Experience (months	23.31 (13.8)	22.8 (14.14)	*t(22)*=-0.086	*p*=0.896
Leg Length (cm)	39.69 (6.69)	39.52 (7.59)	*t(22)*=-0.057	*p*=0.96
Joint Laxity Scores (deg)	58.48 (14.16)	81.75 (19.89)	*t(22)*=3.138	*p*=0.002

Obstacle Crossing Strategy

Obstacle crossing strategies, as discussed in the methodology, include successful obstacle crossing, unsuccessful obstacle crossing, bear crawling over the obstacle, walking around the obstacle, and refusing to cross the obstacle. Table 1 includes the distribution of obstacle crossing strategies at 10% obstacle height for each group during each condition. During barefoot obstacle crossing at 10% obstacle height, both groups attempted to cross the obstacle as their choice of strategy. However, the SMO group had substantially fewer successful attempts and more unsuccessful attempts. Secondary strategies, or strategies not consisting of stepping over the

obstacle, were far fewer, with bear crawl being the strategy that was least used between both groups during each condition. The SMO group had a higher percentage of refusing attempts. When footwear was donned, the SMO group demonstrated an increase of nearly 10% of successful obstacle crosses, owing to the medial/lateral support of the SMO. Unsuccessful attempts in the SMO group were similar, indicating that there was an increase in the primary strategy used during the crossover attempt. The SMO group also presented with fewer secondary strategies attempts, notably fewer refusals to cross the obstacle. While there was also an increase in the distribution of the primary strategy in the non-SMO group, successful attempts were similar between barefoot and footwear conditions, along with more unsuccessful attempts. Overall, the non-SMO group had a higher percentage of successful obstacle crossing attempts than the SMO group,

Table 3-2: Percentage of each crossing strategy used during trials at 10% obstacle height.

10% Height	Successful	Unsuccessful	Bear Crawl	Walk Around	Refused
SMO BF	39.74%	25.64%	3.85%	14.10%	16.67%
Non-SMO BF	65.26%	8.42%	1.05%	18.95%	6.32%
SMO FW	50.00%	25.81%	1.61%	12.90%	9.68%
Non-SMO FW	67.11%	14.47%	2.63%	11.84%	3.95%

At the 30% obstacle height, there was a similar distribution of strategies used in both groups between barefoot and footwear conditions. When attempting to cross while barefoot, 50.82% of the crossover attempts were successful in the SMO group, with an increase to 58.70% when they wore their SMOs. While there was an increase in unsuccessful attempts from barefoot to footwear conditions, both groups had a larger proportion of stepping over the obstacle as a

strategy when their footwear was donned. There were also fewer refusals to cross the obstacle by both groups when footwear was donned. Thus, the shift in choice of strategy was distributed to walking around or stepping over the obstacle.

Table 3-3: Percentage of each crossing strategy used during trials at 30% obstacle height.

30% Height	Successful	Unsuccessful	Bear Crawl	Walk Around	Refused
SMO BF	50.82%	21.31%	6.56%	9.84%	11.48%
Non-SMO BF	67.74%	14.52%	4.84%	6.45%	6.45%
SMO FW	58.70%	28.26%	0.00%	10.87%	2.17%
Non-SMO FW	65.71%	28.57%	1.43%	4.29%	0.00%

Spatiotemporal Parameters

During the preparatory phase, the SMO group had longer preparatory times and stood further away from the obstacle before crossing compared to the non-SMO group. During obstacle crossing, the SMO group had slower whole body obstacle crossing velocities, longer step lengths, wider step widths, and higher toe to obstacle clearances for each limb compared to the non-SMO group, regardless of condition and height. The overall multivariate ANOVA model for the spatiotemporal variables resulted in significant effects for group ($F_G(1,21) = 4.785$, $p < 0.001$, $\eta^2 = 0.333$), condition ($F_C(1,21) = 5.295$, $p < 0.001$, $\eta^2 = 0.356$), height ($F_H(1,21) = 23.303$, $p < 0.001$, $\eta^2 = 0.708$), and group*condition ($F_{G*F}(1,21) = 1.867$, $p = 0.017$, $\eta^2 = 0.163$). Group*height, condition*height, and group*condition*height interactions were not statistically significant. The influence of group demonstrates a large effect size, with 33.3% of the variance explained in spatiotemporal measures, indicating that the differences in SMO use versus shoes alone strongly influenced gait timing and distance parameters during obstacle crossing.

Condition explained 35.6% of the variance, where spatiotemporal parameters are largely influenced whether the subject crossed the obstacle barefoot versus with their respective footwear (SMO + shoes or shoes only). Height had the largest influence in affecting spatiotemporal parameters, explaining 70.8% of the variance. As expected, higher obstacles require more substantial adjustments in time and distance parameters during obstacle crossing. The group*condition interaction also demonstrates a large effect, with 16.3% of the variance explained, indicating that the SMO group responded differently to barefoot vs footwear conditions compared to non-SMO users, influencing spatiotemporal strategies. Although the multivariate analysis for the group*height interaction, was not statistically significant, there was a moderate effect size, indicating that there may be an influence between the SMO and non-SMO group as height changes.

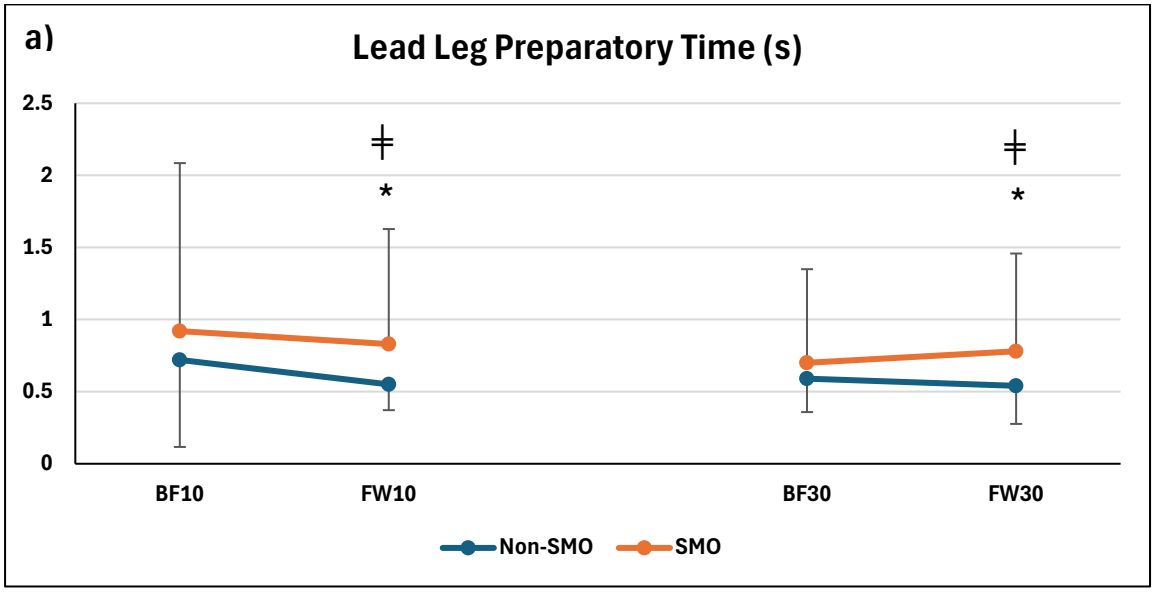
Preparatory Parameters

Preparatory Phase Timing

The non-SMO group's lead leg preparatory time decreased from 0.72 ± 06 seconds when barefoot to 0.55 ± 0.178 seconds with shoes on before crossing the obstacle set at 10% leg length height (Fig. 2). However, with the height set at 30% leg length, there was a negligeable decrease from 0.59 ± 0.23 seconds when barefoot to 0.54 ± 0.26 seconds with shoes on. The SMO group had longer preparatory phase times compared to the non-SMO group. At 10% obstacle height, their preparatory time was 0.92 ± 1.17 seconds when barefoot and decreased to 0.83 ± 0.80 seconds with their SMOs on. Conversely, at 30% obstacle height, the lead leg preparatory time increased from 0.70 ± 0.65 seconds when barefoot to 0.78 ± 0.68 seconds with their SMOs on. Statistical analysis on the lead preparatory phase time was significant in the group effect

($F_G(1,21) = 6.132$, $p = 0.014$) and in the group*condition effect between groups when footwear was donned ($F_{GC}(1,21) = 4.624$, $p = 0.033$).

The trail leg preparatory time was similar in the non-SMO group and SMO group across conditions when the obstacle height was 10% of the subject's leg length. Larger differences were observed at the 30% obstacle height. The non-SMO group's trail leg preparatory time when barefoot was 1.06 ± 0.55 seconds and decreased to 0.78 ± 0.25 seconds with their shoes on. Conversely, the SMO group's trail leg preparatory time was 0.89 ± 0.35 seconds when barefoot and 0.93 ± 0.37 seconds with their SMOs on. Statistical analysis for the trail leg preparatory time was only significant for the height effect ($F_H = 5.709$, $p = 0.018$).



