Original Article

Evaluation of a Viscoelastic Ankle-Foot Prosthesis at Slow and Normal Walking Speeds on an Able-Bodied Subject

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Objectives: This paper describes further improvement and preliminarily evaluation of a novel viscoelastic ankle-foot prosthesis prototype. The objective was to control the ankle hysteresis at slow and normal walking speeds.

Methods: Inspired by the ankle biomechanics, in which the hysteresis differs based on the gait speeds, a manually damping control mechanism imbedded in the prosthesis for adjusting the ankle damping at slow and normal walking speeds. The prototype was then preliminarily tested on an able-bodied subject wearing an adaptor which simulates the amputee walking. The ankle joint kinetics and kinematics were measured in a gait analysis lab at different walking speeds.

Results: The results suggest that the viscoelastic ankle foot prosthesis prototype could provide a smooth normal-like walking for most of the measured gait characteristics in slow and normal speeds.

Discussion: Therefore, it is suggested to apply a controllable damping mechanism based on the gait speeds in the design of new prosthetic feet.

Keywords: Ankle-foot prosthesis, walking speed, ankle damping, viscoelastic

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Introduction

Viscoelastic prosthetic feet have been recently introduced that combine the adjustable hydraulic dampers with the conventional carbon feet. These prostheses are claimed to imitate natural ankle biomechanics during walking and adjust the foot to uneven surfaces and slopes. Despite the fact that such devices have the potential to provide natural ankle biomechanics, (1-4) they are not widely commercially available. This may be as a result of their complexity and high cost. The successful prosthetic foot should ideally be capable of imitating the entire human ankle biomechanics (5-7). Ankle function, which is described best by the moment-angle relation, is influenced by the walking speed. At slower walking speed, a clock-wise moment - angle loop, indicating an overall damping behavior of the ankle joint, is shown. However, in a normal walking speed, the hysteresis fades away, i.e. energy consumption and work done are nearly balanced. The moment-angle loop changes to a counter clockwise direction at higher speeds (i.e., work done is more than the energy consumption) (6-11). Hence, the viscoelastic properties of a prosthetic foot need to be adapted to the walking speed in order to mimic the behavior of ankle for a more normal walking (7, 8, 10). It has been suggested that ankle function can be reproduced by passive mechanical mechanisms in slow and normal walking speeds without any need for power generating systems. An adjustable spring-damper system at slow walking speed would be beneficial, while the damping effect vanishes at the

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normal speed (6-8, 11). Moreover, findings of previous research demonstrate that a prosthetic foot incorporating the hydraulic system could reduce the stress on the residual limb as well as diminish the compensatory mechanisms in other joints while the amputee walking at different speeds (1-4).

The aim of the current study was to further improve a viscoelastic ankle foot prosthesis prototype for different walking speed. An adjustable storage-damping mechanism was embedded in the design to control the ankle hysteresis at slow and normal walking speeds. It was hypothesized that if the damping characteristics of the prosthesis is controlled based on the walking speed, more human-like ankle biomechanics would be revealed. Moreover, the experimental evaluation of the prosthesis on a healthy young male is described.

Methods

Study design: In the previous study, a viscoelastic prosthetic ankle-foot was developed that incorporated two pneumatic assemblies described as Dorsiflexor (DF) and Plantarflexor (PF) units which are engaged in a specific portion of the gait cycle. The units provide adaptable stiffness properties during a gait cycle (12). In the further improvement, a damping control mechanism was added to the PF unit. A pressure two-way valve on the heel directed the compressed air to either direction between the two ports depending on the applied load. At the heel strike instant, the valve handle beneath the heel was loaded and closed the first port. This port did not have any resistance to the air flow. At the heel off and unloading the handle, the compressed air was directed to the second port. The second port included a manual regulator for damping control. According to the walking speed, damping could be manually regulated in late stance by adjusting the opening size of the damping valve. An adjustment knob was turned clockwise or counterclockwise to decrease or increase the valve opening, respectively. Decreasing the opening provided greater resistance to the compressed air passing through the port and therefore, greater damping (Figure 1).

