


Mechanical testing of frontal plane adaptability of commercially available prosthetic feet

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Abstract

Introduction: Prosthetic feet have limited adaptability in the frontal plane. Research shows walking on uneven terrain is difficult for many prosthesis users. A new prosthetic foot, the META Arc, was designed with a polycentric ankle joint that allows relatively free movement in the frontal plane to address this limitation. Previous simulations of the polycentric ankle mechanism found potential benefits such as reduced lateral movement of a proximal mass during forward progress and reduced forces being transferred upward from the ground through the foot.

Methods: Standard mechanical testing protocols were used to evaluate the Meta Arc prosthetic foot's performance and six comparable feet commercially available.

Results: The results found the META Arc prosthetic foot had increased frontal plane adaptability as well as reduced lateral forces, and reduced inversion eversion moment compared to the six comparison feet on 10-degree cross-slope test conditions. All included prosthetic feet had similar results for the percent of energy return and dynamic force in the sagittal plane.

Conclusions: These results suggest the inclusion of the polycentric ankle within the META Arc foot will provide more stability without sacrificing forward walking performance.

Keywords

Limb Prosthetics, Limb Prosthetic Mechanisms: Multi-Body Dynamics, Mobility Devices, Rehabilitation Devices, Ankle, Inversion and Eversion, Socket forces

Background

Frontal plane adaptation of the anatomic foot in response to ground contact frequently occurs during activities of daily living. In addition to uneven ground and cross-slopes, mediolateral placement of the foot relative to the body center of mass occurs during weight shift with two-legged standing, side-stepping,¹ turning,² repositioning of the foot at initial ground contact,³ and responding to balance control.^{4,5}

Limited frontal plane adaptability of prosthetic feet causes mediolateral reaction forces and torques to be

propagated proximally up the lower kinetic chain,⁶ resulting in gait instability,⁷ residual limb discomfort,⁸ and skin breakdown.⁶ Segal and Klute⁵ studied foot placement in response to mediolateral perturbations in 10 people with

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transfemoral amputation and 12 without amputation. The researchers found that balance was disrupted by variances of the prosthetic limb when compared to people without amputation. Other research has found that trunk accelerations increased during the prosthetic stance phase for people with transfemoral amputation compared to people without amputations during cross-slope gait.^{9,10} Similarly, step width variability changed the frontal plane relationship of the ground to the foot and was found to increase as a response to uneven ground and cross-slopes.¹⁰ Hak et al.¹¹ found that step width was increased in response to cross-slopes. Gates et al.¹² added that step width variability increased on uneven rock surfaces depending on gait speed.

Different walking surfaces and alignments have been shown to govern socket interface mechanics. Walking on uneven ground was shown to increase peak pressure and sub-maximal load and time-period compared to gait on flat ground.¹³ Translational and angulation misalignment in the sagittal and frontal planes significantly influenced socket moments.¹⁴ Damavandi et al.⁷ stated that the inability of prosthetic feet to adapt to side-slopes may introduce increased fall risk.

Two surveys, administered to lower-limb prosthesis users, indicated the high prevalence of skin sores and irritation within the socket.^{15,16} Ulcers are the most common clinical skin problem,¹⁵ with the incidence of chronic or chronic-recurrent ulcers as high as 50% in people with traumatic lower-limb amputation.¹⁷ The primary cause of limb ulceration is a combination of high pressure and shear loading on the residual limb skin. These adverse loading conditions are created through a combination of the mechanical loading, created as the interaction between prosthetic foot compliance and the terrain, the contours of the prosthetic socket, the prosthetic suspension system, and the interface materials.