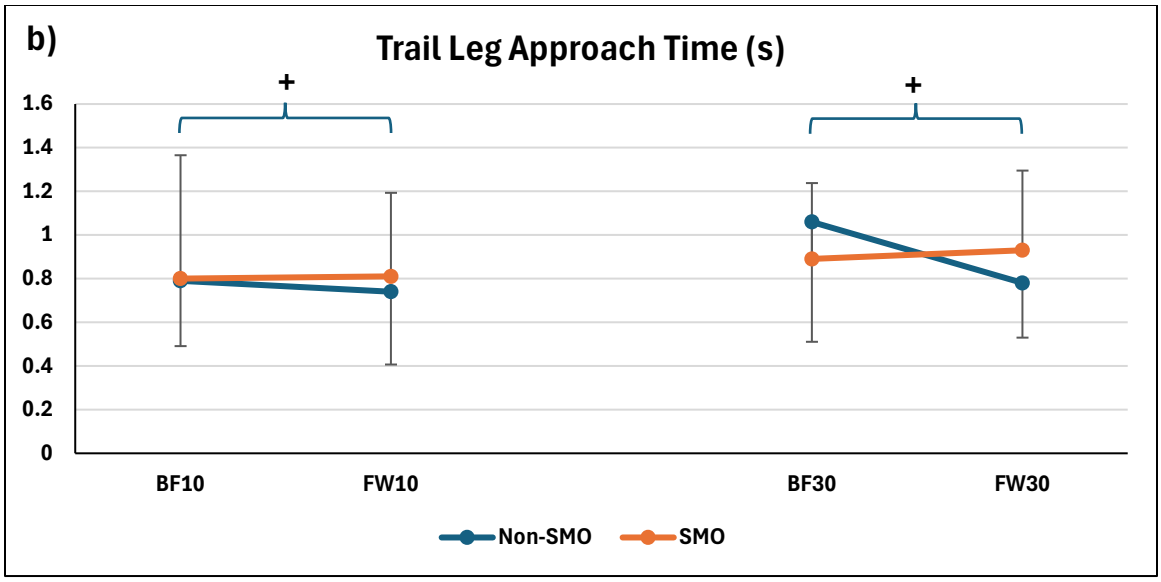


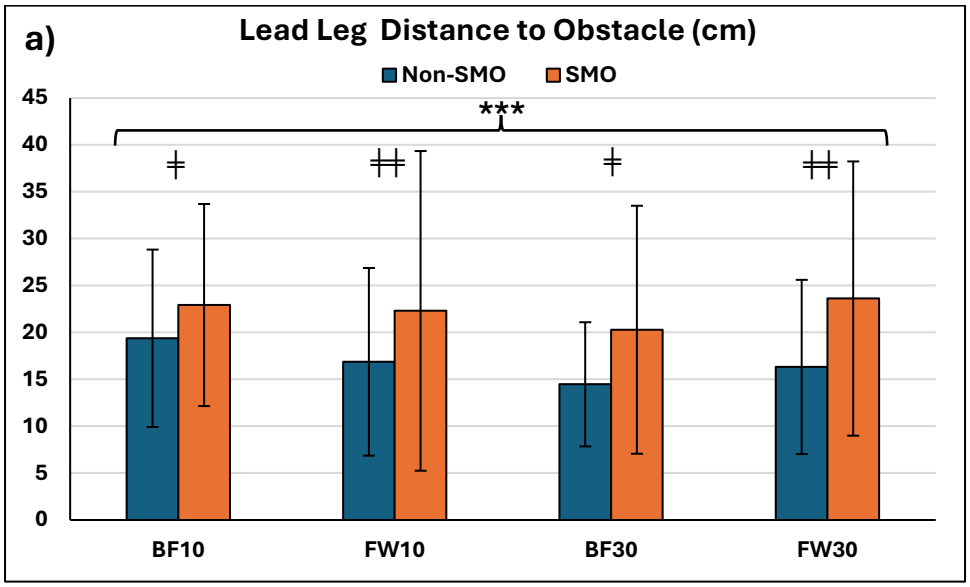
*Figure 3-3: Lead leg (a) and trail leg (b) preparatory phase time (s). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

Preparatory Phase Distance to Obstacle

Overall, lead leg distance was closer to the object in the non-SMO group than the SMO group during each condition and obstacle height (Fig. 3). At 10% obstacle height, the non-SMO group's lead leg was 19.37 ± 9.46 cm from the obstacle during barefoot crossing and decreased to 16.87 ± 10.01 cm when wearing shoes. The SMO group was 22.92 ± 10.78 cm from the obstacle when crossing barefoot, and remained relatively unchanged, with a distance of 22.30 ± 17.04 cm from the obstacle when they wore their SMOs.

When the obstacle height increased to 30% of the subject's leg length, the non-SMO group decreased the preparatory phase distance to the obstacle to 14.47 ± 6.62 cm while barefoot and slightly increased to 16.31 ± 9.29 cm with their shoes on. The SMO group followed a similar trend at this height. Their preparatory distance to the obstacle was 20.28 ± 13.23 cm when

barefoot and increased to 23.61 ±14.63 cm with their SMOs on. Statistical analysis revealed that there was a group effect ($F_G(1,21) = 12.256$, $p < 0.001$), and a significant group by condition interaction effect, with pairwise comparisons revealing differences between each group while barefoot ($F_{GC}(1,21) = 4.502$, $P = 0.035$) and with footwear donned ($F_{GC}(1,21) = 7.962$, $p = 0.005$). Compared to the lead leg, the distance of the trailing leg was positioned closer to the obstacle in both groups across conditions and obstacle heights. Both the non-SMO and SMO group's trail leg preparatory distance was closer to the obstacle when transitioning from barefoot to footwear conditions. The trail leg distance to the obstacle was statistically significant in the condition effect ($F_C(1,21) = 3.878$, $p = 0.05$) and height effect ($F_H(1,21) = 16.007$, $p < 0.001$). There was a significant group*condition interaction ($F_{GC}(1,21) = 4.736$, $p = 0.031$) where the non-SMO group's trail leg was closer to the bar when shoes were on.



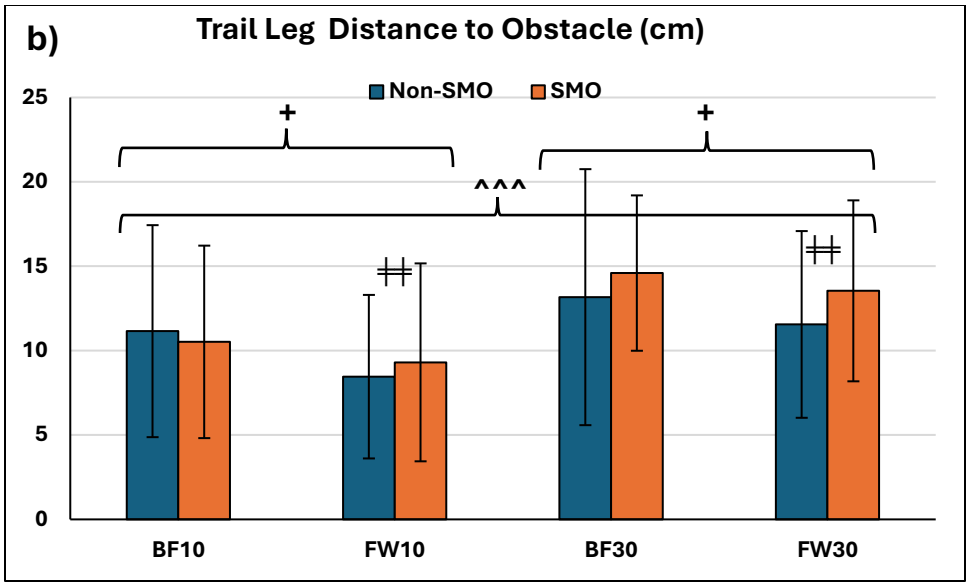


*Figure 3-4: Lead leg (a) and trail leg (b) distance from obstacle (cm). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

Crossing Parameters

Crossover Time

At 10% obstacle height, when barefoot, the non-SMO crossed the obstacle with their lead leg at 0.52 ± 0.16 seconds and slightly decreased to 0.48 ± 0.17 seconds with shoes on (Fig. 4). In the SMO group, when crossing the obstacle at 10% height when barefoot, the crossover time with the lead leg was 0.59 ± 0.16 seconds. With their SMOs on, they crossed the obstacle in 0.49 ± 0.14 seconds. When the obstacle was raised to a height at 30% of the subject's leg length, the non SMO group crossed the obstacle at 0.66 ± 0.20 seconds when barefoot, which decreased to 0.57 ± 0.17 seconds with shoes on. Conversely, the SMO increased the lead leg crossover duration from 0.59 ± 0.16 seconds when barefoot to 0.61 ± 0.14 seconds when they wore their SMOs. The lead leg crossover time was statistically significant in the condition effect ($F_C(1, 21) = 4.969$, $p = 0.031$) and in the height effect ($F_H(1, 21) = 12.959$, $p < 0.001$). Group*condition

interaction was statistically significant ($F_{GC}(1,21) = 5.772$, $p = 0.017$) where crossover time was significantly less in the non-SMO group when shoes were on versus barefoot.

For both groups, the trail limb crossover timing was shorter in duration compared to the lead limb. At the 10% obstacle height, the non-SMO crossed the obstacle at 0.39 ± 0.09 seconds when barefoot, with similar timing at 0.40 ± 0.08 seconds with their shoes on. The SMO group crossed the 10% obstacle height at 0.39 ± 0.10 seconds when barefoot, and the timing was similar at 0.41 ± 0.09 seconds with their SMOs on. At the 30% obstacle, both groups had an increase in crossover time. The non-SMO group presented with no change between the conditions, crossing the obstacle at 0.45 ± 0.122 seconds when barefoot, and 0.45 ± 0.07 seconds with their shoes on. The SMO group also had similar timing between conditions. When barefoot, they crossed the 30% obstacle height at 0.45 ± 0.09 seconds and increased to 0.51 ± 0.12 seconds with their SMOs on. The trail crossover time was significant for the height effect ($F_H(1, 21) = 26.109$, $p < 0.001$) and there were trends towards significance in the group*condition interaction where the SMO group had longer crossover times than the non-SMO group with their respective footwear on ($F_{GC}(1, 21) = 3.551$, $p = 0.061$) and where the SMO group increased their crossover time from barefoot to footwear conditions ($F_{GC}(1,21) = 2.849$, $p = 0.093$).

