Effects of changing Prosthetic Foot Stiffness on 3D Hip Angles in Toddlers with versus without Unilateral Transtibial Amputations

Honors Thesis

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Abstract

Background: Pediatric prosthetists and physical therapists have observed that use of prosthetic feet with different stiffnesses affects external hip rotation during walking in toddlers with unilateral transtibial amputations (TTAs). Though some previous research has determined the effects of prosthetic foot stiffness during walking in adults with TTAs, these results likely cannot be directly translated to toddlers with TTAs due to the differences in gait patterns between the age groups; toddlers demonstrate an immature gait that is characterized by wider steps, increased cadence, and slower self-selected walking speeds compared to adults.

Methods: 12 toddlers participated in this study (9 non-amputee, 3 with a TTA). Three custom passive prosthetic feet (recommended stiffness, less stiff, and more stiff) were made for each toddler with a TTA. Then, we collected and compared kinetic and kinematic data from toddlers with and without a TTA walking at 0.50 m/s. Toddlers with a TTA used different stiffness prosthetic feet. Peak hip joint angles and range of motion were determined in the sagittal, frontal, and transverse planes. We used a one-way ANOVA and Bonferroni Post Hoc analysis to determine differences between toddlers with and without a TTA and between prosthetic feet.

Results: The data suggest that use of a prosthetic foot more stiff than recommended most closely resembles the hip joint angles of non-amputees in the *transverse* plane throughout a stride. Use of the recommended stiffness prosthetic foot led to a trend of greater peak hip external rotation compared to the non-amputee toddlers ($p=0.32$). Toddlers with a TTA exhibit a trend of greater peak hip joint flexion ($p=0.32$) compared to non-amputee toddlers. However, there was no change in range of motion between groups or prosthetic foot stiffness. Additionally, symmetry in peak joint angles and range of motion between the affected leg (AL) and unaffected leg (UL) were not affected by prosthetic foot stiffness when comparing toddlers with a TTA to non-amputee toddlers.

Discussion: Our results suggest that prosthetic foot stiffness does not affect frontal or sagittal plane hip joint angles, but does affect transverse plane hip joint angles. Future research is needed to determine the ideal degree of hip external rotation to inform prosthetic foot design and minimize long-term functional deficits in toddlers with a TTA.

Introduction

Toddlers (2-5 years old) with unilateral transtibial amputations (TTAs) are recommended pediatric prosthetic feet based on their prosthetist's subjective opinion and manufacturer guidelines. However, prosthetic foot stiffness guidelines are arbitrarily based on body mass and the unaffected leg's foot size (length). The subjectivity behind prosthetic prescription may result in the restriction of normative biomechanics for toddlers with TTAs during walking and lead to injuries that could persist for life. To address this problem, it is essential to develop objective prosthetic foot stiffness (quotient of force and displacement or torque and angle) prescription guidelines that optimize biomechanics given the maturation of the unaffected foot, and match the growth patterns of toddlers without TTAs[1].

Adults with a TTA are recommended prosthetic feet in a similar manner as toddlers with a TTA. Adults with a TTA who use passive-elastic prosthetic feet exhibit atypical biomechanics during walking compared to non-amputee adults. Specifically, those with a TTA exhibit different spatio-temporal parameters that include shorter stride length, slower self-selected speed, and a wider base of support compared to adults without a TTA[2]. Additionally, they exhibit asymmetric sagittal, frontal, and transverse plane hip and knee joint angles between their affected leg (AL) and unaffected leg (UL) [2–4]. In general, the UL has a greater range of motion compared to the AL. However, adults with a TTA have greater hip external rotation in their AL compared to their UL[2].

The studies conducted in adults provide a basis for what may be observed in toddlers with a TTA, but cannot be directly translated. This is because non-amputee toddlers exhibit different biomechanical characteristics than non-amputee adults during walking[1,5–7]. Specifically, they have different spatio-temporal parameters (e.g. increased cadence, slower absolute speed, and wider steps relative to pelvic width) and exhibit higher peak ground reaction forces (GRFs) in all planes when normalized to body weight[8–11]. Additionally, toddlers do not utilize the same biomechanics as adults during single limb support, such as the inverted pendulum model, that are present in mature walking[11,12]. These biomechanical differences lead to decreased mechanical energy exchange during single support, slower preferred walking speeds, and larger changes in vertical center of mass (COM) position normalized to height in toddlers compared to adults. Because of these differences, research from adults with a TTA may not be applicable to inform prosthetic prescription in toddlers with a TTA.

To our knowledge, there is no research on how pediatric prosthetic foot stiffness affects the biomechanics of toddlers with a TTA during walking. A previous study measured the axial (quotient of force and displacement) and torsional (quotient of torque and angle) stiffness of four commonly prescribed pediatric prosthetic feet[13]. They found little difference in axial stiffness across brands of the same size with the exception that the TRS (Boulder, CO) prosthetic foot was more stiff compared to other brands during mid-foot loading. However, there was a large variation in dorsiflexion torsional stiffness across brands. These findings suggest that there is no agreed upon standard for pediatric prosthetic foot stiffness across manufacturers. This likely leads to inconsistent prescription of prosthetic feet between toddlers with a TTA, which may lead to additional injury.