One approach to optimize the performance, comfort, and safety of prosthetic feet kinetics is to mimic the motions of anatomical feet to adapt to frontal plane perturbations. The META Arc prosthetic foot (Figure 1) was developed to maintain the optimal center of mass movement with minimal force input. The META Arc has a polycentric ankle that allows $\pm 10^\circ$ of motion in the frontal plane, which rotates and shifts the foot, intending to provide a more stable joint. The benefits of the foot design were previously explored through simulations of various foot designs with and without a mechanism at the ankle.¹⁸ Here, the performance of the META Arc is compared to other popular foot designs in controlled laboratory experiments.

Methods

Mechanical testing machines and standardized protocols (ISO 16955,²⁰ AOPA Test Guidelines¹⁹) were used to explore the differences in performance between the META



Figure 1. The META Arc foot with a polycentric ankle joint that rotates and shifts the foot was designed to provide a more stable joint with frontal plane adaptability.

Arc and six other prosthetic foot designs (Comparison Feet (CF) 1–6). The Percent of Energy Return Experiment measured the amount of energy stored and released when a load was applied and removed to the heel and keel, from which the percentage of energy return for both the keel and heel portions of the feet samples were calculated. The Frontal Plane Rotation Experiment measured frontal plane rotation of the feet in response to an applied load. The Ground Reaction Forces and Moments Experiment investigated the ground reaction forces and moments in response to a dynamically applied load.

Test Samples

The META Arc and six other prosthetic feet (Table 1) that are recommended for the CMS (Centers for Medicare and Medicaid Services) L5986 reimbursement Code (Multiaxial Ankle Unit) were tested. The comparison feet were not bought specifically for this study, but instead collected from a convenient sample of feet and therefore differ in length and stiffness category. Note, that these feet were tested before the CMS changes in prosthetic foot classification, which resulted in some of these feet no longer qualifying for the L5986 code per the Pricing Data Analysis and Coding (PDAC) review.

Percentage of Energy Return Experiment

The team followed the test protocol specified in the AOPA test guidelines for keel and heel percentage of energy return.¹⁹ Feet were installed in the test machine according to the standard test procedures with a 20-degree and a 15-degree

Table 1. Foot samples that were mechanically tested.

Foot sample	Description	Size and category	Recommended user weight (kg, median (range))
META Arc	Carbon fiber split keel with polycentric ankle	27–4	72 (68–76)
CF1	Carbon fiber split keel with hydraulic ankle	25–5	83 (78–88)
CF2	Carbon fiber split keel with hydraulic ankle	27–7	108 (101–116)
CF3	Fiberglass split keel	30–8	123 (117–130)
CF4	Carbon fiber split keel	28–5	83 (78–88)
CF5	Carbon fiber split keel	27–5	83 (78–88)
CF6	Carbon fiber with urethane multiaxial ankle	28–5	83 (78–88)

sagittal plane angles for testing the keel and heel, respectively (Figures 2(a) and (b)). A linear actuator drove a plate with a sliding face into the keel or heel of the foot sample under force control, and the amount of displacement was recorded. Both heel and keel of all feet were loaded to 1246N.

Frontal Plane Rotation Experiment

The AOPA test guideline for multiaxial feet¹⁹ served as the basis for measuring frontal plane rotation. The procedures were modified to better establish the force input required to rotate the foot in the frontal plane (Figure 2(c)). Instead of applying one force and recording the resulting rotation, forces were applied from 20% to 100% of the prescribed patient weight based on the stiffness category of each foot sample in 20% load increments. The angle of frontal plane motion was measured by a calibrated inclinometer and recorded at each load level.