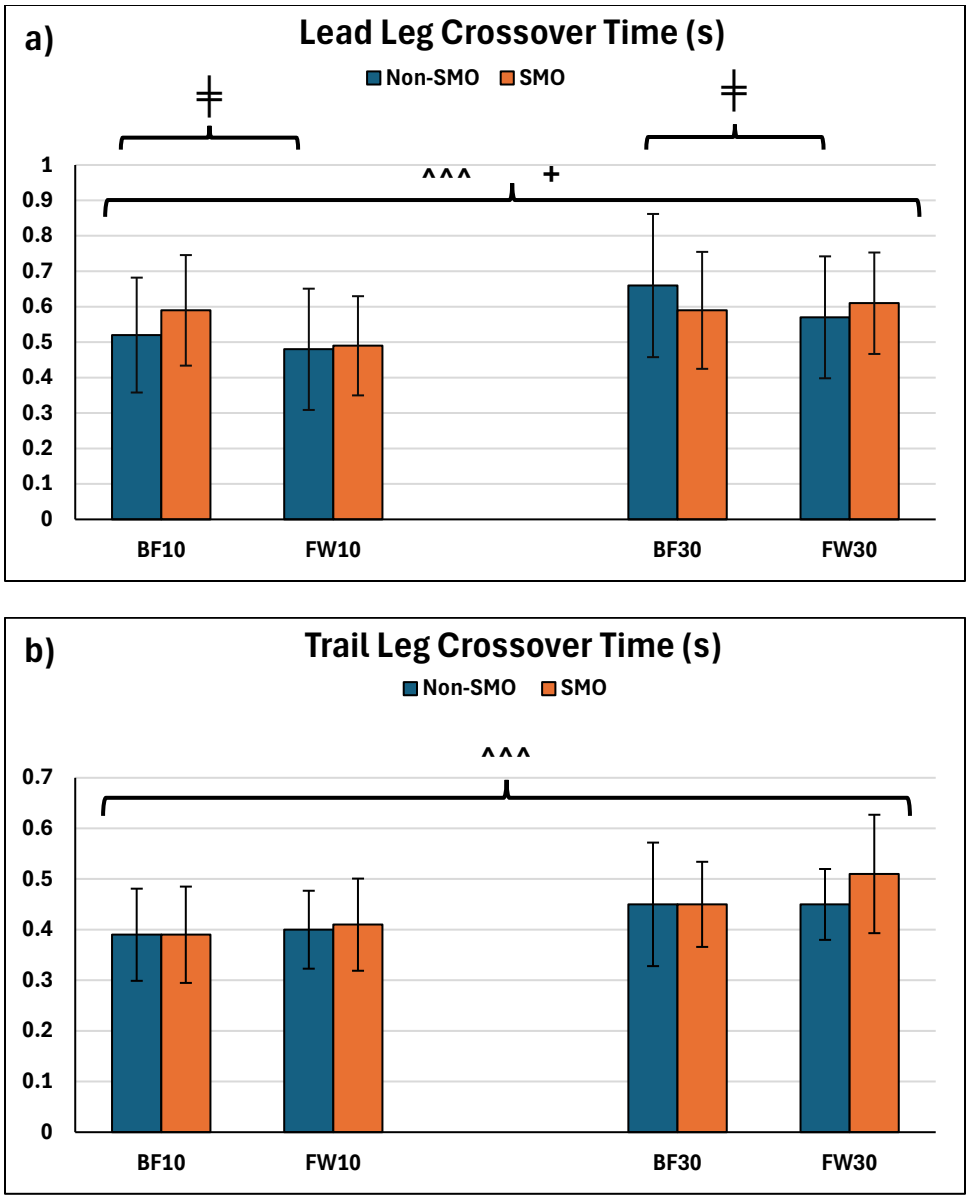


*Figure 3-5: Lead leg (a) and trail leg (b) crossover time (s). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

Obstacle Clearance

Lead leg obstacle clearance increased from barefoot to footwear conditions for both groups at both heights. At 10% obstacle height, the non-SMO group had a 10.8 ± 4.41 cm obstacle

clearance at barefoot, which increased to 11.39 ± 3.79 cm with their shoes on. At the same height, the SMO group cleared the obstacle at 9.93 ± 4.00 cm barefoot, which also increased to 12.99 ± 3.85 cm with their SMOs on. When the height increased to 30% of the subject's leg length, each group presented similar values when they crossed the 10% height obstacle. The non-SMO group, when barefoot, crossed the obstacle at 9.4 ± 3.93 cm, which increased to 10.22 ± 4.82 cm with their shoes on. Similarly, the SMO group crossed the 30% height obstacle at 8.16 ± 4.02 cm barefoot, which increased to 12.20 ± 3.68 cm with their SMOs on. Lead leg obstacle clearance was statistically significant for the condition effect ($F_C(1, 21) = 13.02$, $p < 0.001$), height effect ($F_C(1, 21) = 4.704$, $p = 0.031$), and group*condition interactions were significant where obstacle clearance was higher in the SMO group versus the non-SMO group when footwear was donned ($F_{GC}(1, 21) = 4.497$, $p = 0.035$) and higher in the SMO group with their SMOs on versus barefoot ($F_{GC}(1,21) = 13.951$, $p < 0.001$).

There was an overall decrease in obstacle clearance for the trail leg for both groups. At the 10% height, the non-SMO cleared the obstacle at 6.74 ± 4.81 cm when barefoot and decreased to 5.19 ± 4.87 cm with shoes on. Similarly, the SMO group cleared the obstacle at 6.98 ± 4.12 cm when barefoot and decreased to 5.74 ± 4.87 cm with their SMOs on. When the obstacle height increased to 30% of the subject's leg length, the non-SMO group cleared the obstacle at 6.09 ± 6.52 cm when barefoot and decreased to 4.89 ± 4.97 cm with shoes on. Conversely, the SMO group cleared the obstacle at 7.77 ± 6.13 cm when barefoot, which increased to 9.16 ± 7.96 cm with their SMOs on. The group effect was statistically significant ($F_G(1, 21) = 4.694$, $p = 0.031$), and there was a group*condition interaction between the groups when footwear was donned ($F_{GC}(1, 21) = 4.712$, $p = 0.031$).

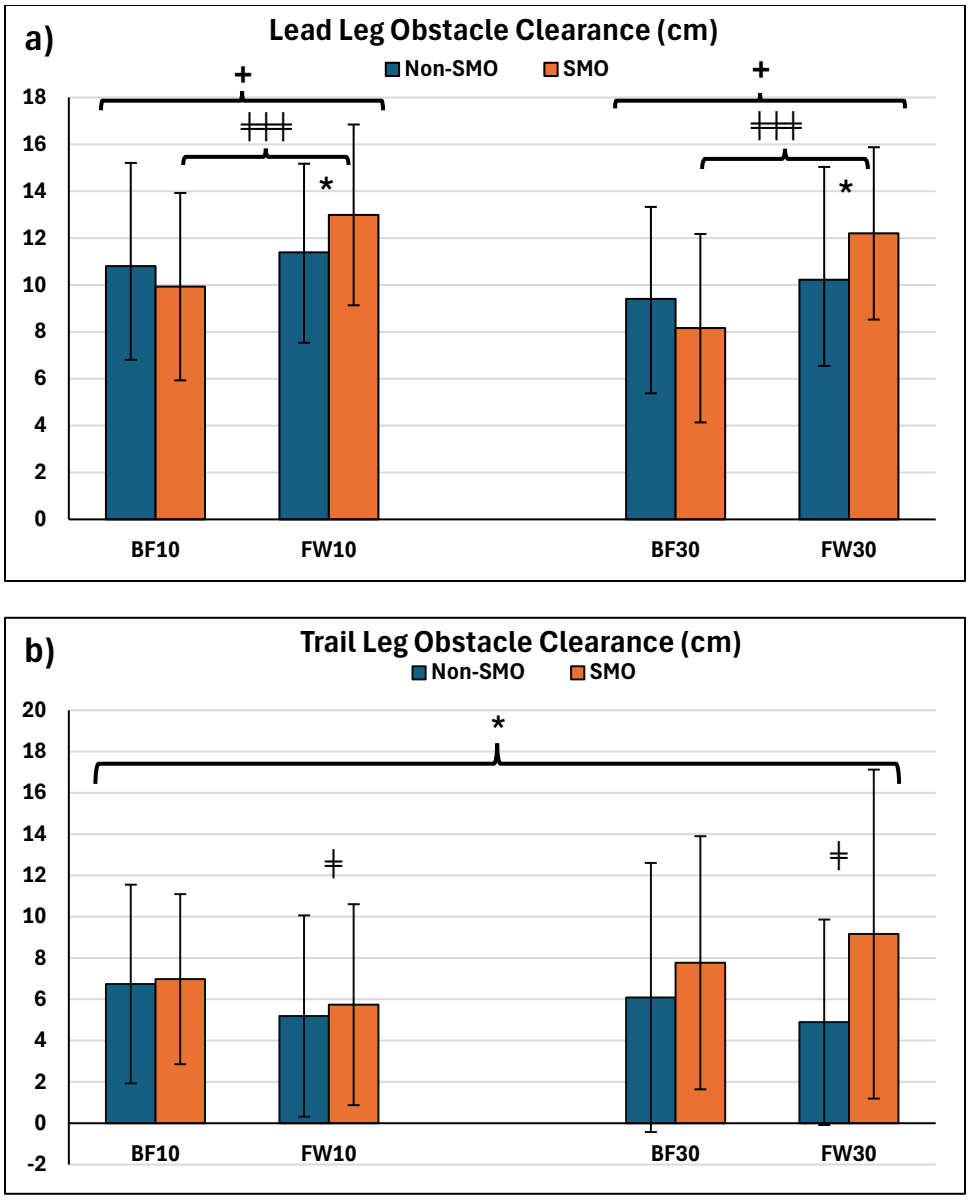


*Figure 3-6: Lead leg (a) and trail leg (b) obstacle clearance (cm). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

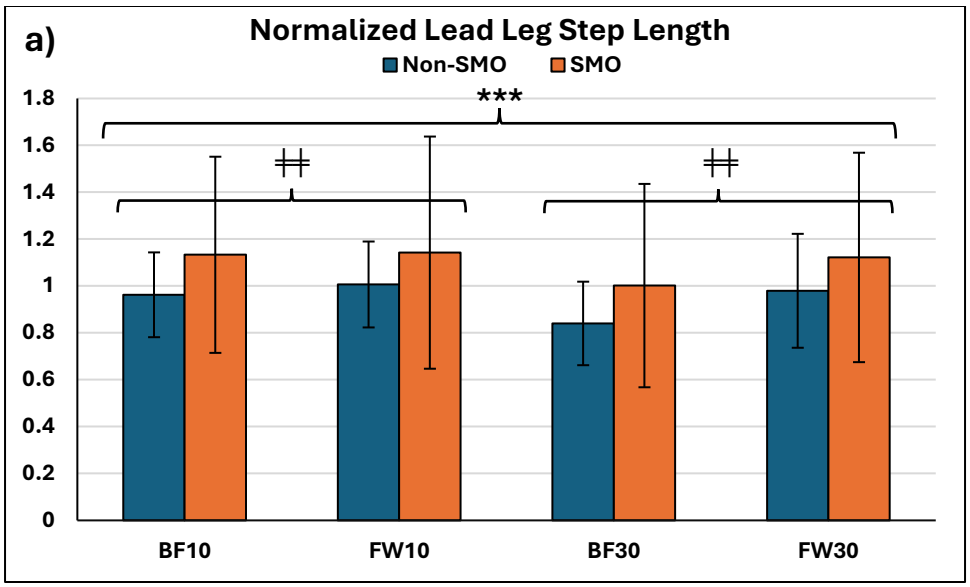
Step Length

Both groups increased their step length when their footwear was donned, during each height (Fig. 6). Additionally, the SMO group presented with longer step lengths compared to the non-