To help minimize injury and optimize prosthetic foot prescription, we aimed to quantify the biomechanics of toddlers with a TTA using prosthetic feet of different stiffnesses and compare these with the biomechanics of non-amputee toddlers. Based on clinical observations from pediatric physical therapists and prosthetists, use of a prosthetic foot that is too stiff results in greater hip external rotation in the AL compared to UL[14,15]. Thus, we hypothesized that use of a prosthetic foot that is less stiff than recommended would reduce peak hip external rotation of the AL in toddlers with a TTA and result in more normative biomechanics compared to non-amputee toddlers during walking. Further, we hypothesized that use of a prosthetic foot that is more stiff than recommended would increase asymmetry in range of motion and peak hip joint angles between the AL and UL and result in greater peak hip external rotation for toddlers with a TTA compared to non-amputee toddlers.

Methods

Subjects

The parents of 14 toddlers (3 with a TTA; 11 non-amputee) gave informed written consent prior to enrollment in the study. We collected anthropometric data from each toddler at the beginning of each session (Table 1). Two of the non-amputee children were excluded from data analysis due to the prevalence of cross-over steps on the dual-belt force-measuring treadmill. Only children between ages 2-5 were included. Participating toddlers had no neuromuscular impairment other than a unilateral TTA.

Table 1. Anthropometric data for three toddlers with an amputation and nine non-amputee toddlers.

Average (SD)	Amputee	Non-Amputee
Subjects (n)	3	9
Age (years)	3.1 (1.3)	4.3 (1.2)
Weight (kg)	14.3 (3.0)	17.3 (3.3)
Height (cm)	93.7 (9.9)	103.3 (9.3)
Leg length (cm)	42.0 (6.9)	46.6 (13.4)

Testing Procedure

At the beginning of the testing session, we gave each subject at least 2 minutes to acclimate to walking on the treadmill. We asked subjects to walk at 0.10 m/s and then increased treadmill speed by 0.10 m/s until the child or parent deemed the speed to be too fast for the child to walk comfortably. Parents were allowed to hold their child's hand if needed. Prior to experimental trials, we attached reflective markers with double sided tape and athletic tape strips. We used a modified Helen Hayes marker set. Markers were placed bilaterally on the pelvis and lower limbs. We placed markers at joint centers and clusters of at least four markers on each segment.

We collected kinematic data at 100 Hz and kinetic data at 1000 Hz using a motion capture system (Vicon, Centennial, CO) and dual-belt force-measuring treadmill (Bertec, Columbus, OH). We collected data for 20-sec while toddlers with a TTA walked with each prosthetic foot stiffness at each speed (ranging from 0.30 – 0.90 m/s) and while non-amputee toddlers walked at each speed. We analyzed hip joint angles in the sagittal, frontal, and transverse planes. We calculated and compared peak positive (flexion, adduction, internal rotation) and negative (extension, abduction, external rotation) angles for each plane during a stride. We also calculated range of motion as the maximum angle minus the minimum angle observed in each plane over a stride. We used a 5 N vertical ground reaction force (GRF) threshold to determine a stride.

TRS Little Feet (Boulder, CO) created three custom prosthetic feet of the same size (length, cm) with different stiffnesses for each toddler with a TTA. We then had each toddler with a TTA use these feet, which included prosthetic feet of the same size with recommended stiffness, more stiff than recommended, and less stiff than recommended. Stiffness was altered by changing the length of the carbon fiber keel (Fig. 1). The more stiff prosthetic foot used a keel typical for a prosthetic foot one size larger (+1 cm). The less stiff prosthetic foot used a truncated keel typical for a prosthetic foot one size smaller (-1 cm). A prosthetist ensured that each prosthetic foot was attached and aligned properly before data collection. At the recommendation of the prosthetist, we tested the prosthetic feet in the order: recommended, more stiff, and then less stiff[15].