Ground Reaction Forces and Moments Experiment

ISO 16955 Ankle-Foot Quantification protocol²⁰ was used to evaluate ground reaction forces and moments of the feet (Figure 2(d)). This test differs from the AOPA multiaxial test results because it measures forces and moments during a dynamic gait simulation. Feet were installed in the test machine per standard recommendations (7° toe-out). The foot was dynamically loaded with the pylon traveling vertically and loading the foot against the bottom plate of the test machine driven by a force controller. A plate was fixed at an angle to the bottom plate of the test machine and was oriented so the angle of the plate would induce inversion of the foot during gait simulation. Experimental trials were completed with a plate angle of 0° (flat terrain) and 10° (cross-slope) as to the guideline. Trials were completed with the bottom plate of the test machine stationary (static) and with a wave-like motion pattern (dynamic) with an initial angle of –20° at heel strike (inducing plantarflexion) rotating to 40° at push-off (inducing dorsiflexion). A 6-axis load cell in series with the test sample measured forces and moments throughout the experiment at

1000 Hz. The team followed the loading conditions specified in the ISO standard, and data were normalized as described below.

Data Analysis

The percentage of energy return for the keel and heel of the feet samples were calculated from the difference in the area under the force-deflection curves during the load and unload phases. The area was calculated by integrating the force-deflection curves using the trapezoidal rule. Frontal plane angles were measured by a calibrated inclinometer and recorded for each test load during the Frontal Plane Rotation Experiment. With the Ground Reaction Forces and Moments Experiment, the forces generated by the foot sample and test machine mass due to gravity and acceleration were subtracted from the data signals. Raw data were exported to Excel (Microsoft Corporation) for processing. Forces and moments data were normalized by the average of the recommended weight range for each particular foot as described by the manufacturer. Finally, a 100 ms low pass filter was used to smooth the data.

Results

Sagittal plane energy return (Table 2) shows that the performance in the sagittal plane of all non-hydraulic feet was comparable, showing energy return above 88% (AOPA guidelines for dynamic keel and heel are >75% and >82%, respectively). Feet with hydraulic ankles were tested in their highest and lowest damper settings, and the results averaged. Hydraulic feet showed lower energy return in both the heel and keel.

The frontal plane rotation experiment showed that at just 20% of the prescribed patient weight, the META Arc achieved almost 12 times the amount of inversion/eversion that the comparison feet achieved at 100% body weight (Figure 3). At 100% prescribed body weight, the META Arc rotated 14.8°. The range of rotation for comparison feet at 100% prescribed body weight was between 1.1 – 6.8°, with all but one of these feet offering less than 2 degrees of rotation.

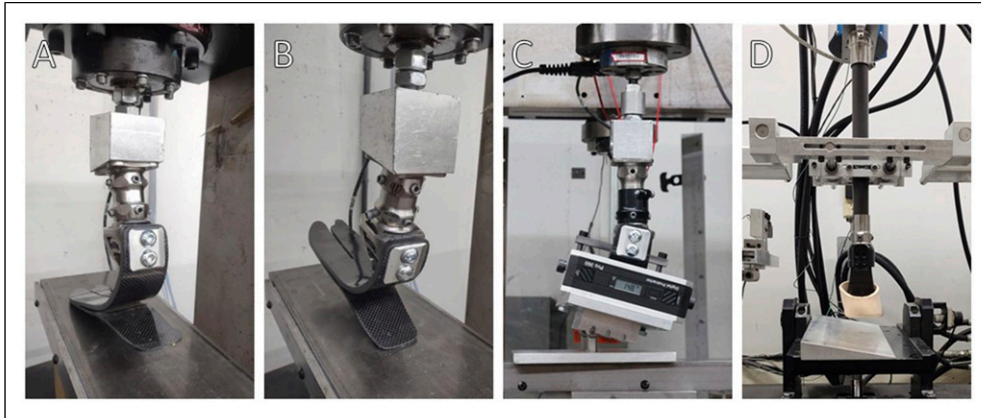


Figure 2. Test setups for: A) Keel percentage of energy return; B) Heel percentage of energy return; C) Frontal Plane Rotation; and D) ISO 16955 (shown with 10° cross-slope plate installed on the wave platform).

Table 2. Energy return measured for each test sample.

Sample	Energy return (%)	
	Keel	Heel
META Arc	96	98
CF1	85 ^a	74 ^a
CF2	66 ^a	77 ^a
CF3	97	93
CF4	88	97
CF5	94	99
CF6	88	97

^aHydraulic ankles were tested in their highest and lowest damper settings, and the results averaged.