SMO group during each condition. At 10% obstacle height, the non-SMO group's normalized step length was 0.96 ± 0.18 when barefoot and increased to 1.01 ± 0.18. The SMO group's normalized step length at barefoot was 1.13 ± 0.42 and increased to 1.14 ± 0.49. At the 30% obstacle height, the non-SMO group's normalized step length was shorter than their obstacle crossing attempts at 10% height during each condition. When barefoot, their normalized step length was 0.84 ± 0.18 and with shoes on, their normalized step length was 0.98 ± 0.24. The SMO group also presented with shorter normalized step lengths at this height. When barefoot, their normalized step length was 1.00 ± 0.43 and increased to 1.12 ± 0.45 with their SMOs on. Normalized lead step length was statistically significant in the group condition ($F_G(1, 21) = 11.816$, $p < 0.001$) and presented with a significant group*condition interaction in each condition, where the SMO group had longer crossover steps than the non-SMO group when barefoot ($F_{GC}(1, 21) = 7.172$, $p = 0.008$) and in the footwear condition ($F_{GC}(1, 21) = 4.791$, $p = 0.03$). The condition effect ($F_C(1, 21) = 3.103$, $p = 0.08$) and height effect ($F_C(1, 21) = 2.888$, $p = 0.091$) each trended towards significance. A trend towards significance was also observed in the group*condition interaction, where the non-SMO group increased their lead step length with their shoes on versus barefoot alone ($F_{GC}(1,21) = 3.048$, $p = 0.053$).

Compared to the lead limb, the trailing limb presented with longer normalized step lengths. There was a similar trend in each group, where normalized step lengths increased when footwear was on. At 10% obstacle height, the non-SMO group's normalized step length was 1.28 ± 0.21 when barefoot and increased to 1.32 ± 0.20 with their shoes on. Similarly, the SMO group's normalized step length at barefoot was 1.28 ± 0.33, with an increase to 1.43 ± 0.37 when they wore their SMOs. At 30% obstacle height, the non-SMO group's normalized step length was 1.23 ± 0.27 when barefoot and increased to 1.37 ± 0.26 when they wore their shoes. Again, the

SMO group presented with a similar trend, with their normalized step length being 1.27 ± 0.34 when barefoot, increasing to 1.54 ± 0.41 with their SMOs on. Normalized trail leg step length during obstacle crossing was statistically significant in the condition effect ($F_C(1, 21) = 13.17$, $p < 0.001$) and a trend towards significance in the group effect ($F_G(1, 21) = 3.616$, $p = 0.059$). There were significant group*condition interactions where the SMO group had longer trail leg crossover steps than the non-SMO group during the footwear condition ($F_{GC}(1, 21) = 5.4$, $p = 0.021$). and longer crossover steps when the SMO group wore their SMOs versus barefoot ($F_{GC}(1, 21) = 9.829$, $p = 0.002$). In the group*condition interaction, there was a trend towards significance in the non-SMO group, who presented with longer trail leg crossover steps when they wore shoes versus barefoot ($F_{GC}(1, 21) = 3.472$, $p = 0.064$).



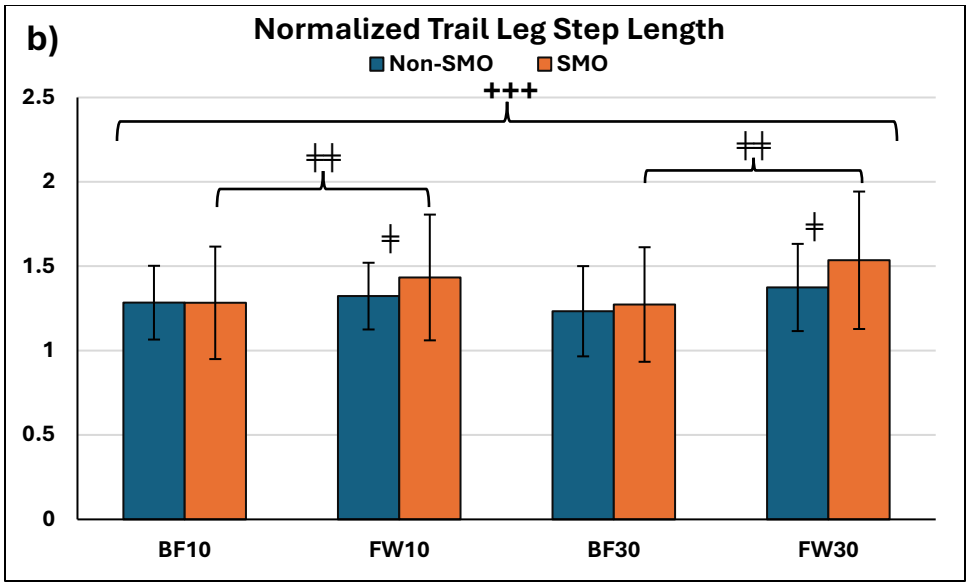


*Figure 3-7: Lead leg (a) and trail leg (b) step length (%). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$..*

Step Width

Following the lead leg crossover with the obstacle height at 10% of the subject's leg length, the non-SMO group's step width was 10.24 ± 5.15 cm when barefoot and decreased to 9.84 ± 3.71 cm with their shoes on (Fig. 7). The SMO group had a step width of 9.79 ± 6.86 cm and increased their step width to 12.41 ± 6.74 cm. When the obstacle height increased to 30% of the subject's leg length, the non-SMO group's step width following the lead leg crossover was 11.08 ± 5.48 cm when barefoot, with a similar step width of 11.03 ± 4.77 cm with their shoes on. The SMO group's step width at 30% obstacle height was 12.54 ± 8.11 cm when barefoot and increased to 15.34 ± 5.99 cm with their SMOs on. Statistical significance was found in the group effect ($F_G(1, 21) = 5.93$, $p = 0.016$), height effect ($F_H(1, 21) = 5.685$, $p = 0.018$), and had a significant group*condition interaction ($F_{GC}(1, 21) = 7.393$, $p = 0.007$), where the SMO group

had a wider step width than the non-SMO group during the footwear condition. The SMO group also had significant interaction between barefoot and footwear condition, where their step width was wider with SMOs on versus barefoot ($F_{GC}(1, 21) = 4.333$, $p = 0.039$).

Step width following trail leg crossover at 10% leg length obstacle height for the non-SMO group was 14.53 ± 5.48 cm when barefoot and increased to 16.91 ± 7.16 cm when their shoes were on. The SMO group followed a similar trend, where their step width following the trail leg crossover at 10% leg length obstacle height was 12.60 ± 7.05 cm when barefoot and increased to 17.42 ± 7.87 cm with their SMOs on. When the height increased to 30% of the subject's leg length, the non-SMO group had a step width of 16.13 ± 6.38 cm when barefoot and decreased to 13.81 ± 8.17 cm with their shoes on. Conversely, the SMO group's step width following trail limb crossover was 18.47 ± 6.19 cm and increased to 21.28 ± 10.16 cm with their SMOs on. Statistically significant group effect ($F_G(1, 21) = 5.93$, $p = 0.042$), height effect ($F_H(1, 21) = 4.006$, $p = 0.047$), and a significant group*condition interactions where the SMO group had wider step widths compared to the non-SMO group following trail limb crossover during the footwear condition ($F_{GC}(1, 21) = 7.393$, $p = 0.007$) and the SMO group had wider step widths with their footwear donned versus barefoot ($F_{GC}(1, 21) = 5.325$, $p = 0.022$).

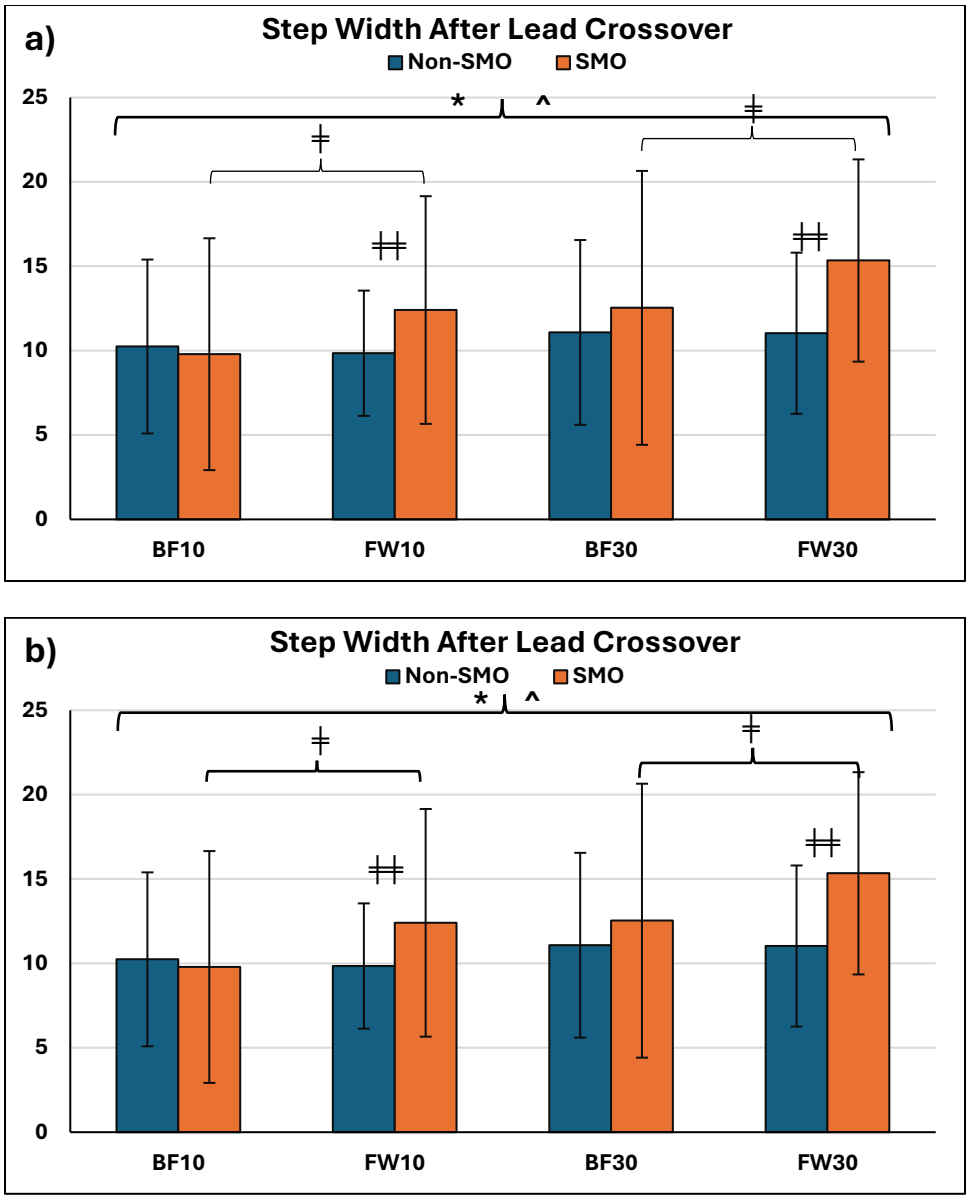


*Figure 3-8: Lead leg (a) and trail leg (b) step width (cm). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