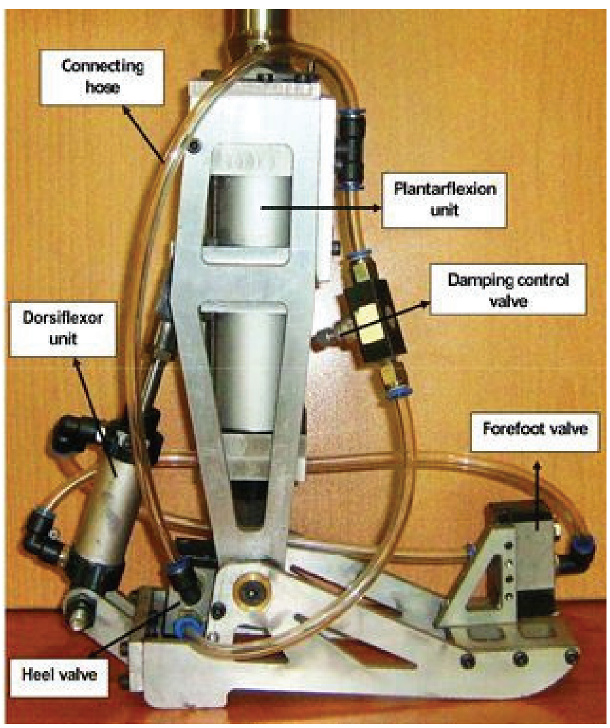

Fig 1. Photograph of the prototype

Evaluation and data processing: The manufactured prototype was preliminary tested on a healthy volunteer using an adaptor. The subject was a male with 26 years of age, 70 kg of body mass, and 180 cm of height. The participant provided the written informed consent. Gait analysis was performed with five cameras (Vicon 460, Vicon Motion System Ltd., UK) and two Force plates (Kistler Instrument

AG, Switzerland). Reflective markers were placed on the anatomical landmarks included the ankle (lateral malleolus), toe (dorsum of the foot between first and second metatarsals), tibia (one third distal), knee (lateral femoral condoyle), femur (one third distal) and ASIS (anterior superior iliac spines) markers (7). A marker was placed on the sacrum for computing the walking speed (Figure 2). The participant was asked to walk barefoot at self-selected slow and normal walking speeds with wearing the prosthesis. Before starting to walk and at the slow speed, the adjustment knob was turned clockwise to allow the damping effect during the gait; while, at the normal speed, the knob was adjusted counterclockwise to remove the damping. Each test was repeated six times to check the repeatability of the results.

The marker positions and ground reaction forces were processed with the lower body Vicon PIG model (Workstation version 4.6, Vicon Motion System Ltd., UK) to compute the ankle angle (degree), moment (N m) and power (W/kg). According to the manual (Vicon Motion System Ltd., UK), the lower body PIG model represents the lower limb as rigid segments of pelvis, femur, tibia and foot. The marker data and anthropological measurements were used to create virtual marker trajectories for kinetic and kinematic modeling. Walking speed was calculated as the total displacement of the sacrum marker divided by the time traveled in one gate cycle. Kinetic and kinematic data were low-pass filtered using zero-lag, sixth-order Butterworth filter with a cut-off frequency of 10 Hz(13, 14). Linear interpolation was applied to the data points to get equal lengths of data sets.

Fig 2. Gait analysis on healthy subject using an adaptor (Since the device was reflective, it was covered during the experiment)

Results and Discussion

The aim of this study was further improvement of a passive ankle-foot prosthesis that adjusts the ankle damping characteristics based on the slow and normal walking speeds. In the Figure (3), the moment-angle curves at slow and normal walking speeds are shown. The graph displayed clock-wise hysteresis loop (negative work) at both speeds. However, the hysteresis at normal speed was smaller. The Preliminarily results confirmed the study hypothesis since the general shape of the moment-angle loop at slow walking speed was in agreement with the normal ankle in which the curve showed a clock-wise hysteresis loops. It should be noted that the smaller hysteresis at normal speed compared to the slow speed shows the effect of the damping control mechanism imbedded in the prosthesis. However, the small amount of hysteresis in normal walking speed might likely be due to the frictional effects of the mechanical components.