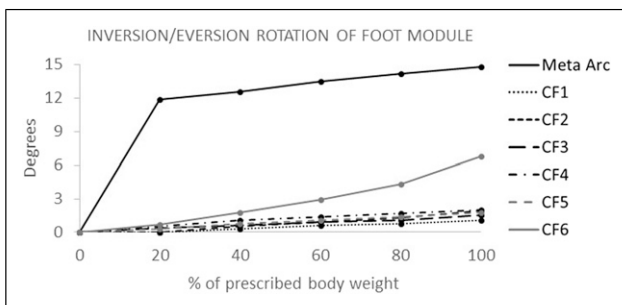


Figure 3. Plot of the ankle frontal plane rotation as a function of the normalized applied load.

Normalized data from the Frontal Plane Forces and Moments Experiment with static wave platform (static) for the flat ground and 10° cross-slope conditions are shown in Figure 4. Negative forces and moments correspond with a downhill direction on the cross-slope. On flat terrain, lateral force and inversion/eversion moments had similar profiles for all feet. On the 10° cross-slope condition, all feet had a

negative lateral force and inversion/eversion moment except for the META Arc, which had positive values with early and late peaks associated with the accommodation of the ankle unit.

Normalized lateral forces and moments with wave plate motion of the bottom plate (dynamic) for the flat ground and 10° cross-slope conditions are shown in Figure 5. On flat terrain, lateral force and inversion/eversion moments had similar profiles for all feet. On the 10° cross-slope condition, all feet had a negative lateral force and inversion/eversion moment except for the META Arc, which had a midstance peak resulting in a positive force and moment.

Normalized frontal forces and moments with dynamic wave motion of the bottom plate for the flat ground and 10° cross-slope conditions are shown in Figure 6. Frontal forces and dorsiflexion/plantarflexion moments had similar profiles for all feet in both the flat ground and 10° cross-slope conditions. The same results were observed in the normalized frontal forces and moments with a static wave platform (static).

The vertical force was not analyzed since it was an input to the test and equivalent for all test samples. The measured moments in the transverse plane were below the noise floor of the load cell for all test samples.

Discussion

There were differences between the META Arc foot compared to all comparison feet for the frontal plane rotation experiment. Most of the other foot designs used in this comparison had very little inversion/eversion of the foot even at 100% body load. The greatest inversion/eversion was exhibited by CF6 due to the urethane ankle, offering an increasing rate of adaption as the maximum load was approached. The META Arc provided the greatest inversion/eversion with 20% of the prescribed body weight. Also, the META Arc provided up to 12 times the exhibited rotation