Crossing Velocity

Both groups demonstrated increases in their crossing velocity during the footwear condition (Fig. 8). When crossing the obstacle at 10% of the subject's leg length, the non-SMO groups

normalized velocity was 0.27 ± 0.19 when barefoot and increased to 0.37 ± 0.18. Similarly, during barefoot crossing at 10% of the subject's leg length, the SMO group's velocity was 0.23 ± 0.23 and increased to 0.29 ± 0.28 %. When the height increased to 30% of the subject's leg length, the non-SMO group had a crossing velocity of 0.21 ± 0.16 when barefoot and increased to 0.31 ± 0.24 when their shoes were on. At the same height, the SMO group crossed at a speed of 0.25 ± 0.28 when barefoot. With their SMOs on, the SMO group increased their crossing velocity to 0.37 ± 0.29 %. Normalized crossing velocity was statistically significant for condition effect ($F_{GC}(1, 21) = 8.991$, $p = 0.003$), where crossing velocity was faster in the footwear condition, and for the group*condition interaction, where the non-SMO group had a faster crossing velocity with their shoes on versus barefoot ($F_{GC}(1, 21) = 7.427$, $p = 0.007$). Similarly, there was a trend towards significance for the group*condition interaction where the SMO group also had a faster crossing velocity with their SMOs on versus barefoot ($F_{GC}(1, 21) = 2.95$, $p = 0.087$),

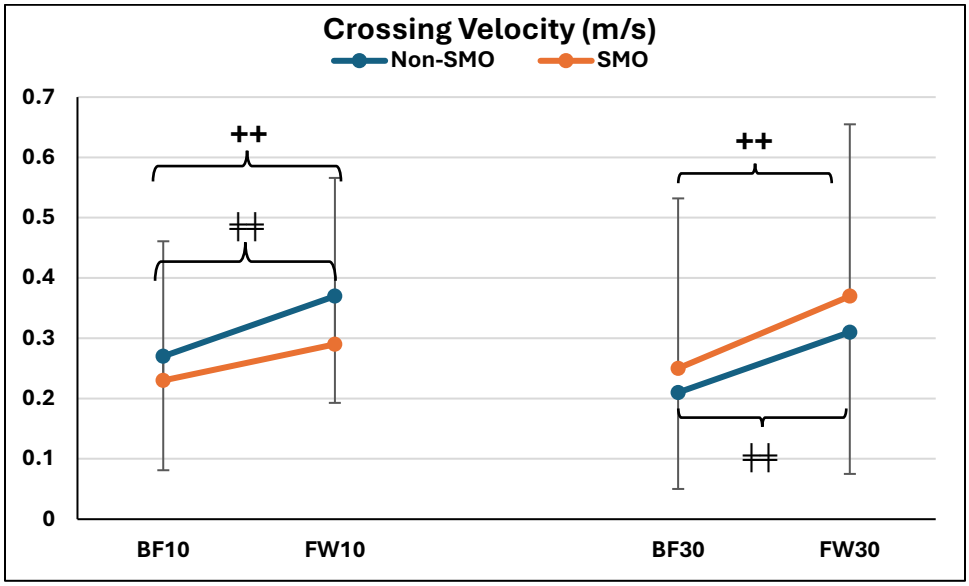


*Figure 3-9: Lead leg and trail leg crossing velocity (m/s). SMO = supramalleolar orthotic group, non-SMO = shoe only group, BF10 = barefoot at 10% height, FW10 = footwear at 10% height, BF30 = barefoot at 30% height, FW30 = footwear at 30% height. Group effect: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, Condition effect: + $p < 0.05$, ++ $p < 0.01$, +++ $p < 0.001$, Height effect: ^ $p < 0.05$, ^^ $p < 0.001$, ^^^ $p < 0.001$Group*Condition interaction: ╪ $p < 0.05$, ╪╪ $p < 0.001$, ╪╪╪ $p < 0.001$.*

Joint Kinematics

Both groups had similar increases in hip and knee flexion when the lead and trail limb were directly over the obstacle as they donned their respective footwear and when the obstacle heights increased. However, there was an inverse pattern in the hip abduction and ankle dorsiflexion angles during obstacle crossing. When more hip abduction was used to cross the obstacle, such as when the height increased and footwear was donned, then less ankle dorsiflexion was used to clear the obstacle. Whereas when less hip abduction was used to cross the obstacle, more ankle dorsiflexion was used to clear the obstacle.

The overall multivariate ANOVA model for the combined set of kinematic variables resulted in significant effects for condition ($F_C(1,21) = 4.69$, $p < 0.001$, $\eta^2 = 0.276$), group ($F_G(1,21) = 5.531$, $p < 0.001$, $\eta^2 = 0.311$), obstacle height ($F_H(1,21) = 7.592$, $p < 0.001$, $\eta^2 = 0.383$), and group*condition ($F_{G*F}(1,21) = 2.375$, $p = 0.003$, $\eta^2 = 0.162$). Group*height, condition*height, and group*condition*height interactions were not statistically significant. Condition explained 27.6% of the variance in peak joint kinematics during obstacle crossing, suggesting that footwear condition of each group meaningfully alters joint positions during obstacle crossing. The group factor reveals a large effect size, where 31.1% of the variance in the combined set of kinematic variables are explained by whether the child uses or does not use SMOs, indicating that the differences in SMO use versus shoes alone strongly influenced peak joint kinematics during obstacle crossing. As with the spatiotemporal model, obstacle height had the largest influence in

affecting joint kinematics during obstacle crossing, explaining 38.3% of the variance. As expected, higher obstacles naturally induce greater joint excursions.

The group*condition interaction effect was also large, with 16.2% of the variance explained, indicating that each group responded differently to barefoot vs footwear conditions compared to non-SMO users, influencing their peak joint kinematics when crossing the obstacle. The interaction is clinically meaningful, suggesting group-specific benefits or compensatory strategies between both groups, within their respective footwear conditions. The multivariate ANOVA was not statistically significant for condition*height, group*height, or condition*group*height interactions and had small to moderate effect sizes.

Table 3-4: Mean and standard deviation (SD) lead limb joint angles when the lead limb is over the obstacle.

Obstacle Crossing Lead Limb Joint Kinematics									
	Condition	BF10		FW10		BF30		FW30	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sagittal Hip	Non-SMO	46.72	16.989	48.56	12.202	62.54	15.082	63.38	15.097
	SMO	40.85	9.843	49.61	13.088	53.18	13.048	62.2	11.941
Frontal Hip	Non-SMO	11.38	19.897	10.87	17.688	33.66	32.91	30.52	34.357
	SMO	3.19	9.689	15.4	22.117	8.91	13.946	20.11	20.562
Sagittal Knee	Non-SMO	79.86	22.67	91.32	17.288	92.07	16.359	102.35	16.213
	SMO	84.77	16.126	90.44	19.713	91.83	24.454	102.42	14.042
Sagittal Ankle	Non-SMO	12.48	11.619	16.15	10.561	11.39	15.042	14.76	13.813
	SMO	16.58	10.173	14.02	10.31	19.53	6.151	16.09	9.655

Table3-5: Mean and standard deviation (SD) trail limb joint angles when the trail limb is over the obstacle.

Obstacle Crossing Trail Limb Joint Kinematics									
	Condition	BF10		FW10		BF30		FW30	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sagittal Hip	Non-SMO	8.17	10.347	4.77	14.211	12.49	14.663	18.85	28.993
	SMO	1.63	9.391	6.9	11.74	5.93	8.941	10.98	14.085
Frontal Hip	Non-SMO	17.82	15.177	14.92	18.923	27.99	18.646	27.41	17.766
	SMO	4.97	8.999	9.65	12.708	14.23	6.849	24.25	14.572
Sagittal Knee	Non-SMO	70.23	22.099	70.2	23.776	82.62	26.658	91.17	25.039
	SMO	72.88	18.17	71.58	21.13	84.78	32.394	99.75	21.307
Sagittal Ankle	Non-SMO	-17.95	20.924	-13.96	25.939	-17.99	25.933	-21.5	22.299
	SMO	-21.44	12.954	-15.64	15.344	-23.87	17.817	-19.33	11.378

Hip Joint Kinematics

Sagittal Plane Hip Joint Angles

As expected, each group presented with increasing lead limb peak hip flexion as the obstacle height increased. At 10% obstacle height, the non-SMO group's lead leg hip flexion when the toe marker was above the obstacle was 46.72 ± 16.99° when crossing barefoot. The non-SMO group increased their hip flexion at this height with their shoes on, obtaining a hip flexion of 48.56 ± 12.20°. At the 10% obstacle height, the SMO group presented with a substantial increase between conditions. When crossing the obstacle while barefoot, the SMO group's lead leg hip flexion was 40.85 ± 9.84°., which then increased to 49.61 ± 13.10° when crossing attempts were performed with their SMOs. At the 30% obstacle height, the non-SMO had a lead leg peak hip flexion of 62.54 ± 15.08°, which was similar when they wore their shoes to cross the obstacle,

with hip flexion at 63.38 ± 15.10°. The SMO group had a slight decrease in lead leg hip flexion to cross the obstacle at 30% obstacle height. When barefoot, the SMO group required 53.18 ± 13.05° of lead leg peak hip flexion to cross the obstacle at 30% obstacle height. The lead leg peak hip flexion when the limb was over the bar increased to 62.2 ± 11.94° when they wore their SMOs. The statistical analysis revealed that there was a condition effect ($F_C(1,21) = 6.566$, $p = 0.011$) and an obstacle height effect ($F_H(1,21) = 48.418$, $p < 0.001$). A statistically significant group*condition interaction was observed, where lead leg peak hip flexion increased in the footwear condition compared to obstacle crossing barefoot ($F_{GC}(1,21) = 7.637$, $p = 0.006$).

