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Comparing a Passive-Elastic and a Powered Prosthesis in Transtibial Amputees

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Abstract— **Passive-elastic foot prostheses cannot produce net work. Consequently, passive-elastic foot prostheses are limited in their ability to enable a biologically-realistic gait pattern in transtibial amputees. This shortcoming results in difficulties in balance and walking and leads to high levels of oxygen consumption during locomotion. A powered prosthesis has the potential for overcoming these problems and allowing transtibial amputees to achieve a biologically-realistic gait pattern. In this study, we compared the effects of the Ceterus by Össur, a traditional passive-elastic prosthesis, with those of the PowerFoot Biom (iWalk, Cambridge, MA), a recently-developed powered prosthesis. Gait biomechanics and metabolic cost were compared in a group of 5 transtibial amputees during level-ground walking. The results provided preliminary evidence that the use of a powered prosthesis leads to a decrease in the level of oxygen consumption during ambulation due to improvements in ankle kinematics and kinetics primarily during late stance. An average decrease in oxygen consumption of 8.4% was observed during the study when subjects used the PowerFoot compared to the Ceterus. An average increase of 54% was observed in the peak ankle power generation during late stance. Our results suggest that powered prostheses have the potential for significantly improving ambulation in transtibial amputees.**

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I. Introduction

THE human ankle provides a significant amount of net positive work during stance, especially at moderate to fast walking speed. Previous studies have shown that a major function of the human ankle is to provide adequate power generation for forward progression [1-3]. Clinical studies indicate that individuals with transtibial amputation who use conventional passive-elastic foot prostheses exhibit higher metabolic rates during level-ground walking compared to individuals with an intact ankle [4-5]. The main cause for such an increase in metabolic cost of ambulation appears to be the inability of conventional passive-elastic prostheses to provide net positive work during terminal stance [6]. Studies measuring the rate of oxygen consumption during gait of individuals with transtibial amputation have reported a 40% increase in metabolic cost compared to individuals with an intact ankle [7-8]. In order to achieve biological realism, a prosthetic ankle-foot device should be able to actively control joint impedance, motive power, and joint position.

Au et al. [6, 9] designed the first prototype of a powered ankle-foot prosthesis that was then further developed into a product, the PowerFoot Biom (iWalk, Cambridge, MA),

Figure 1 The PowerFoot BiOM

shown in Figure 1. The system has human-like characteristics. It uses control algorithms that adjust the stiffness of the prosthetic ankle during the gait cycle.

The PowerFoot system was shown to be capable of mimicking normal ankle-foot walking behavior in the sagittal plane. The states of the PowerFoot controller are: 1) controlled dorsiflexion, 2) controlled plantarflexion, and 3) powered plantarflexion. Preliminary evaluations of the system showed that the PowerFoot prosthesis is capable of delivering high mechanical power output during terminal stance, with peak power generation values approximately twice as large as the values provided by state-of-the-art passive-elastic prostheses [9].

In this paper, we present a preliminary study aimed at evaluating the differences in the biomechanics of gait and in oxygen consumption in individuals wearing the PowerFoot by iWalk, a powered ankle-foot prosthesis, compared to the Ceterus by Össur, a passive-elastic prosthesis.

II. Methods

Five male adults (age 39.4 ± 9 years) with a history of traumatic unilateral transtibial amputation were recruited in the study. To be considered eligible to participate in the experimental procedures, subjects had to be high-level ambulators, i.e. levels E or F according to the Special Interest Group of Amputee Medicine (SIGAM) mobility grade [10]. In order to score a level E or F on the SIGAM mobility grade, subjects have to be independent community ambulators with the ability to walk at variable cadence without the use of an assistive device.

A. Data Collection

All experimental procedures were performed according to a protocol approved by Spaulding Rehabilitation Hospital Internal Review Board.