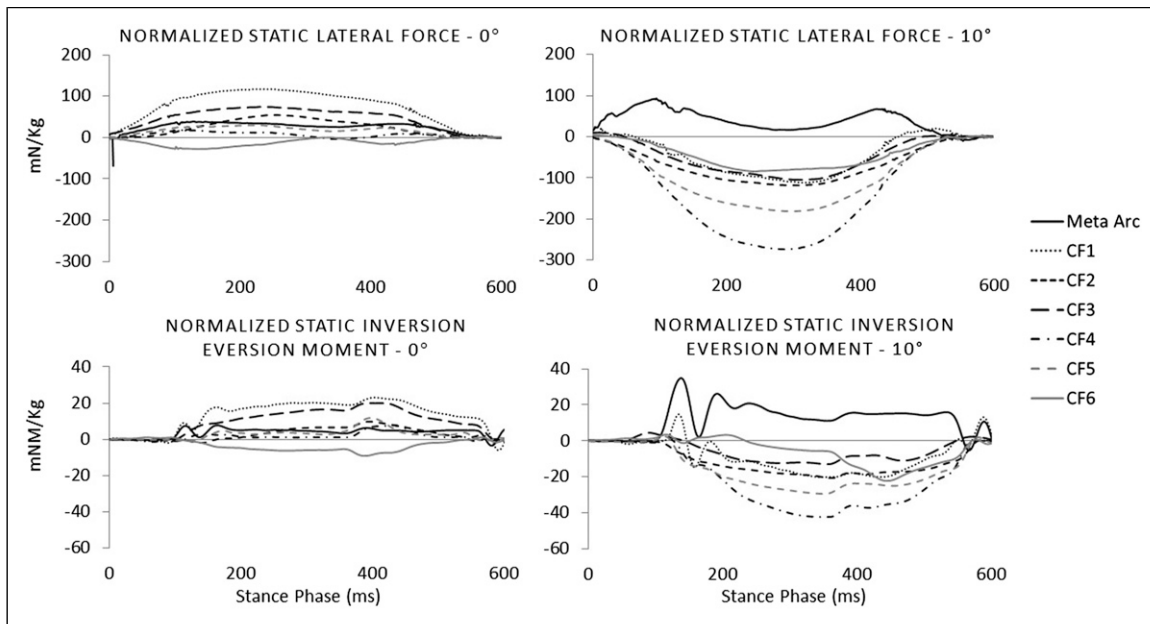


Figure 4. Static forces and moments in the frontal plane. All feet tested exhibited similar profiles on flat conditions. In the 10° cross-slope conditions, the META Arc shows positive values in contrast to the other feet, which show negative values.

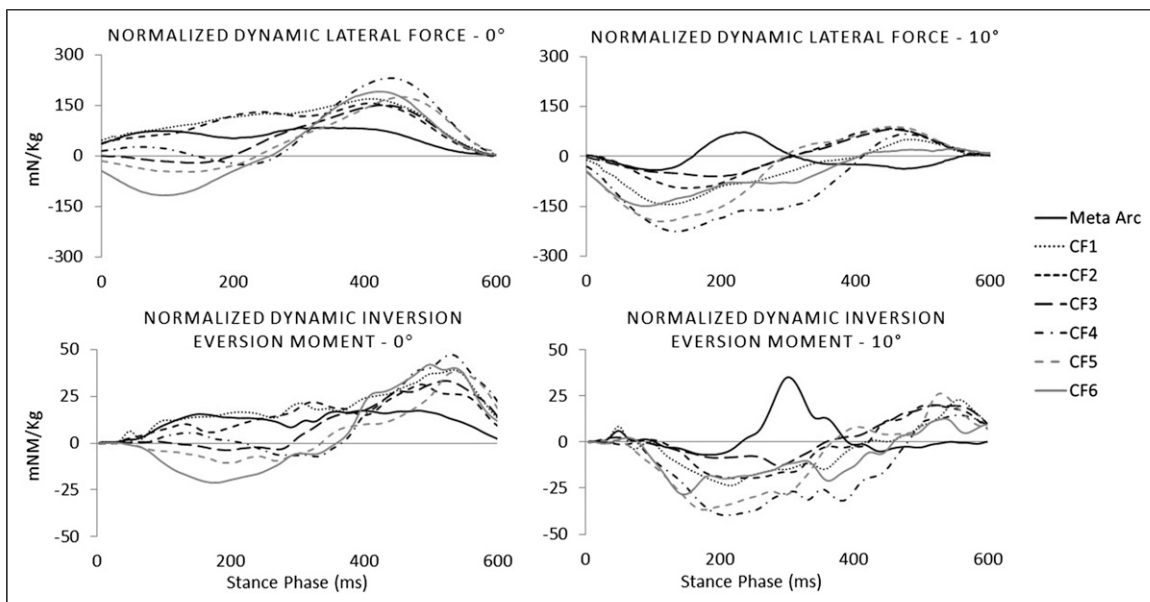


Figure 5. Dynamic forces and moments in the frontal plane. All feet tested exhibited similar profiles on flat conditions. The META Arc shows a midstance peak resulting in a positive force and moment, while the other feet did not exhibit this force.