Trail limb peak hip flexion at 10% leg length obstacle height in the non-SMO group was 8.17 ± 10.35° when barefoot and decreased to 4.77 ± 14.21° when crossing with their shoes on. Conversely, while the SMO group peak hip flexion angle was 1.63 ± 9.39° when barefoot, this value increased to 6.9 ± 11.74° when crossing the 10% obstacle height with their SMOs on. At 30% obstacle height, both groups presented with an upward trend in the trail limb peak hip flexion angle when moving from barefoot to footwear conditions. The non-SMO group generated 12.49 ± 14.66° of hip flexion to cross the higher obstacle when barefoot and required more peak hip flexion, with a value of 18.85 ± 28.99° when crossing the obstacle with their shoes. At 10% obstacle height, the SMO group mean peak hip flexion values was 5.93 ± 8.64° when barefoot and increased to 10.98 ± 14.09°. The statistical analysis revealed a significant group effect ($F_G(1,21) = 4.076$, $p = 0.045$) and a significant height effect ($F_H(1,21) = 8.229$, $p = 0.005$). There was a significant group*condition interaction between the groups during the barefoot condition, with the SMO group generating less trail limb peak hip flexion during barefoot obstacle crossing ($F_C(1,21) = 4.032$, $p = 0.046$).

Frontal Plane Hip Joint Angles

In lead frontal plane hip joint angles, at 10% obstacle height, the non-SMO group required 11.38 ± 19.90° of hip abduction when crossing barefoot and was 10.87 ± 17.69° when crossing with shoes on. The SMO group required 3.19 ± 9.69° of hip abduction to cross the obstacle when barefoot. The hip abduction angle increased to 15.4 ± 22.12° with their SMOs on, in order to cross the obstacle. When the obstacle height increased to 30% of the individual's leg length, the non-SMO group produced 33.66 ± 32.91° of hip abduction to cross the obstacle while barefoot. The value slightly decreased to 30.52 ± 34.36° of hip abduction needed to cross the obstacle with shoes on. At the 30% obstacle height, the SMO group generated 8.91 ± 13.95° of hip abduction to cross over the obstacle while barefoot. Their hip abduction value while crossing the obstacle increased to 20.11 ± 20.56° to cross the obstacle with their SMOs on. Statistical analysis of the frontal plane lead leg hip joint angles revealed a group effect ($F_G(1,21) = 7.973$, $p = 0.005$), a height effect ($F_H(1,21) = 14.508$, $p < 0.001$). Group*condition interactions were significant in the SMO group between conditions, generating more hip abduction with during the footwear condition when crossing the obstacles of either height ($F_{GC}(1,21) = 7.637$, $p = 0.006$).

In trail leg frontal-plane hip joint angles, at 10% obstacle height, the non-SMO group required 17.82 ± 15.18° of hip abduction when crossing barefoot, which decreased to 14.92 ± 18.92° when crossing with shoes on. Conversely, the SMO group required 4.97 ± 9.00° of hip abduction to cross the obstacle barefoot, which increased to 9.65 ± 12.71° when wearing shoes with SMOs. When the obstacle height increased to 30% of the individual's leg length, the non-SMO group produced 27.99 ± 18.65° of hip abduction to cross the obstacle barefoot, with similar values at ° 27.41 ± 17.77° when crossing in shoes. Similarly, at the 30% obstacle height, the SMO group generated 14.23 ± 6.85 of hip abduction when barefoot, while hip abduction

increased to 24.25 ± 14.57° when crossing the obstacle with shoes and SMOs on. Statistical analysis for the trail limb frontal plane hip joint angles revealed significant group effect ($F_G(1,21) = 15.48$, $p < 0.001$) and a height effect ($F_H(1,21) = 27.294$, $p < 0.001$). There was a group*condition interaction in the SMO group, which generated more hip abduction during the footwear condition when crossing the obstacles of either height ($F_{GC}(1,21) = 4.198$, $p = 0.042$).

Knee Joint Kinematics

As with the hip angles, the lead and trail sagittal knee joint angles were collected at the point in which the toe marker was directly over the obstacle. For the lead leg knee joint, when the obstacle was set at 10% obstacle height, the non-SMO group generated 79.86 ± 22.67° of knee flexion when crossing the obstacle barefoot. With shoes on, the non-SMO group increased their peak knee flexion to 91.32 ± 17.29° at the same obstacle height. While barefoot crossing at the 10% obstacle height, the SMO group generated 84.77 ± 16.13° of peak knee flexion, slightly increased to 90.44 ± 19.71° when crossing the obstacle with their SMOs on. When the obstacle was raised to 30% height of the individual's leg length, the non-SMO group lead leg peak knee flexion was 92.07 ± 16.36° when crossing barefoot and increased to 102.3 ± 16.21° crossing with their shoes on. At the same height, the SMO group's lead leg knee flexion angle was similar across conditions, with values at 91.83 ± 24.54° when barefoot and 102.42 ± 14.04° with their SMOs on. Statistical analysis for the lead leg knee joint angles revealed a condition effect ($F_C(1,21) = 12.748$, $p < 0.001$) and a height effect ($F_H(1,21) = 15.771$, $p < 0.001$). A significant group*condition interaction was observed in the non-SMO group, which generated a higher knee flexion angle with shoes on versus barefoot ($F_{GC}(1,21) = 11.887$, $p < 0.001$). There was a trend towards significance in the group*condition interaction for the SMO group, who also presented with higher knee flexion angle values with their SMOs on ($F_{GC}(1,21) = 3.595$, $p = 0.059$).

For the trail leg knee joint, when the obstacle was set at 10% obstacle height, the non-SMO group generated 73.09 ± 22.10° of peak knee flexion when crossing the obstacle barefoot, with values remaining similar at 70.20 ± 23.78° when crossing in shoes. The SMO group showed comparable knee flexion angles, producing 72.88 ± 18.17° of knee flexion when barefoot and 71.58 ± 21.13° when crossing with SMOs on. When the obstacle was raised to 30% of the individual's leg length, the non-SMO group increased their trail knee flexion to 82.62 ± 26.66° when crossing barefoot, which further increased to 91.17 ± 25.04° when crossing with shoes on. At the same obstacle height, the SMO group produced 84.78 ± 32.39° of trail limb peak knee flexion when crossing barefoot and increased to 99.75 ± 21.31° when crossing with SMOs on. Statistical analysis revealed a height effect for the trail knee joint angle, in which the higher obstacle generated a higher knee joint angle ($F_{GC}(1,21) = 28.5$, $p < 0.001$).

Ankle Joint Kinematics

For the lead limb ankle joint when the limb is over the bar, at 10% obstacle height, the non-SMO group produced 12.48 ± 11.62° of dorsiflexion when crossing barefoot, increasing to 16.15 ± 10.56° when crossing with shoes on. The SMO group generated greater dorsiflexion values than the non-SMO group when barefoot at 16.58 ± 10.17° and decreased to 14.02 ± 10.31° with SMOs on. When the obstacle was raised to 30% of the individual's leg length, the non-SMO group produced 11.39 ± 15.04° of dorsiflexion when barefoot, increasing to 14.76 ± 13.81° with shoes on. Conversely, the SMO group produced 19.53 ± 6.15° of dorsiflexion while barefoot at the higher obstacle height, which decreased to 16.09 ± 9.66° when crossing with SMOs on. The statistical analysis revealed no significant effects for condition, group, or height factors. The lead limb ankle joint revealed a significant group*condition interaction during the barefoot condition, where the SMO group produced more ankle dorsiflexion ($F_{GC}(1,21) = 6.893$, $p = 0.009$). There

was a trend towards significance in the group*condition interaction for the non-SMO group, who produced more ankle dorsiflexion with shoes on versus barefoot ($F_{GC}(1,21) = 3.17$, $p = 0.076$).

For trail limb ankle joint values when the limb is over the bar, at 10% obstacle height, the non-SMO group produced -17.95 ± 20.92° of plantarflexion when crossing barefoot and decreased to -13.96 ± 25.94° when crossing with shoes on. The SMO group produced more plantarflexion overall at this height, generating -21.44 ± 12.95° of plantarflexion when barefoot and decreased to -15.64 ± 15.34° with shoes and SMOs on. When the obstacle was raised to 30% obstacle height, the non-SMO group obtained -17.99 ± 25.93° of plantarflexion when crossing barefoot, increasing to -21.50 ± 22.30° with shoes on. Similarly, the SMO group produced -23.87 ± 17.82° of plantarflexion while barefoot at the higher obstacle height, which decreased to -19.33 ± 11.38° when crossing with shoes and SMOs on. As with the lead limb ankle joint, the trail limb ankle joint revealed no significant effects for condition, group, or height factors.

DISCUSSION

In this study, we assessed the obstacle crossing strategies and biomechanical parameters in young children with DS who wear SMOs versus those who use only shoes for daily walking. The subjects crossed over two obstacle heights, 10% and 30% height relative to each individual's leg length, both barefoot and with their respective footwear, which was shoes + SMOs for the SMO group and shoes only for the non-SMO group. Overall, we observed favorable changes in obstacle crossing strategies, spatiotemporal parameters, and kinematic parameters when the children in each group used their respective footwear versus obstacle crossing while barefoot. The use of footwear appeared to provide the stability needed to achieve favorable outcomes in each group, which was possibly due to the differences in joint laxity scores between the groups. The SMO group had significantly higher joint laxity scores than the non-SMO group, thus may

have benefited more from the added medial lateral stability that SMOs provide at the ankle [2, 4]. In this discussion, I will address the findings from obstacle crossing strategies, spatiotemporal parameters, and kinematic parameters.