During the first session, subjects were fitted with both the PowerFoot by iWalk and the Ceterus by Össur by a certified prosthetist. The settings of the PowerFoot prosthesis were chosen on a subject-by-subject basis using qualitative feedback from the subjects. Then subjects were asked to walk indoor with each of the two prostheses for about one hour to make sure that they were properly fitted and comfortable with the selected PowerFoot settings. Subjects were given additional time to acclimate to the prostheses if they asked for it.

During the second session, subjects completed laboratory gait analysis tests with both the PowerFoot and the Ceterus prosthesis. The order used to test the prostheses was randomized for each subject. Gait trials were performed on a level walkway. Reflective markers were attached to the pelvis and lower extremities using a standardized setup for the study of lower limb biomechanics. Kinematic curves were reconstructed from the marker trajectories recorded by an 8-camera motion capture system (Vicon 512, Vicon Peak, Oxford, UK) using a standard biomechanical model (Vicon Plug-in-Gait). Kinetic curves were estimated using two staggered force platforms (AMTI, Watertown, MA) embedded in the walkway.

A third experimental session was performed to assess oxygen consumption during ambulation. These tests were conducted at an indoor athletics track. We selected the indoor track space because conditions could be more closely controlled than in an outdoor setting. Also, subjects were able to walk undisturbed in such an environment. Subjects were first asked to choose their comfortable walking speed. The speed was used for testing both prostheses.

Oxygen consumption was measured using a Cosmed K4b2 portable gas analysis system (Cosmed USA). During testing, subjects were asked to breathe through a portable, non-rebreathing facemask attached to a harness supporting the portable unit. To measure baseline metabolism, each subject was first asked to rest for 8 minutes. Then, subjects were instructed to walk at their comfortable walking speed for about 8 minutes without stopping. A staff member drove a motorized kart set to the desired speed next to the subject to help them maintaining the target walking speed. Finally, subjects were instructed to rest for about 8 minutes. Data was collected continuously through the three above-described experimental procedures.

B. Biomechanics data processing

Kinematic and kinetic data (sampled at 120 Hz) were extracted for each stride (from foot contact to foot contact of the same foot) and then re-sampled to obtain 100 samples per stride. Kinematic and kinetic curves were compared to normative data previously collected in the Motion Analysis Laboratory.

Quantitative analyses were performed to compare kinematic and kinetic behaviors observed when subjects walked with the Ceterus foot compared to when they walked with the PowerFoot. The focus on our analyses was on

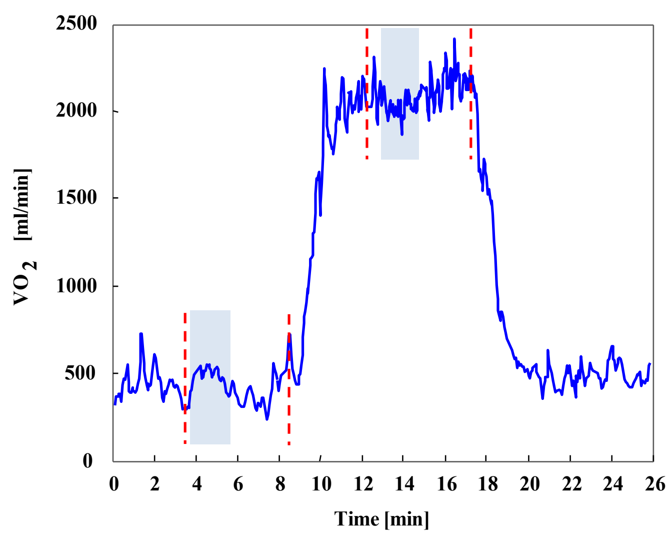

Figure 2 Oxygen consumption curve. The vertical dashed lines represent the 5 minutes of data in which the subject reached steady-state conditions. The shaded area represents the 2-minutes window with minimal standard deviation that was chosen for the analysis

terminal stance, the phase of the gait cycle during which the PowerFoot prosthesis generates power thus leading to expected major differences between behaviors observed when using the two prosthetic technologies. To capture such differences we derived the following biomechanical features from the kinematics and kinetics of terminal stance: maximum ankle plantarflexion, maximum ankle dorsiflexion moment, and peak power generation. The same features were extracted from the above-mentioned normative database and averaged for comparison. Non-parametric statistics (Wilcoxon test) was used to compare data gather with the two prosthetic technologies.