compared to other feet. At 100% of prescribed body weight, the META Arc exhibited over seven times more rotation than CF1-CF5 and almost double that of CF6. This result shows the META Arc may provide benefits for prosthetic users for stability on a variety of terrains. The early accommodation to the ground should enhance stability by

providing a solid contact point for the user. Prosthetic users have often expressed the feeling of loading the medial or lateral border of the foot unevenly when traversing cross-slopes with current prosthetic feet. The data here demonstrates the limited rotation of the foot designs tested, and a dramatic difference in performance with the META Arc.

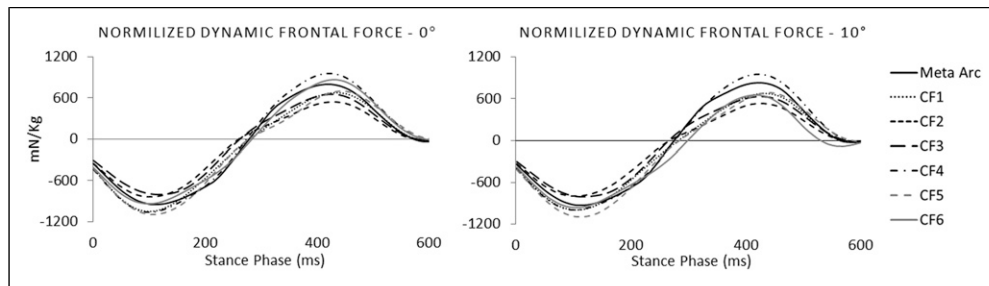


Figure 6. Dynamic force in the sagittal plane. All feet tested exhibited similar profiles on flat, and 10° cross-slope conditions.

Not explored in this test was the benefit of the polycentric nature of the META Arc ankle. The authors believe this type of motion, which rotates and shifts the foot, should provide a more stable joint by maintaining the center of mass within the base of support for greater degrees of foot adaption. Clinical testing will be the best method for evaluating this hypothesis and will be done in future studies.

The increased ability of the META Arc to rotate under low forces resulted in another difference in the Ground Reaction Forces and Moments Experiment compared to the other feet that were tested. During the flat static test condition, the lateral forces and moments were relatively similar between all feet. During the dynamic flat test condition, with the waveform motion of the bottom plate, the META Arc had the lowest magnitude and most flat profile for lateral force and inversion eversion moment. This suggests it would provide the most consistent sideward loading compared to other feet that had steeper slopes or even crossed the neutral axis.

Greater differences were found for the 10 degrees of cross-slope condition. The META Arc was the only foot design with a positive force vector during the static test conditions. This is possible because the repositioning of the ankle provides a positive response to the terrain. This repositioning changes the lever arm from the load cell and completely flips the direction of forces and moments that the user would experience. When comparing the profiles between flat and uneven ground, the META Arc provided the most consistent force profiles between the conditions, suggesting it would be the most consistently performing foot design independent of terrain. Prosthesis users with conventional prostheses have expressed the feeling of the foot throwing them off their desired path, particularly in response to a downhill cross-slope. This is an activity that requires them to exert additional energy to maintain their desired path and suffer from excessive limb pressure as the ground reaction forces are transferred from the ground to their limb. The data suggests the META Arc would behave in an opposite manner to current foot designs by applying forces and torques that compensate for the effect of the slope. The least negative force profile was offered by CF6, exhibiting marginal force reductions compared to the other

foot designs. This suggests that the urethane ankle was more effective than other foot designs to accommodate side slopes. However, due to the need for compression under loading, it did not demonstrate the level of adaptability that the META Arc produced.