Obstacle Crossing Strategies

I hypothesized that the SMO group would increase the frequency of stepping over the obstacle as a strategy, while the non-SMO group would not show improvement. We observed that the proportion of successful crossing attempts was less in the SMO group than the non-SMO group when they attempted to cross the obstacle barefoot across all heights. The proportion of successful attempts increased in the SMO group when they were provided with their SMOs. The non-SMO group had a similar proportion of successful crossing attempts whether they attempted barefoot or with shoes. Additionally, secondary strategies, such as bear crawling, walking around the obstacle, or refusing to cross, were used less frequently when they had their respective footwear on.

When assessing obstacle crossing strategies in new walkers with DS versus typically developing (TD) children, Mulvey, et al. (2011) discussed that DS toddlers perceive affordances accurately and manage risk by choosing safer strategies rather than risking falling upright. They highlighted that motor planning differences reflect risk management, rather than perceptual deficits [10]. In our study, subjects in the SMO group used secondary crossing strategies at least 34% of the time while the non-SMO group used secondary crossing strategies around 24% of the time. While our subject's average walking experience was around 23 months of age, the SMO group had higher joint laxity scores, which may have contributed to having a higher percentage of secondary strategies than the non-SMO group. The SMO group may have perceived more instability due to the higher joint laxity scores, thus choosing the secondary strategy more

frequently than the non-SMO group. Additionally, despite the increased proportion of successful obstacle crossing, they experienced similar unsuccessful crossing attempts with the SMOs on versus barefoot, while the non-SMO group had a smaller proportion of unsuccessful crossing attempts both barefoot and with their shoes on. In a study by Chen et al. (2016), when observing obstacle crossing in TD children and children with DS, the DS group had more unsuccessful trials than the TD group. Children with DS have more difficulty crossing the obstacles than TD children, due to hypotonia, instability, and delayed motor development. The lower joint laxity scores in the non-SMO group may provide better motor development, thus having less gait impairments than the SMO group, who had lower joint laxity scores. These findings may explain the differences in obstacle strategy proportions between the groups. Additionally, the perception of stability likely varied between the two groups, thus influencing the choice of more conservative strategies, as well as their improvements when crossing the obstacle with their respective footwear [6, 10, 11].

Spatiotemporal Variables

We assessed spatiotemporal variables during the preparatory phase and the crossing phase. As described by Chen et al. (2016), during obstacle crossing of 10%, 20%, and 30% of the participants leg length, children with DS present with slower speeds, larger step widths and greater toe clearance compared to their TD peers. The author describes that while slower speeds and wider step widths were expected, the longer step lengths may be attributed to visual-perceptual deficits, impairing the interpretation of the obstacle in the environment, altering the preparatory timing and the motor pattern of obstacle crossing by overcompensating the step [6].

Preparatory Phase

We measured the preparatory time, which was the amount of time spent between the heel strike of the step prior to crossing obstacle, to the toe off for the obstacle crossing. We observed that the SMO group generally took longer to cross over the obstacle with the lead limb compared to the non-SMO group during each condition, and footwear vs barefoot was not an influence on the timing. There were no differences in the trail limb preparatory time, possibly due to the visual interpretation of the obstacle and the risk management that had occurred during the lead limb preparatory time [6, 10]. The non-SMO group may have presented with better visual-motor integration and motor pattern selection, requiring less time to initiate the crossover step than the SMO group.

The distance between the lead leg and the obstacle was longer in the SMO group, whereas the trail limb was similar in distance between the two groups and positioned closer to the obstacle than the lead limb. This presents as a more staggered position, as when walking up to the obstacle in a step through pattern. It's possible that the differences in distance from the obstacle was a result of the change in the motor pattern as a result of visual interpretation of the obstacle as the child prepares for the crossover.

Obstacle Crossing

As reported in other studies, children with DS display with reduced crossing velocities as a result of a compensatory mechanism to improve stability than efficiency [6, 10]. It was observed that both groups demonstrated increased crossing velocities with their shoes on, possibly due to the improvement in stability that their footwear provides, thus reducing compensatory mechanism in gait.

Toe clearance when crossing the obstacle with the lead and trailing limb was higher in the SMO group, especially when crossing the obstacle with their SMOs on, regardless of the height. Virji-Babul & Brown (2004) assessed obstacle crossing in DS and TD children of 4-7 years of age. The participants crossed obstacles at 1% and 15% of their body height. At the lower height, the DS children had lower toe clearances than the TD children, but at the higher height, the DS children had a higher toe clearance than TD children. The authors concluded that lower toe clearances increases the risk of tripping, suggesting deficits in visual perception, but the children with DS demonstrated robust toe elevation scaling as the height increased, thus the emergence of anticipatory responses [11]. Conversely, Chen et al. reported that the DS group had a higher obstacle clearance of the lead leg. The author discussed that this was a result of overcompensating the crossover step as a conservative strategy to reduce the risk of falls [6]. It's possible that with our study cohort, the SMO group adopted a more conservative strategy as a result of increased joint laxity, to reduce the risk of falls when stepping over the obstacle. In addition to the increased obstacle clearance height, the SMO group had longer normalized lead leg step lengths than the non-SMO group, further explaining their more conservative strategy to cross the obstacle. Both groups also increased their step height clearance and step length as they transitioned from barefoot to footwear conditions. Both groups may have had an increased demand in perceptual requirements when their shoes were on, due to the slight change in height and the weight of the shoe. We can speculate that the non-SMO group may have been affected by using footwear if they walk barefoot for the majority of the day.

Another characteristic of DS versus TD children during obstacle crossing was their wider step widths during the obstacle crossing [6, 10]. A higher level gait does not require a wider step width as a compensation for added stability. Both groups had similar step widths at low obstacles

when barefoot, but with footwear, the SMO group widened their step width. As the obstacle height increased, both groups exhibited wider step widths, but the SMO group increased their step width with their SMOs on. Though the added stability of the SMO provided more assurance to cross the obstacle safely, the SMO group may have adopted a more compensatory motor pattern during obstacle crossing than the non-SMO group.

Kinematics

Hip Joint

Overall, the non-SMO produced larger peak hip angle values in both the frontal and sagittal plane during barefoot walking in the low obstacle, and during both conditions in the higher obstacle, compared to the SMO group. Sagittal hip joint kinematics revealed an interesting trend for the lead limb. As expected, the peak hip joint flexion angle when the lead limb was over the obstacle increased as the obstacle height increased. However, while the non-SMO group produced similar values between conditions, the SMO group compensated by increasing their peak hip flexion when they wore their SMOs. In addition to producing more hip flexion from the barefoot to footwear conditions, the SMO group produced a similar response with frontal plane peak hip joint angles between conditions. The SMO group increased the amount of peak hip abduction to be able to clear the obstacle, while the non-SMO produced similar results between conditions. While the standard deviation values in the sagittal plane hip values were low, the frontal plane standard deviation values were high, indicating a large variability in the use of hip abduction to clear the obstacle between the groups. Additionally, both hip sagittal and frontal plane standard deviation values for the trail limb in each group, condition, and height were high, indicating a large variability of proximal joint use, reflecting the variability in motor patterns seen in early age.

Knee Joint

At the knee joint, both groups had similar trends of peak lead limb knee flexion values between barefoot and footwear conditions. When their respective footwear was donned, both groups generated more lead limb knee flexion when crossing the obstacle than when they crossed barefoot. At low obstacles, both groups had similar trail limb knee flexion angle values when crossing the obstacle, with no significant changes between barefoot and footwear conditions. When the obstacle height was raised, both groups increased their trail limb knee flexion angle at barefoot compared to the low obstacle angles. When footwear was introduced, both groups increased their trail limb knee flexion angles to clear the obstacle safely.

Ankle Joint

At the lead limb ankle joint, the non-SMO group increased dorsiflexion use when they wore their shoes compared to barefoot, thus using more distal motion to clear the obstacle. Conversely, the SMO group's ankle dorsiflexion did not alter between the conditions, possibly due to the restriction that the SMOs provide, limiting the use of the ankle joint during obstacle crossing. The trail limb was positioned in ankle plantarflexion in both groups during obstacle crossing, regardless of condition and height. The trail limb ankle angles did not produce significant results in either group, across conditions or heights.

Motor Adaptations

Both groups in this study utilized more proximal control to cross the obstacles. Despite the lower joint laxity scores, the SMO group used more sagittal hip plane of motion to cross the obstacle while barefoot, making the obstacle crossing strategy less efficient, but safer [6]. However, this pattern changed as they recruited more hip abduction to clear the obstacle with their shoes on. With the accompanying hypotonia and lower joint laxity scores, the SMO group

may have had a larger degree of muscle weakness. The extra weight of the shoe and SMO may have altered their crossing mechanics, despite the SMOs' ability to control medial-lateral motion at the ankle. The increased use of hip abduction may have also affected the step widths in the SMO group. Given that the SMOs provide support at the ankle in the frontal plane, it's possible that the added support restricted ankle sagittal plane motion, impairing push-off from the ankle joint to cross the obstacle and relying more on proximal joints to cross. Despite these kinematic changes, the SMO group presented with favorable changes when using their SMOs. Longer step lengths and faster crossing velocity are indicators of increased stability that the SMOs would provide [6, 10, 12].

Limitations

This study was not without limitations. One limitation was that we were unable to accurately collect kinetic data for each limb. Because these were young children with DS, they often had two feet on the force plate at once due to their shorter stature, which would impair the kinetic data we obtained. Additionally, we were unable to record muscle activity with the wireless EMGs in the lab. Because of their small stature, it would be difficult to place an EMG sensor over a specific muscle. Additionally, many of the young children with DS have difficulty tolerating the reflective markers. Extra sensors attached to the body may increase the difficulty of these subjects to participate in the data collection. Another limitation to this study is that we were not able to develop a crossover design, where the non-SMO group would use SMOs in addition to their shoes, and the SMO group would use shoes alone. SMOs are custom made orthotics therefore we were unable to provide this group with an SMO during their one-time visit. Conversely, the SMO group uses shoes larger than their foot size to accommodate for the added space from the SMO. Assessing the SMO group without their SMOs may impair their gait and

ability to cross the obstacle with footwear that is larger in size. Because the SMO group wears their SMO and shoes throughout the day, they may not be accustomed to the shoes only condition. This study involved young children with DS with an average age range of about 40 months of age. Younger children tend to have more movement variability as they continue to develop, which may also impair their visuo-motor perception.