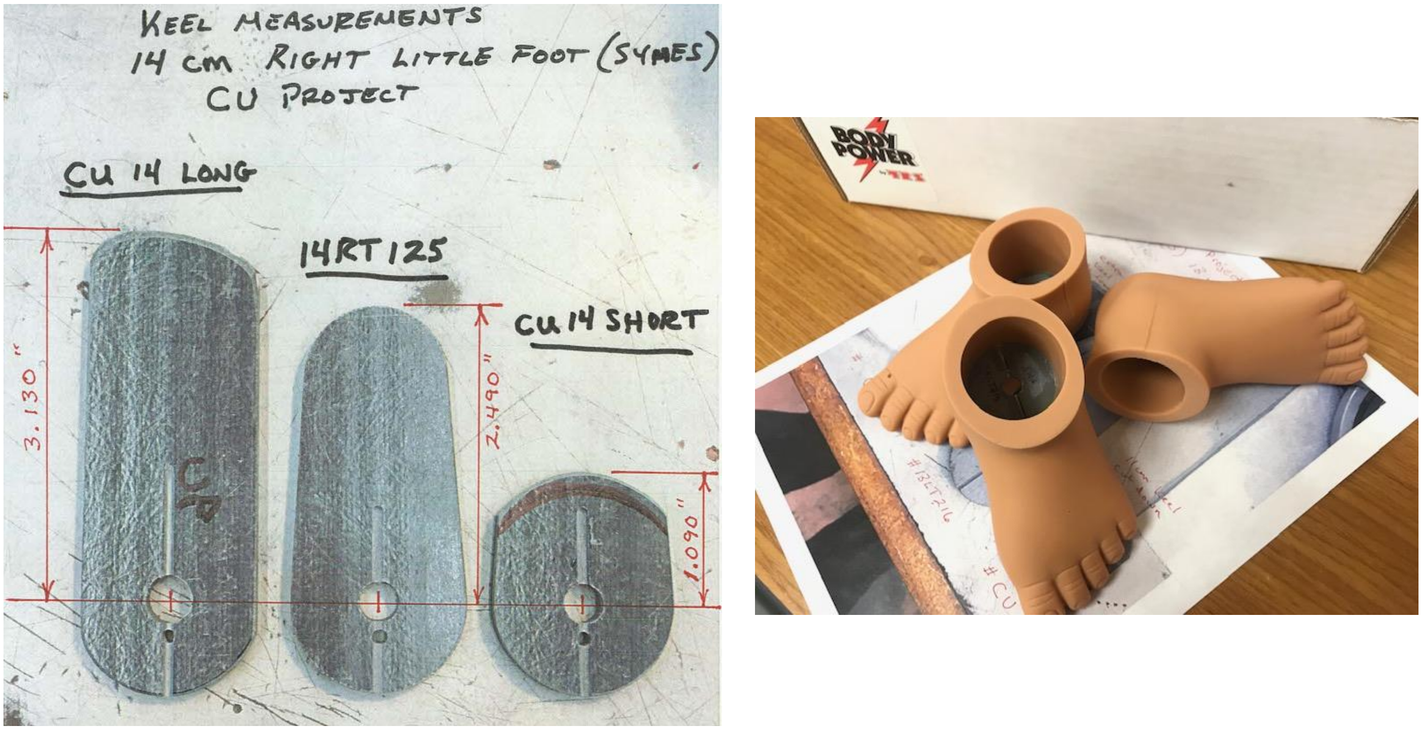

Figure 1. **Left** - Carbon Fiber keels that were used inside a 14 cm foot. “CU 14 LONG” represents the more stiff prosthetic foot with a longer keel. This specific keel is typical for a 15 cm prosthetic foot. “14RT125” is the standard keel for a 14 cm prosthetic foot and was not modified. “CU14SHORT” represents the less stiff prosthetic foot with the truncated keel from a 13 cm prosthetic foot. **Right** – Three left TRS little feet for subject with a Symes amputation. The carbon fiber keels are enclosed in a rubber cosmesis that mimics the appearance of a foot. Each toddler with a TTA used three feet with an identical cosmesis covering the modified keels.

We digitized kinematic data using motion analysis software (Vicon Nexus, Centennial, CO), imported these data to Visual 3D (C-Motion, Germantown, MD), and processed the data using a custom MATLAB (Mathworks, Natick, MA) script. We created a model in Visual 3D to determine hip angles in the sagittal, frontal, and transverse planes. These angles were normalized across a stride starting with heel-strike. Range of motion and peak joint angles were determined and compared for each leg and for each prosthetic foot stiffness condition.

Sagittal plane hip angle refers to the angle between the trunk and the thigh where 0˚ indicates that the thigh is directly beneath the trunk. Any motion that caused the thigh to be positioned anterior relative to the trunk was considered flexion and represented by a positive value. Any motion that caused the thigh to be positioned posterior relative to the trunk was considered extension and represented by a negative value (Fig. 2). Frontal plane hip angles refer to the angle between the trunk and the thigh where 0˚ indicates that the thigh is directly beneath the trunk. Any motion that caused the thigh to be positioned medial relative to the trunk was considered adduction and is represented by a positive value. Any motion that caused the thigh to be positioned laterally relative to the trunk was considered abduction and represented by a negative value (Fig. 2). The transverse plane refers to the angle between the sagittal plane of the pelvis and the sagittal plane of the thigh where 0˚ indicates that both planes are parallel. Any motion that caused the thigh sagittal plane to deviate inward was considered internal rotation and represented by a positive value. Any motion that caused the thigh sagittal plane to deviate outward was considered external rotation and represented by a negative value (Fig. 2).