More similarities between foot designs were found when examining the dynamic movement for the condition with the 10° cross-slope of the Frontal Plane Forces and Moments Experiment. However, a distinct early midstance peak was present in the META Arc and absent from the other feet. Before this peak, the META Arc moment is a relatively flat profile near zero force and moment. This peak can be explained by the accommodation of the ankle immediately before and after this peak since no moment would be measured until the ankle reached the end of its range of motion, generating the peak. Since the foot was shifted during the rotation, it produced a positive force and moment. Inclusion of the ankle joint decouples foot motion from pylon motion, preventing the generation of undesirable ground reaction forces, and providing a joint between the ground and the residual limb, preventing any residual forces and moments from traveling proximally along the kinematic chain. This may have benefits for more comfortable ambulation on various terrains for prosthesis users.

References to energy storage and return are often made when describing prosthetic feet and were measured to determine the effect the ankle of the META Arc had on the percentage of energy return. Typically, feet with ankles have been associated with a lower percentage of energy return. This is a result of ankle units that historically used hydraulic ankles with damping that enable faster foot flat for stability, but inadvertently dissipated energy with their hydraulic dampers. The hydraulic added motion also limit the ability to store energy by delaying the engaging of the carbon spring to a later instance of the stance phase of gait. Urethane, used in the multiaxial ankle for CF6, had intrinsic damping that dissipated energy as heat during compression/expansion, appearing to have resulted in some loss of energy return for the keel of that foot. In this study, we found that the META Arc, with ankle motion perpendicular to the long axis of the composite foot, had a percentage of energy

return similar to non-hydraulic feet and greater than feet with hydraulic and urethane multiaxial ankles.

Lastly, sagittal plane forces were found to be similar for all foot designs. Given the results obtained in the Energy Return Experiment, this was not particularly surprising but important to note. The results show that a prosthetic device can be made to include frontal plane adaptability at the ankle without compromising forward walking kinetics. The literature shows that uneven terrain is the second most common surface that causes prosthetic users to fall. Therefore, prosthetic technology that can improve stability without sacrificing other performance characteristics associated with forward propulsion is greatly needed.

The main limitations of the study are the small sample size of feet tested and that two of the eight foot designs had different user weight ratings since these foot designs were from a convenient sample that was not obtained specifically for this study. While the data was normalized to account for this effect, is it possible differences could exist if the same weight rating were used for each foot. Also, it is unknown whether the mechanical testing results would have a functional impact on prosthetic users.

Conclusion

The META Arc foot using a polycentric ankle was found to have increased frontal plane adaptability and reduced inversion eversion moment while exhibiting similar sagittal plane kinetics compared to six commercially available foot designs. The differences in frontal plane kinetics may significantly improve lower extremity prosthesis users' ability to overcome some of their current challenges in mobility. While the differences were found in controlled laboratory cross-slope conditions, human subject testing is needed to verify these results and compare differences on flat to uneven terrain. The test machines are ideal for simulating consistent steps, but do not replicate the variability of human gait. Further, the flat and cross slope conditions tested in this laboratory test are representative of some surfaces that users may encounter, but do not fully replicate all the types of obstacles and surfaces experienced by patients in their community.

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Author's Contribution

All authors helped conceive the study. MW, EF, and ZT executed the protocol and all authors reviewed data. MW wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

Declarations of Conflicting interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: MW, EF, ZT, AA, and JC are all employees of WillowWood.

