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Assessment of the effects of carbon fiber and bionic foot during overground and treadmill walking in transtibial amputees

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A B S T R A C T

Objective: To determine the energy cost of walking (ECW) of a bionic foot (Proprio-Foot®) during ambulation on floor and on treadmill (at different slopes) compared to walking with a dynamic carbon fiber foot (DCF). We evaluated transtibial amputees (TTAs) perceived mobility with the prosthesis and their walking ability on stairs and ramps.

Method: TTAs were enrolled. The ECW tests were conducted on a regular floor surface and on treadmill with −5%, 0% and 12% slopes. In all conditions, TTAs were asked to walk at their own self-selected speed. Metabolic and cardiac data were collected using a portable gas analyzer. Tests were performed at six data collection points: first with a standard suction system (SSS) and the DCF; second, with the DCF after 7 weeks of using a hypobaric suspension system (HSS) with the DCF; third, after 1 h of Proprio-Foot® use together with the HSS; three more testing sessions were carried out at 30-day intervals, i.e., after 30, 60 and 90 days of Proprio-Foot® use together with the HSS. TTAs perceived mobility using the prosthesis and walking ability on stairs and ramps were assessed.

Results: Ten TTAs completed the measurements. ECW with the Proprio-Foot® obtained in the final floor-walking test was significantly lower than ECW with the DCF ($p = 0.002$). No significant improvements were observed for perceived mobility or walking ability.

Conclusions: Results suggest that use of the Proprio-Foot® can lower the ECW for TTAs in spite of its added weight compared to DCF.

1. Introduction

As the ability to walk is one of the most important activities of daily living, transtibial amputees (TTAs) experience discomfort in their everyday life. Prosthesis feet design development has lead to more complex feet, thanks to the use of carbon fiber and of microprocessor driven motors or actuators.

Recently, a new microprocessor-controlled adaptive prosthetic ankle (i.e. Proprio-Foot®, Össur) was designed to improve the prosthetic technology for lower limb amputees. As claimed by the producer, the Proprio-Foot® has a wide and automated range of ankle flexion that responds to the underlying terrain. The microprocessor allows the Proprio-Foot® to automatically increase dorsiflexion during the unloaded swing phase in ambulation, on level ground, stairs and ramps. (Fig. 1). Some studies have reported benefits deriving from Proprio-Foot® use. Alimusaj [1] reported that walking with Proprio-Foot® results in kinematics and kinetics that are closer to physiological patterns for the involved side. This could reasonably produce a more energy efficient walking pattern. Wolf et al. [2] reported that adapting the ankle angle of the Proprio-Foot® on stairs and ramps modified the pressure data registered at the stump making them more similar to those in level walking. Agrawal et al. [3] reported that Proprio-Foot® resulted to have the highest degree of symmetry between the intact and the prosthetic limb (94.5%; a symmetry index of 100% means that an equal amount of work is done by the two legs) indicating that the vertical kinetic and potential energy changes in the body center of mass caused by the Proprio-Foot® were similar to those produced by the intact foot.

On the other hand, it has to be taken into account that the Proprio-Foot® has an additional weight, compared to a

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Fig. 1. The Proprio-Foot®; during the swing phase it automatically lifts the toe to reduce the risk of trips. Note the battery on the rear side of the socket and the Seal In X5® liner under the test socket.

conventional prosthetic ankle (about 2-fold), that raises the importance of a good socket fitting since for "heavy" prosthetic device pistoning effects have been reported occasionally [1]. Pistoning is the vertical movement of the stump within the socket [4,5]. It is minimized by an appropriate suspension system that secures the socket to the amputee's stump, guaranteeing prosthesis efficiency [6,7]. When pistoning occurs, the prosthesis fit is deteriorated and as a consequence occur the reduction of amputee's mobility and autonomy [6,8].