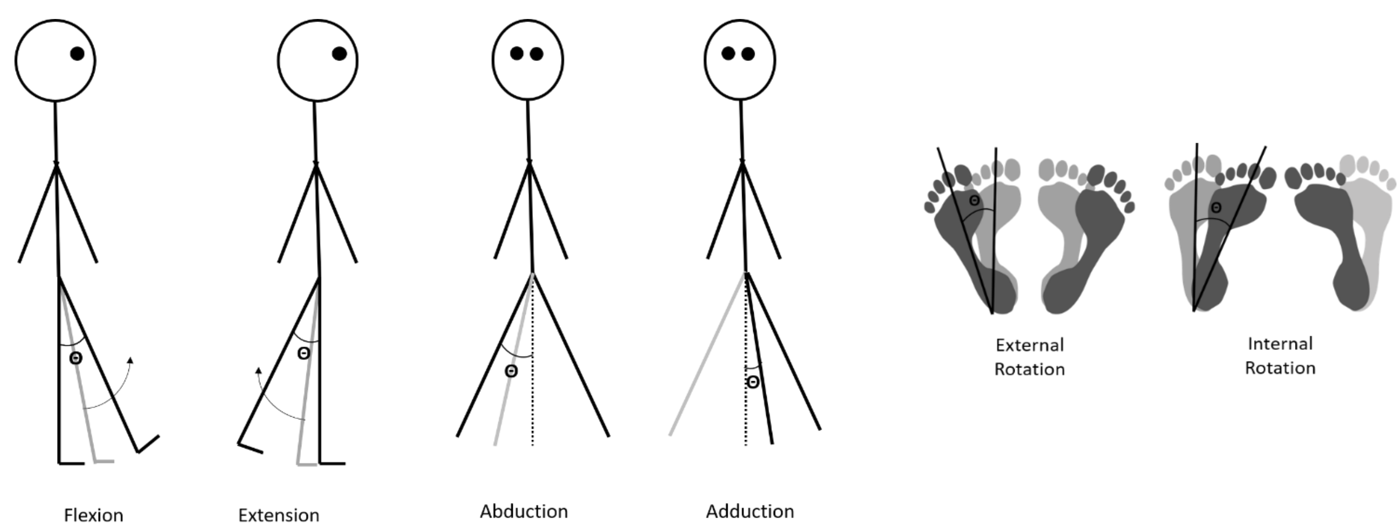

Figure 2. Depiction of the measured hip joint angles (Θ). Hip flexion is anterior and hip extension is posterior movement of the thigh relative to the trunk. Hip abduction is lateral and hip adduction is medial movement of the thigh relative to the midline of the trunk. External rotation is a lateral and internal rotation is a medial twist of the thigh relative to the pelvis.

We determined symmetry between legs using percentage difference, where perfect symmetry equals zero percent (Eq. 1). We calculated mean symmetry from the average of the absolute values of percentage differences. This allowed us to directly compare the difference between limbs of each subject and determine standard deviations within each condition.

Equation 1. $$Symmetry\ (\%) = \frac{Left - Right}{0.5(Left + Right)}\ x\ 100\ or = \frac{AL - UL}{0.5(AL + UL)}\ x\ 100$$

Statistical Analysis

R studio (Boston, MA) was used to determine statistical significance between conditions. Significance was set as a p-value less than 0.05. We used a one-way ANOVA to determine overall significance across all conditions. A Bonferroni Post Hoc test was used to further differentiate significance between non-amputee toddlers and toddlers with a TTA using different stiffness prosthetic feet. Additionally, we used a repeated measures ANOVA to determine overall significance across prosthetic foot stiffness. A Bonferroni post hoc test was used to differentiate significance between prosthetic foot stiffness. We compared maximum and minimum joint angles and ROM at the hip for the sagittal, frontal, and transverse planes between non-amputees, recommended stiffness, more stiff, and less stiff prosthetic feet. All data were compared at 0.50 m/s as this was the common speed recorded for all subjects.

Results

Range of Motion

There were no statistical differences in affected leg hip joint range of motion (ROM) in any plane for toddlers with a TTA due to using different prosthetic foot stiffness (p=1.0) or between toddlers with a TTA using a recommended stiffness prosthetic foot and non-amputee toddlers (sagittal: p=1.0, frontal p=1.0, transverse: p=1.0). Toddlers with a TTA using the recommended prosthetic foot stiffness had 30.5˚ ROM in the sagittal plane, 8.6˚ ROM in the frontal plane, and 12.0˚ ROM in the transverse plane for their affected leg hip joint (Table 2).

Table 2. Mean (SD) hip joint range of motion (ROM) and peak values during walking for the affected leg of toddlers with a TTA using different prosthetic foot stiffness and non-amputee toddlers. There were no significant differences between conditions.

	Sagittal		
	ROM	**Peak Flexion**	**Peak Extension**
Non-amputee	29.2 (7.6)	18.0 (8.3)	-11.2 (7.2)
Less Stiff	34.4 (5.2)	33.1 (10.8)	-1.3 (13.8)
Recommended	30.5 (3.0)	30.0 (8.8)	-0.5 (10.5)
More Stiff	31.1 (7.4)	29.8 (6.4)	-1.3 (12.6)
	Frontal		
	ROM	**Peak Adduction**	**Peak Abduction**
Non-amputee	7.2 (1.7)	-1.4 (4.0)	-8.6 (4.4)
Less Stiff	7.8 (1.6)	-8.7 (11.4)	-16.5 (9.9)
Recommended	8.6 (2.3)	-9.7 (12.0)	-18.3 (9.9)
More Stiff	9.2 (4.2)	-8.0 (11.3)	-17.2 (8.5)
	Transverse		
	ROM	**Peak Internal Rotation**	**Peak External Rotation**
Non-amputee	8.0 (4.7)	-1.5 (7.4)	-9.5 (6.2)
Less Stiff	10.8 (3.4)	2.75 (13.1)	-8.06 (13.9)
Recommended	12.0 (5.2)	-8.3 (8.4)	-20.3 (3.6)
More Stiff	15.8 (0.7)	0.83 (7.0)	-15.0 (7.3)