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Guarantor

MW

References

1. Ficanha EM, Rastgaar M and Kaufman KR. Ankle mechanics during sidestep cutting implicates need for 2-degrees of freedom powered ankle-foot prostheses. *J Rehabil Res Dev* 2015; 52: 97–112.
2. Paquette MR, Fuller JR, Adkin AL, et al. Age-related modifications in steering behaviour: effects of base-of-support constraints at the turn point. *Exp Brain Res* 2008; 190: 1–9.
3. Hof AL, van Bockel RM, Schoppen T, et al. Control of lateral balance in walking: experimental findings in normal subjects and above-knee amputees. *Gait Posture* 2007; 25: 250–258.
4. Hak L, Houdijk H, Steenbrink F, et al. Stepping strategies for regulating gait adaptability and stability. *J Biomech* 2013; 46: 905–911.
5. Segal AD and Klute GK. Lower-limb amputee recovery response to an imposed error in mediolateral foot placement. *J Biomech* 2014; 47: 2911–2918.
6. Highsmith MJ, Kahle JT, Klenow TD, et al. Interventions to manage residual limb ulceration due to prosthetic use in individuals with lower extremity amputations: a systematic review of the literature. *Technol Innov* 2016; 18: 115–123.
7. Damavandi M, Dixona PC and Pearsall DJ. Kinematic adaptations of the hindfoot, forefoot, and hallux during cross-slope walking. *Gait Posture* 2010; 32: 411–415.
8. Lee WC, Zhang M and Mak AF. Regional differences in pain threshold and tolerance of the transtibial residual limb:

- including the effects of age and interface material. *Arch Phys Med Rehabil* 2005; 86: 641–649.
9. Howcroft J, Lemaire ED, Kofman J, et al. Understanding dynamic stability from pelvis accelerometer data and the relationship to balance and mobility in transtibial amputees. *Gait Posture* 2015; 41: 808–812.
 10. Sturk JA, Lemaire ED, Sinitski EH, et al. Maintaining stable transfemoral amputee gait on level, sloped and simulated uneven conditions in a virtual environment. *Disabil Rehabil Assist Technol* 2017; 24: 226–235.
 11. Hak L, van Dieën JH, van der Wurff P, et al. Walking in an unstable environment: strategies used by transtibial amputees to prevent falling during gait. *Arch Phys Med Rehabil* 2013; 94: 2186–2193.
 12. Gates DH, Dingwel JB, Scott SJ, et al. Gait characteristics of individuals with transtibial amputations walking on a destabilizing rock surface. *Gait Posture* 2012; 36: 33–39.
 13. Dou P, Jia X, Suo S, et al. Pressure distribution at the stump/socket interface in transtibial amputees during walking on stair, slop and non-flat road. *Clin Biomech* 2006; 21(10): 1067–1073.
 14. Kobayashi T, Arabian A, Orenduff M, et al. Effect of alignment changes on socket reaction moments while walking in transtibial prostheses with energy storage and return feet. *Clin Biomech* 2014; 29(1): 47–56.
 15. Meulenbelt HE, Geertzen JH, Jonkman MF, et al. Determinants of skin problems of the stump in lower-limb amputees. *Arch Phys Med Rehabil* 2009; 90(1): 74–81.
 16. Dudek NL, Marks MB, Marshall SC, et al. Dermatologic conditions associated with use of a lower-extremity prosthesis. *Arch Phys Med Rehabil* 2005; 86(4): 659–663.
 17. Hertel R, Strebler N and Ganz R. Amputation versus reconstruction in traumatic defects of the leg: Outcome and costs. *J Orthop Trauma* 1996; 10(4): 223–229.
 18. Maitland ME, Allyn KJ, Ficanha E, et al. Finite element simulation of frontal plane adaptation using full-foot, split-toe and cam-linkage designs in prosthetic feet. *J Prosthetics Orthotics* 2022; 34: 14–21. Published ahead of print. March 15, 2021. DOI: [10.1097/JPO.0000000000000363](https://doi.org/10.1097/JPO.0000000000000363).
 19. American Orthotic & Prosthetic Association. *AOPA's Prosthetic Foot Project*, 2010. Available from: https://www.aopanet.org/wp-content/uploads/2013/12/Prosthetic_Foot_Project.pdf.
 20. International Standard Office. *Prosthetics – Quantification of Physical Parameters of Ankle Foot Devices and Foot Units*. First Edition. Technical Specification, 2016. ISO 16955: 2016.