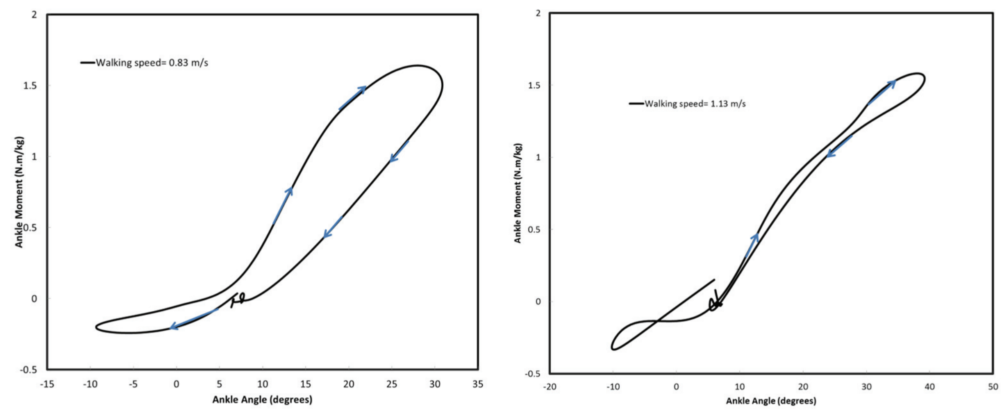

Fig 3. The prosthetic side ankle angle versus moment at slow (0.83 m/s) and normal (1.3 m/s) speeds.

Figures (4-5) represent the prosthetic joint angle, moment and power versus percentage of the gait cycle at six walking trials with slow and normal speeds. The data appeared to be consistent at different walking trials. These findings approved the performance of the mechanical units and their control system.

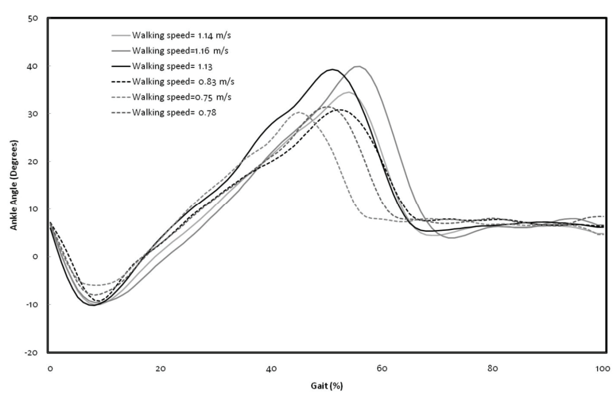

Fig 4. The prosthetic side ankle angle versus gait cycle percent for six walking trials with slow (dashed lines) and normal (solid lines) speeds

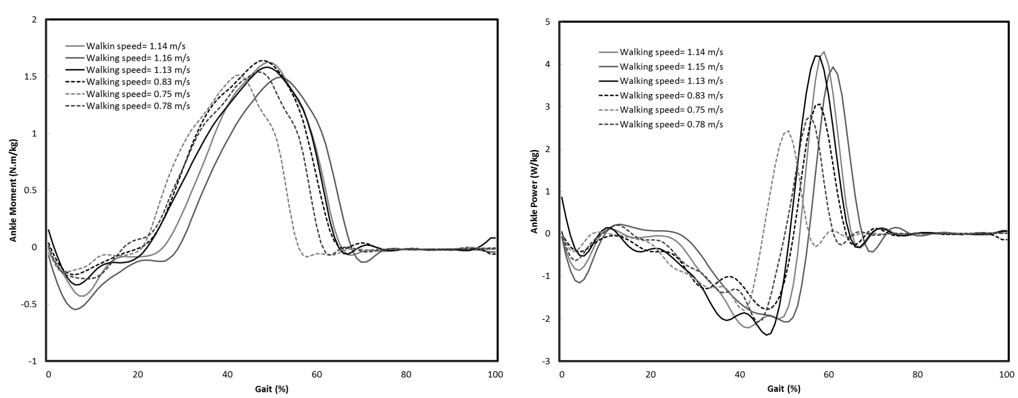

Fig 5. The prosthetic-side ankle moment (left) and power (right) versus gait cycle percent for six walking trials with slow (dashed lines) and normal (solid lines) speeds

The current manufactured prototype's weight and dimensions limits the application of the prototype for amputees in real situations. Therefore, safety issues limited testing the prototype on a real amputee. Thus, we chose an able-bodied subject to reduce the risk of falling while testing the new prototype.

Conclusion

In summary, the findings of this study suggest that the viscoelastic ankle foot prosthesis prototype could mimic the natural ankle biomechanics in slow and normal walking speeds. Furthermore, the ankle damping was adjusted based on different walking speeds. The novel mechanical mechanism is an advantage of this approach which excludes the need for electronic circuitry and power sources.

Conflict of Interest - None declared. The authors have no conflict of interest.

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