Sagittal Plane

Toddlers with a TTA utilize a more flexed hip joint angle in the affected leg throughout a stride compared to non-amputee toddlers (Fig. 3). However, there were no statistical differences in peak sagittal plane hip joint angles between toddlers with a TTA and non-amputees or between different prosthetic foot stiffnesses. Though not significant, peak hip joint flexion trended 13.0˚ greater (less stiff: p=0.12, recommended: p=0.32, more stiff: p=0.35) in toddlers with a TTA compared to non-amputee toddlers. Similarly, peak extension trended 10.2˚ lower (less stiff: p=0.90, recommended: p=0.73, more stiff: p=0.90) in toddlers with a TTA for each prosthetic foot stiffness compared to non-amputee toddlers.

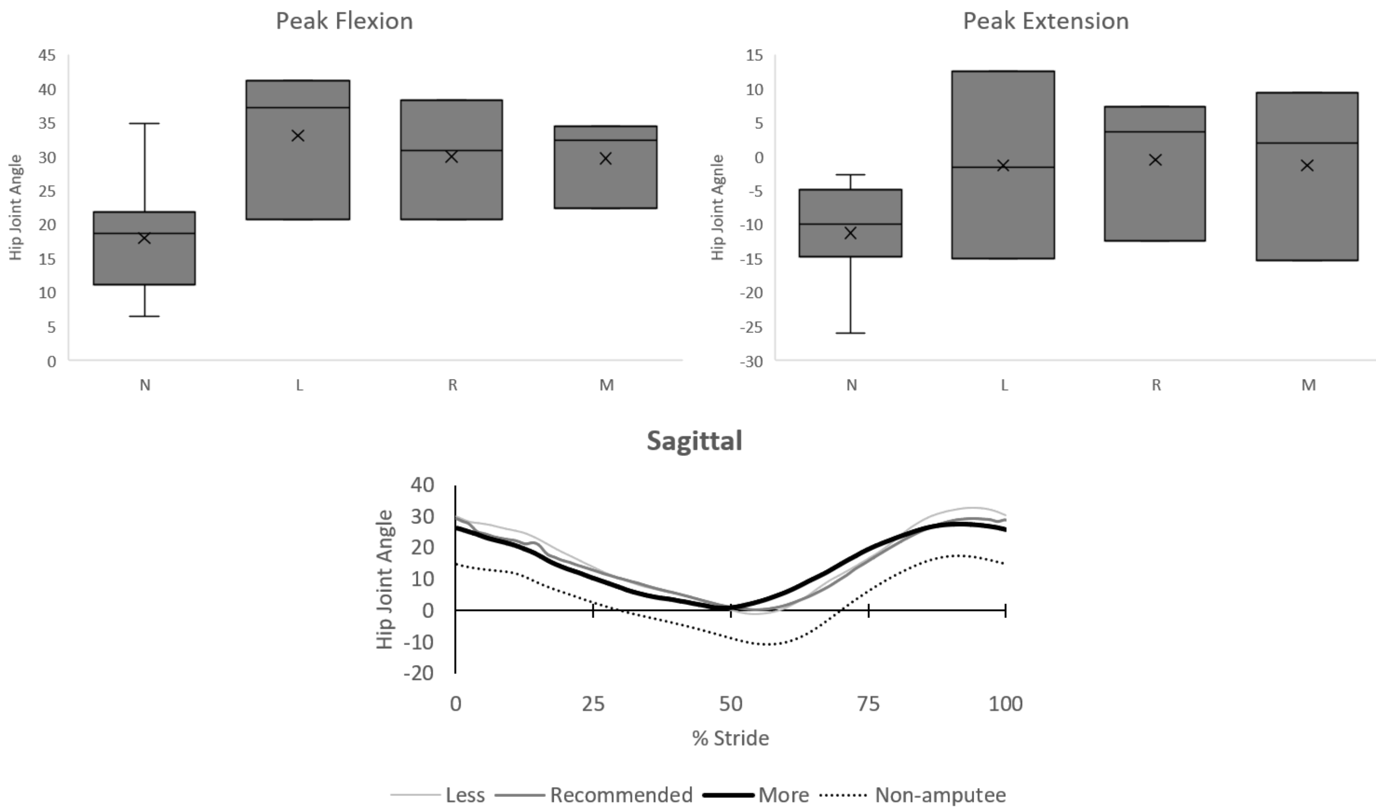

Figure 3. A) Boxplot showing the distribution of peak hip joint flexion angles for non-amputees (N), and the affected leg of toddlers with a TTA using less stiff (L), recommended (R), and more stiff (M) prosthetic feet. B) Boxplot showing the distribution of peak hip joint extension angles. C) Average sagittal plane hip joint angles throughout a stride of the affected leg in toddlers with a TTA and the left leg of non-amputee toddlers. 0% indicates heel-strike. There were no significant differences in peak joint angles between conditions.