Conclusion

The results of this study demonstrate that SMOs can provide support needed to improve successful crossing strategies, step length and crossing velocity. However, prescription of these orthotics may need to be individualized based on necessity, such as increased joint laxity, muscle hypotonia, increased risk of falls, and the degree of motor delay. To our knowledge, this study is the first of its kind to assess obstacle crossing in young children with Down syndrome who wear SMOs versus those who do not. The study may lay a foundation for longitudinal studies to assess the impact of SMOs on gait and obstacle crossing over time and provide further details on subject characteristics that may or may not benefit from SMOs.

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APPENDICES

Appendix A

Parental Permission Form

Georgia State University
Department of Kinesiology and Health
Parental Permission Form

Title: Gait Biomechanics with and without supramalleolar orthosis (ankle brace) in children with Down syndrome

Principal Investigator: Jianhua Wu, PhD Student Principal Investigator: Robert Zeid II, PT, DPT, MS

Introduction and Key Information

- Your child is invited to take part in a research study. It is up to you to decide if he/she will be able to take part in the study.
- The purpose of this study is to understand the differences in walking patterns in 2-6 years old children with Down syndrome who use the brace versus children with Down syndrome who do not use them.
- You and your child will come to our lab at Georgia State University for a one-time visit that will take up to 2 hours. We will measure your child's height and weight, and the range of motion of their knees and ankles.
- We will apply stickers on your child's legs. We will use high-speed cameras to record your child's walking. We will also record your child's ability to step over an obstacle.
- Participation in the study may cause fatigue. Stepping over obstacles may cause your child to trip and fall. However, the injury risk is low.
- This study is not designed to benefit your child. Overall, we hope to gain information about the effect of brace use on walking patterns in children with Down syndrome. The information may help clinicians better identify those who can benefit from using the brace.
- If you do not wish to take part in this study, the alternative is to not participate in this study.

Purpose

 We invited your child to take part in a research study. The purpose of this study is to understand the differences in walking patterns in 2-6 years old children with Down syndrome who use ankle braces versus those who do not use them. A total of forty children with Down syndrome will take part in this study.

Procedures

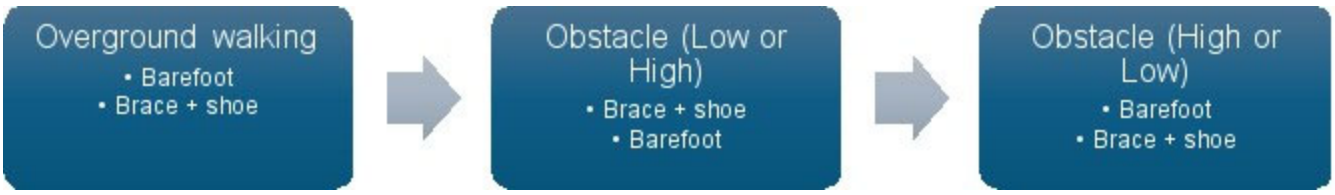
This study will consist of a one-time visit at Georgia State University. It will take about two hours of your time. Your child should use sneakers they usually use for daily activities. If your child has ankle

braces, your child should wear the shoes with them. We will receive informed consent from you. Then, we will provide you with a questionnaire regarding your child's demographics and ankle brace use. If your child uses the brace over 50% of the time of daily walking, then they will be in the brace group. If your child does not use the brace, or has never been given the brace, then they will be in the "non-brace" group. We will then measure your child's height, weight, and knee and ankle range of motion. We will take a picture of your child's feet, but not their face. We will then apply 16 stickers on your child's legs. We will also apply the stickers to the toe and heel regions of both shoes.

Your child will participate in three activities, beginning with walking overground along a 6-meter walkway at their usual walking speed. After that, they will step over an obstacle of a "low" height. They will also step over a "high" height. We will randomize whether they begin with the "low" or "high" height. The obstacle will consist of a foam-padded metal tube. The obstacle would drop off when contacted.

Your child will perform each activity barefoot and with their shoe or shoe with ankle brace. They will either begin the walking activity barefoot or with their shoe or shoe with ankle brace. The number of times we take off their shoes and put them back on will be reduced by beginning the next activity with the condition they finished the previous activity with. For example, if they completed the walking activity barefoot, we would begin the obstacle crossing activity barefoot. We will then switch back to using their shoes or shoes with ankle braces. We will record at least five attempts for each walking condition during each activity.

a)



b)

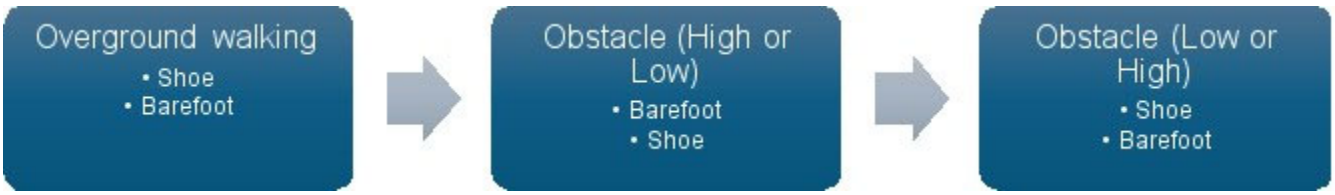


Figure 1: Examples of activity sequences your child may perform. a) An example of an activity sequence for a child in the "SMO" group. b) An example of an activity sequence for a child in the "non-SMO" group.

Future Research

We will remove information that may identify your child. We may use their data for future research. If we do this, we will not ask for any additional consent from you.

Risks

This study is not designed to benefit your child personally as this study is for research purposes. The activities in this study may cause muscular fatigue. However, we have been able to successfully record walking and stepping over obstacle trials in young children with Down syndrome from a previous study. These activities are also similar to your child's daily activities. When stepping over obstacles, there is a risk that your child may trip and fall from the attempt. However, previous studies that tested stepping over obstacles of different heights has been shown to be safe, in both typically developing children and children with disabilities. We will place soft mats along the walkway to protect your child in case they fall. Research assistants will be close by to catch your child if they fall. There will not be social and psychological risks associated with this study. If an injury occurs to the child, we will stop the test and look at the injury. If the injury is minor, we will use a first aid kit to address the injury. If the injury becomes life threatening, we will call 911 and seek emergency services.

Benefits

This study is not designed to benefit your child. Overall, we hope to gain information about the effect of ankle brace use or non-use has on walking patterns in children with Down syndrome. This knowledge will be important to understand the effects that shoes with ankle braces versus shoes alone have on children with Down syndrome. We will also understand the effects that long-term ankle brace use has on walking patterns when walking barefoot. This study may help clinicians understand the effects that ankle braces have on children with DS. This study may also help clinicians better identify those who can benefit from ankle brace use. It can also help clinicians develop rehabilitative strategies to identify and address walking deficits to possibly reduce or stop ankle brace use.

Alternatives

The alternative to taking part in this study is to not take part in this study.

Compensation

Your child will receive $50 for his/her participation at the end of the study. Your child will receive compensation, even if your child decides to leave the study early.

Voluntary Participation and Withdrawal

Your child does not have to be in this study. If you decide to participate in the study and change your mind later, you have the right to drop out at any time. Whatever you decide, your child will not lose any benefits to which he/she is otherwise entitled.

Confidentiality

We will keep your child's records private to the extent allowed by law. The following people and entities will have access to the information you provide:

- PI and research team
- GSU Institutional Review Board
- Office for Human Research Protection (OHRP)

We will use a subject number (such as SMDS01) rather than your child's name on study records. The information provided will be stored on a password-protected desktop computer in the lab. We will save your child's personal information in a locked file cabinet in the principal investigator's office. We will destroy the code sheet five years after the completion of this study. When we present or publish the results of this study, we will not use your child's name and other information that may identify your child. Your child will not be identified personally. Only the principal investigators will have access to it.

Contact Information

Contact Robert Zeid II at 505-715-1239 and rzeid1@gsu.edu or Jerry Wu at 404-413-8467 and jwu11@gsu.edu

- If you have questions about the study or your part in it
- If you have questions, concerns, or complaints about this study
- If you think your child has been harmed by the study

Contact the GSU Office of Human Research Protection at 404-413-3500 or irb@gsu.edu

- If you have questions about your rights as a research participant
- If you have questions, concerns, or complaints about the research

Consent

We will give you a copy of this permission form to keep. If you are willing to volunteer your child to participate in this research, please sign below.

_____

Printed Child's Name

_____	_____	_____
Printed Parent or Guardian's name	Signature	Date

_____	_____	_____
Printed Investigator's name	Signature	Date

APPENDIX B

Subject Demographics Sheet

DS SMO Study

Participant demographics

Participant ID _____ **Date of birth** _____

Age at onset of walking _____

Please circle the appropriate choice below:

Type of Down syndrome	Trisomy 21	Translocation	Mosaicism			
Race	Caucasian	African American	Asian	Native American	Other	
Ethnicity	Hispanic	Non-Hispanic				
Congenital heart defects	Yes	No				
Answer the questions below if your child uses a supramalleolar orthosis (SMO)						
SMO Brand						
At what milestone were the SMOs prescribed?	Before the child began pulling to stand	When the child began pulling to stand	When the child began to stand independently	When the child began to walk independently	Months after walking onset	
At what age were the SMOs prescribed?	6-11 months	12-17 months	18-23 months	2 years	3+ years	
How long has your child been using the current SMO?	< 3 months	3 – 6 months	6 – 12 months	1 year	2 years	3+ years

How often are the SMOs replaced?	Every 6 months		Every 1 year	Every 2 years	Every 3 years
Daily SMO Use (% of time during waking hours)	<25%	25-50%	50-75%	75-100%	

APPENDIX C

Lab Visit Measures Sheet

Gait in children with Down syndrome with and without SMO

Date: _____

Participant Name:_____ Gender: M/F Participant ID: SMDS____

Height:_____ Weight:_____

Anthropometric Measures (unit: cm)

	Right	Left
Leg Length		
Knee Width		
Ankle Width		
Floor to Ankle Barefoot		
Floor to Ankle Shoe On		
10% Leg Length		
30% Leg Length		

Range of Motion (unit: degrees)

	Right	Left
Elbow Hyperextension		
Knee Hyperextension		
Dorsiflexion		
Total		
Joint Laxity Classification: <60° = less lax and ≥60° = more lax		