C. Oxygen consumption data processing

Figure 2 shows an example of oxygen consumption data. The first three minutes of data at rest and during walking were discarded to avoid analyzing transitory behaviors [7, 11]. A two-minute rectangular sliding window was then applied to the remaining five minutes of data (for each testing condition, i.e. rest and walking). Oxygen consumption average and standard deviation values were derived for each position in time of the sliding window used to analyze the data. Wilcoxon tests were performed to compare the data collected with the two prosthetic technologies.

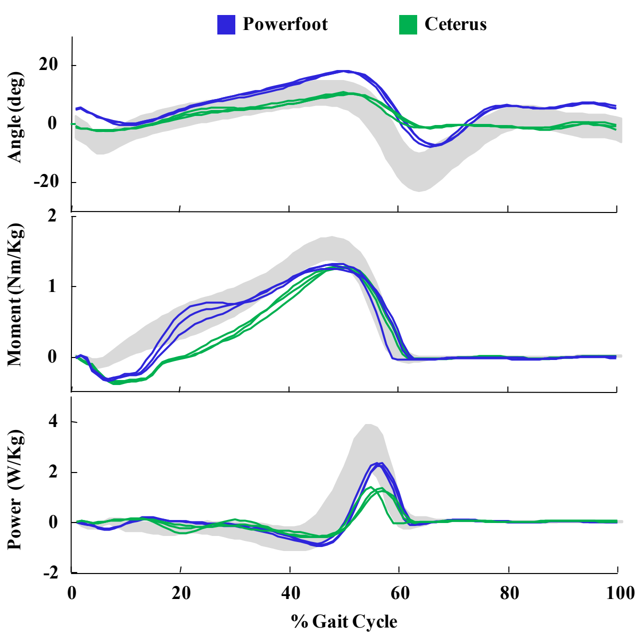

Figure 3 Ankle kinematic and kinetic curves for one subject. Trials collected with the subject wearing the Ceterus Flex Foot and the PowerFoot are presented in different colors. Normative range is shown in the shaded curve.

III. RESULTS

A. Biomechanics

Figure 3 shows ankle sagittal kinematic and kinetic curves for subject 1. From inspection of the curves, it appears that the kinematics and kinetics of ambulation achieved with the PowerFoot prosthesis resemble the main characteristics of biological gait better than those achieved with the Ceterus prosthesis. Table 1 and Figure 4 show the feature values extracted from ankle kinematic and kinetic curves when subjects were wearing the PowerFoot vs. the Ceterus. Figure 4 shows that both the maximum ankle plantarflexion and the peak power generation values were closer to the normative values when subjects used the PowerFoot. The maximum ankle dorsiflexion moment did not appear to differ between the two prostheses in subject 1, subject 3 and subject 4. On the contrary, subject 5 showed an increase in peak dorsiflexion moment when walking using the Ceterus prosthesis compared to the PowerFoot (which showed data