Frontal Plane

Toddlers with a TTA walked on average with a more abducted hip throughout a stride for their affected leg than non-amputee toddlers (Fig. 4), but the peak hip joint angles were not statistically significant (less stiff: $p=0.68$, recommended: $p=0.33$, more stiff: $p=0.52$). Despite the lack of significance, peak adduction trended 8.3˚ lower ($p=0.90$) in toddlers with a TTA using the recommended stiffness prosthetic foot compared to non-amputees. Similarly, peak abduction angles trended 9.7˚ greater in toddlers with a TTA using the recommended stiffness prosthetic foot compared to non-amputee toddlers ($p=0.33$).

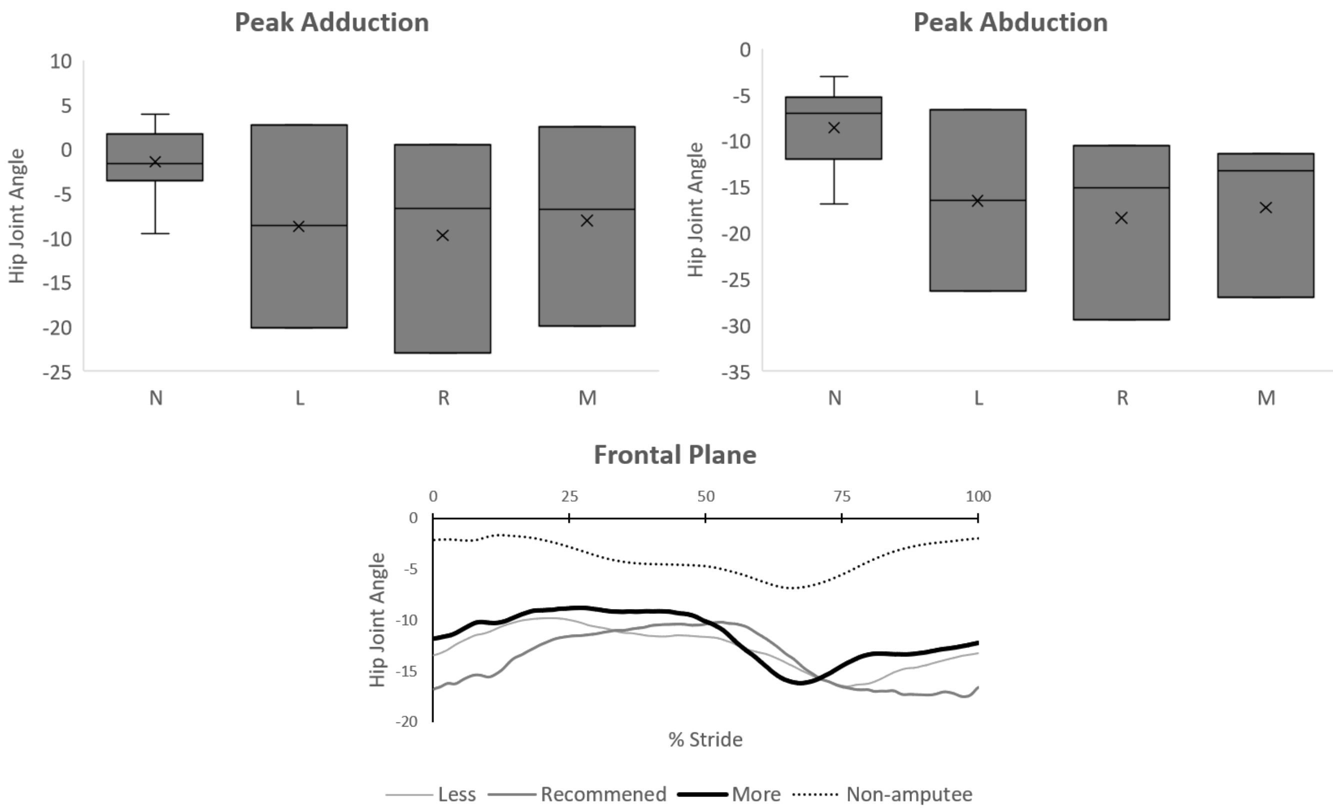

Figure 4. A) Boxplot showing the distribution of peak hip joint adduction angles for non-amputees (N), and the affected leg of toddlers with a TTA using less stiff (L), recommended (R), and more stiff (M) prosthetic feet. B) Boxplot showing the distribution of peak hip joint abduction angles. C) Average frontal plane hip joint angles throughout a stride of the affected leg in toddlers with a TTA and the left leg of non-amputee toddlers. 0% indicates heel-strike. There were no significant differences in peak joint angles between conditions.

Transverse Plane

Use of the more stiff prosthetic foot resulted in hip joint internal/external angles in the affected leg that most closely resembled those from non-amputee toddlers (Fig. 5). The less stiff prosthetic foot also resulted in transverse hip angles that paralleled non-amputee toddlers but were 2.8˚ more internally rotated throughout a stride. However, toddlers with a TTA using a prosthetic foot with recommended stiffness followed a trend of greater hip *external* rotation over a stride compared to non-amputee toddlers, but this was not significant (p=0.32). Even though non-significant, hip external rotation throughout a stride trended 10.8˚ greater in toddlers with a TTA using a recommended stiffness prosthetic foot compared to non-amputee toddlers (p=0.32).