Gholizadeh et al. [7] reported that Seal In X5®, Össur, provided less pistoning than the pin lock system, also when additional overload was applied to the prosthetic foot. Seal In X5® is a prosthetic liner that holds five silicone hypobaric seals that are able to adapt to the internal surface of the socket (Fig. 1). It guarantees vacuum socket suspension creating negative pressure between the liner and the socket by means of a one-way valve positioned in the distal part of the socket.

Although several studies have reported the benefits or otherwise of the Proprio-Foot® [1–3], to our knowledge there are no studies on the energy cost of walking (ECW) using the Proprio-Foot®.

The main aim of the present study was to quantify ECW using the Proprio-Foot® in four different conditions: on the floor and on treadmill with three slopes (0%, −5% and 12%) in TTAs who use the dynamic carbon fiber foot (DCF). Considering the added weight of the Proprio-Foot® and the reduced pistoning of the Seal In X5®, as reported by Gholizadeh et al. [7], the Proprio-Foot® evaluations were carried out together with Seal In X5®.

Other aims were: to compare ECW using the Proprio-Foot® and the DCF; to determine the length of the acclimation period needed to become accustomed to the Proprio-Foot®; to evaluate the effects of using the Proprio-Foot® on perceived mobility and ability to walk on stairs and ramps.

2. Materials and methods

2.1. Inclusion criteria

(a) Unilateral transtibial amputation.
(b) Prosthesis user for at least 1 year.
(c) A mobility K level of 2 or more [9].
(d) DCF user.
(e) Absence of pathological stump conditions counteracting prosthesis use.
(f) Absence of mental/clinical disorders.

The TTAs gave their informed consent and they received no payment. The local ethics committee approved the study.

TTAs underwent several evaluation sessions (see Fig. 2). Before the first evaluation session, TTAs performed at least 2 trials on the treadmill with the slopes needed for the study to avoid possible learning effects of walking on the treadmill.

2.2. ECW data collection

The ECW tests were performed in the following conditions: on the floor (floor walking test: FWT), in a hallway with a regular surface, and on a treadmill at three different slopes, 0%, −5% and 12% (treadmill walking test: TWT0%, TWT-5% and TWT12%, respectively). During the walking tests, TTAs wore the portable metabolimeter K4b^2 (Cosmed, Italy) to collect metabolic data (oxygen consumption – $V'O_2$; carbon dioxide – $V'CO_2$; respiratory exchange ratio – RER, $V'CO_2/V'O_2$) and a heart rate (HR) monitor. In both the FWT and the TWT, TTAs were requested to walk at their own self-selected comfortable walking speed (SSWS).

The TWTs were conducted on a RUNRACE model treadmill (Technogym, Italy), with the speed indicator covered; the TTAs chose their SSWS without knowing the speed indicated on the treadmill. The duration of each test was at least 7 min to allow participants to reach and maintain the steady state (SS) condition of HR and metabolic parameters. The ECW at SS, (ml/m/kg) was calculated as "oxygen consumption/speed". For FWT, mean walking speed was calculated as the ratio of distance to time. The trials were performed in a random sequence. The time interval between each trial was approximately 30 min [10].

2.3. Houghton scale (HS)

The HS was used to measure time spent wearing the prosthesis and its functional use [11]. The HS consists of four items: time spent using the prosthesis, how the prosthesis is used, the need for an assistive device, and the individual's perception of stability while walking outside on a variety of terrains. The maximum score is 12.

2.4. Hill assessment index (HAI)

The HAI [12] evaluates the ability to walk down a ramp. It is measured with an ordinal rating (ranging from 1 to 11) depending on subjects' quality of gait.

2.5. Stair assessment index (SAI)

The SAI [13] evaluates quality of gait by observing TTAs' use of the handrail (or other assistive device) and foot placement while they descend 12 steps. It rates on 14-level items.

2.6. The timed "UP&GO" test (TUGT)

The TUGT, even if not specific for TTAs, was used to assess TTAs motor ability while wearing the prosthesis [14]. The test measures