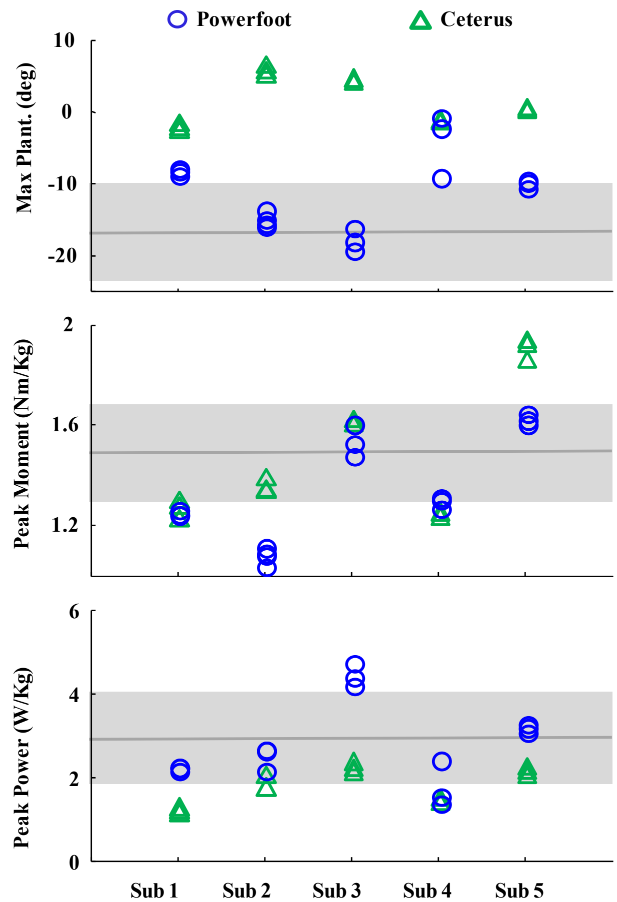

Figure 4 Features extracted from the ankle kinetic and kinematic curves with subjects wearing the PowerFoot and the Ceterus Flex Foot. Normative range is presented in the shaded area.

TABLE 1
FEATURES EXTRACTED FROM KINEMATICS AND KINETICS

	MAX ANKLE PLANTARFLEXION (DEG)		MAX DORSIFLEXION MOMENT (NM/KG)		PEAK POWER GENERATION (W/KG)	
	Ceterus	Powerfoot	Ceterus	Powerfoot	Ceterus	Powerfoot
Subject 1	-1.66	-7.81	1.28	1.26	1.31	2.28
Subject 2	6.46	-14.54	1.37	1.09	1.94	2.59
Subject 3	5.26	-17.34	1.63	1.55	2.33	4.51
Subject 4	-0.63	-3.53	1.26	1.31	1.55	1.84
Subject 5	1.02	-9.54	1.92	1.63	2.24	3.24
Normative	-16.90		1.52		2.92	

closer the normative dataset). Finally, subject 2 did not show any improvements in ankle moment when walking with the powered prosthesis.

The increase in peak ankle plantarflexion observed with the PowerFoot compared to the Ceterus averaged 12.6 deg (Wilcoxon signed rank test, $p = 0.03$). The increase in peak power generation with the PowerFoot compared to the Ceterus was 1.02 W/Kg on average (Wilcoxon signed rank test, $p = 0.03$). There was no significant decrease in maximum dorsiflexion moment (Wilcoxon signed rank test, $p=0.094$).

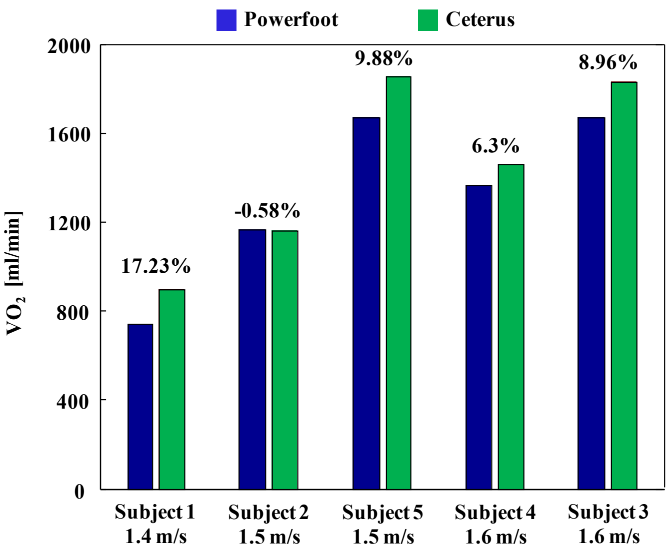

Figure 5 Metabolic consumption (difference walk-rest). In general among the subjects we can see that the oxygen consumption decreased when the subject walked with the PowerFoot (in blue). The percentage difference between conditions is displayed on top of the bars. The self selected walking speed is presented in the y-axis legend.