The transverse plane is the only plane that suggests differences in hip joint angles as a result of changing prosthetic foot stiffness (Fig. 5). Use of the recommended stiffness prosthetic foot resulted in a trend of 11.6˚ more external rotation throughout a stride in the affected leg compared to use of the less stiff prosthetic foot (peak internal: p=0.80; peak external: p=0.43). Similarly, use of the recommended stiffness prosthetic foot resulted in a trend of 7.2˚ more external rotation throughout a stride compared to use of the more stiff prosthetic foot (peak internal: p=0.68; peak internal: p=0.80).

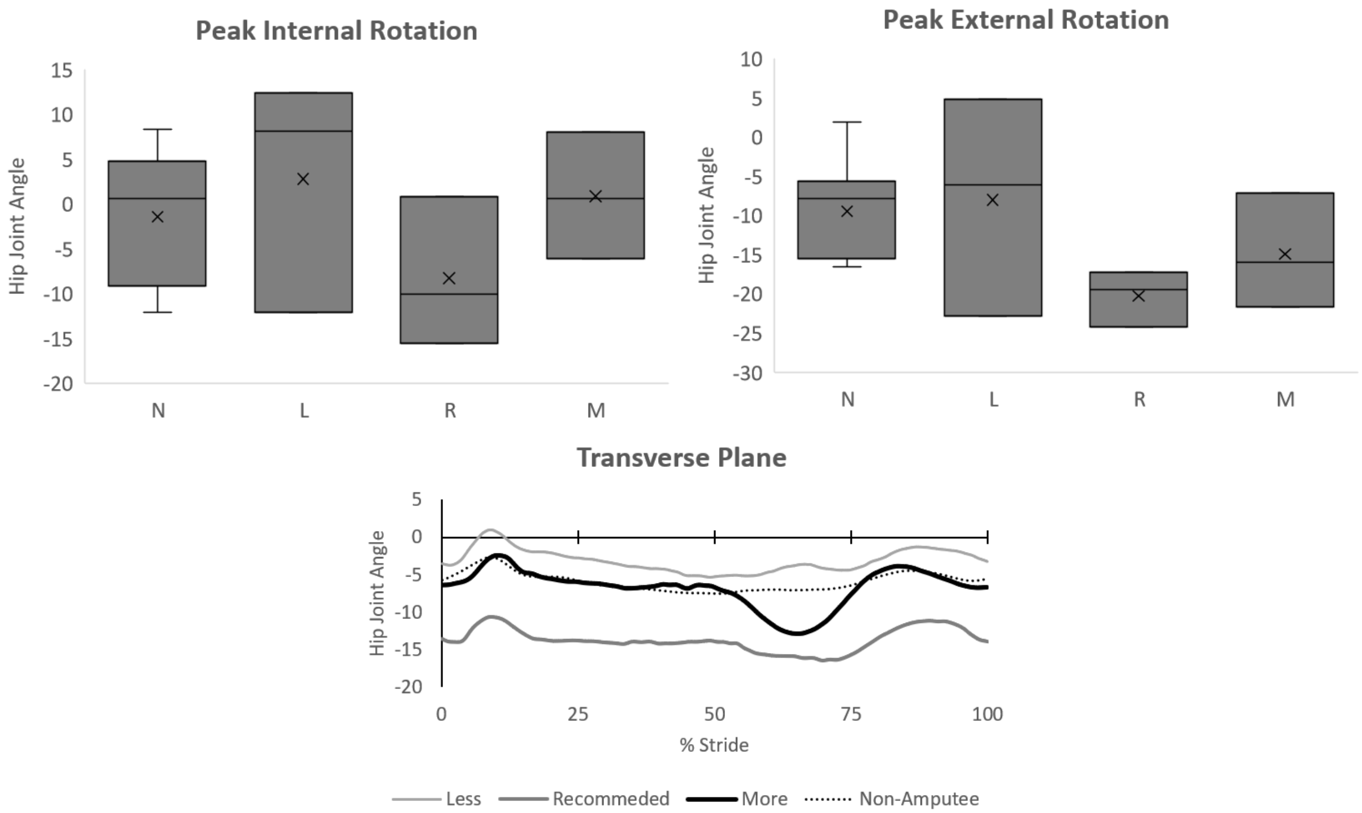

Figure 5. A) Boxplot showing the distribution of peak internal hip joint rotation angles for non-amputees (N), and the affected leg of toddlers with a TTA using less stiff (L), recommended (R), and more stiff (M) prosthetic feet. B) Boxplot showing the distribution of peak external hip joint rotation angles. C) Average transverse plane hip joint angles throughout a stride of the affected leg in toddlers with a TTA and the left leg of non-amputee toddlers. 0% indicates heel-strike. There were no significant differences in peak joint angles between conditions.