B. *Metabolic cost*

Summary results are shown in Figure 5. The plot suggests a trend toward an increase in metabolic cost with gait speed. Differences are apparent between the results derived when subjects were tested with the PowerFoot vs. the Ceterus. Four subjects showed a decrease in metabolic cost when walking with the PowerFoot. This change was rather large in subject 1 who showed a reduction in metabolic cost of 17.2 %. On the other hand, subject 2 did not show a large change in metabolic cost of ambulation when using the PowerFoot compared to the Ceterus prosthesis. The average decrease in oxygen consumption across all five subjects who participated in the study was 8.4% but it was not statistically significant (Wilcoxon signed rank test, $p = 0.06$) although suggesting a strong trend. No association was obvious between the magnitude of the difference in oxygen consumption between the two prosthetic technologies and walking speed.

IV. Discussion

The results herein presented suggest that the PowerFoot prosthesis can allow one to achieve higher biological realism than the Ceterus prosthesis. Most notably, the PowerFoot leads to a decrease in oxygen consumption, an increase in ankle plantarflexion and an increase in peak ankle power generation at push off compared to the Ceterus foot.

It is likely that these results would show larger improvements with the PowerFoot if we allowed a longer acclimation period. At the time of testing, the powered prosthesis was a prototype for laboratory use only and therefore subjects' exposure to the PowerFoot technology had to be limited to the laboratory. Future studies will have to assess the impact of these technologies on a larger number of subjects and across different ambulatory conditions such as ramp ascending/descending and stair climbing.

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References

[1] M. Palmer, "Sagittal plane characterization of normal human ankle function across a range of walking gait speeds," Master's Thesis, Massachusetts Institute of Technology, 2002.

[2] A. L. Hof, *et al.*, "Calf muscle moment, work and efficiency in level walking; role of series elasticity," *J Biomech,* vol. 16, pp. 523-37, 1983.

[3] V. T. Inman, *et al.*, *Human walking*. Baltimore: Williams & Wilkins, 1981.

[4] N. H. Molen, "Energy-speed relation of below-knee amputees walking on a motor-driven treadmill," *Int Z Angew Physiol,* vol. 31, pp. 173-85, Mar 2 1973.

[5] G. R. Colborne, *et al.*, "Analysis of mechanical and metabolic factors in the gait of congenital below knee amputees. A comparison of the SACH and Seattle feet," *Am J Phys Med Rehabil,* vol. 71, pp. 272-8, Oct 1992.

[6] S. K. Au, *et al.*, "Powered Ankle--Foot Prosthesis Improves Walking Metabolic Economy," *Robotics, IEEE Transactions on,* vol. 25, pp. 51-66, 2009.

[7] R. L. Waters, *et al.*, "Energy cost of walking of amputees: the influence of level of amputation," *J Bone Joint Surg Am,* vol. 58, pp. 42-6, Jan 1976.

[8] E. G. Gonzalez, *et al.*, "Energy expenditure in below-knee amputees: correlation with stump length," *Arch Phys Med Rehabil,* vol. 55, pp. 111-9, Mar 1974.

[9] S. K. Au, *et al.*, "An ankle-foot emulation system for the study of human walking biomechanics," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, 2006, pp. 2939-2945.

[10] N. H. Ryall, *et al.*, "The SIGAM mobility grades: a new population-specific measure for lower limb amputees," *Disabil Rehabil,* vol. 25, pp. 833-44, Aug 5 2003.

[11] G. H. Traugh, *et al.*, "Energy expenditure of ambulation in patients with above-knee amputations," *Arch Phys Med Rehabil,* vol. 56, pp. 67-71, Feb 1975.