Variability

Standard deviation (SD) represents the variability between subjects within a condition. The average sagittal plane hip joint angle SD was 4.5˚ greater for the less stiff prosthetic foot, 1.9˚ greater for the recommended stiffness prosthetic foot, and 1.7˚ greater for more the more stiff prosthetic foot compared to non-amputee toddlers. Similarly, the SDs for peak frontal plane hip joint angles were 6.5˚ greater for the less stiff prosthetic foot, 6.8˚ greater for the recommended stiffness prosthetic foot, and 5.7˚ greater for the more stiff prosthetic foot compared to non-amputee toddlers. Finally, the SDs for the peak transverse plane hip joint angles were 6.5˚ greater for the less stiff prosthetic foot, 0.8˚ less for the recommended stiffness prosthetic foot, and 0.4˚ greater for the more stiff prosthetic foot.

Symmetry

Symmetry was calculated in each plane for hip joint range of motion and peak angles (Table 3). There was no change in symmetry for any of these values when comparing the affected leg of toddlers with a TTA to non-amputee toddlers or when comparing prosthetic feet with different stiffness (all p-values > 0.33).

Table 3 - Percent difference between legs. Average values and standard deviations (SD) were calculated using the absolute value of each subject's individual percentage difference. There were no significant differences in percent difference between conditions.

		Sagittal	
	ROM	**Peak Flexion**	**Peak Extension**
Non-amputee	12.2% (9.8)	36.4% (59.0)	27.3% (23.5)
Less Stiff	4.9% (3.1)	8.9% (5.6)	68.5% (109.3)
Recommended	19.8% (13.8)	14.7% (9.8)	41.7% (16.6)
More Stiff	24.2% (37.1)	30.8% (24.3)	195.8% (153.5)
		Frontal	
	ROM	**Peak Adduction**	**Peak Abduction**
Non-amputee	23.7% (25.4)	193.9 % (174.7)	47.6% (23.2)
Less Stiff	13.2% (10.1)	490.1% (657.3)	87.6% (66.7)
Recommended	16.2% (18.1)	213.5% (160.5)	83.0% (28.4)
More Stiff	40.9% (32.8)	1122.2% (1680.9)	83.4% (153.5)
		Transverse	
	ROM	**Peak Internal Rotation**	**Peak External Rotation**
Non-amputee	48.1% (40.1)	515.6% (672.6)	102.4% (138.7)
Less Stiff	19.1% (20.8)	200.7% (176.7)	222.0% (278.3)
Recommended	49.1% (7.8)	11314.8% (19156.1)	1437.6% (140.4)
More Stiff	97.0% (77.3)	253.3% (257.2)	89.1% (82.0)

Discussion

Our results do not support our hypothesis that use of a more stiff prosthetic foot would increase hip joint external rotation of the affected leg and asymmetry, or that use of a less stiff prosthetic foot would decrease hip joint external rotation of the affected leg and asymmetry. However, we likely did not have enough statistical power to support or refute our hypothesis. We performed an *a posteriori* power analysis with power (β) equal to 0.95, alpha (α) equal to 0.05, and an effect size equal to 0.37 and found that a sample size of 33 per group would allow us to detect statistical significance between peak internal hip rotation angles in toddlers with versus without a TTA. Another *a posteriori* power analysis was done with power (β) equal to 0.95, alpha (α) equal to 0.05, and an effect size equal to 0.56 and found that a sample size of 15 per group would allow us to detect statistical significance between peak external hip rotation angles in toddlers with versus without a TTA. Additionally, the high variability in peak joint angles between subjects within each of the groups make it difficult to draw conclusions from these data about how changing prosthetic foot stiffness affects the hip joint angles of toddlers with a TTA. Also, future studies should use a symmetry calculation that accounts for positive and negative values. We used percent difference between legs, but this led to unrepresentatively large numbers in special situations. One subject have a percent difference of 33433.3% in the transverse plane because the angles of each leg were of the same magnitude on opposite sides of 0 (-10.09 and 9.97).

Our findings are in agreement with the sagittal and frontal plane hip joint angles reported in previous studies for people with a TTA[11,16–18] but not in the transverse plane[17,18]. The overall pattern of change in transverse plane hip joint angles over a stride was different in each of the previous studies. One study found that subjects had external hip rotation motion immediately after toe off[17] and the other found an immediate internal hip rotation after toe off[18]. Our findings suggest an initial internal hip rotation after heel strike with a mid-swing external hip rotation.

Our results suggest that there are modifications to transverse plane hip joint angles due to changes in prosthetic foot stiffness for toddlers with a TTA. Future studies with greater numbers of toddlers with a TTA are warranted to determine how prosthetic foot stiffness affects hip joint rotation, which may lead to better prosthetic foot prescription and design for toddlers with a TTA. Further, it is unclear what the optimal magnitude of hip joint external rotation should be. We hypothesized that less hip joint external rotation (0˚) was ideal, but the non-amputee control group exhibited 1.5˚ of external hip joint rotation at a minimum. So, future research should determine the ideal degree of hip joint rotation to minimize injury and long-term deficits.

Hip joint angles in the sagittal and frontal planes tended to be more flexed and abducted in toddlers with a TTA compared to non-amputees, but there was no difference between prosthetic foot stiffness within the toddlers with a TTA. This suggests that the differences in these parameters are based on amputation status and warrants further research to determine the cause of greater hip flexion and abduction in toddlers with a TTA as greater hip joint angles (further from 0˚) may be maladaptive for development and function.

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