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BIOENERGETIC DIFFERENCES DURING WALKING AND RUNNING IN TRANSFEMORAL AMPUTEE RUNNERS USING ARTICULATING AND NON-ARTICULATING KNEE PROSTHESES

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Abstract

Transfemoral amputation (TFA) patients require considerably more energy to walk and run than non-amputees. The purpose of this study was to examine potential bioenergetic differences (oxygen uptake (VO_2), heart rate (HR), and ratings of perceived exertion (RPE)) for TFA patients utilizing a conventional running prosthesis with an articulating knee mechanism versus a running prosthesis with a non-articulating knee joint. Four trained TFA runners ($n = 4$) were accommodated to and tested with both conditions. VO_2 and HR were significantly lower ($p < 0.05$) in five of eight fixed walking and running speeds for the prosthesis with an articulating knee mechanism. TFA demonstrated a trend for lower RPE at six of eight walking speeds using the prosthesis with the articulated knee condition. A trend was observed for self-selected walking speed, self-selected running speed, and maximal speed to be faster for TFA subjects using the prosthesis with the articulated knee condition. Finally, all four TFA participants subjectively preferred running with the prosthesis with the articulated knee condition. These findings suggest that, for trained TFA runners, a running prosthesis with an articulating knee prosthesis reduces ambulatory energy costs and enhances subjective perceptual measures compared to using a non-articulating knee prosthesis.

Keywords

Above-knee amputee; Energy costs; No-knee running prosthesis; Oxygen uptake; Physical therapy; Rehabilitation

INTRODUCTION

Transfemoral amputation (TFA) patients require considerably more energy to ambulate than non-amputees. Studies by Genin et al. (1) and Mengelkoch et al. (2) have reported that the energy costs (oxygen uptake (VO_2)) during walking for TFA patients are 30% to 78% greater than for non-amputee control subjects. Thus, any prosthetic component that could improve energy costs and ambulatory performance would be functionally important to persons with TFA.

Mengelkoch et al. (2) recently reported on the effects of prosthetic foot components on energy costs and ambulatory performance for TFA patients during walking and running. In this study, all TFA subjects were tested using three prosthetic feet conditions: a conventional solid ankle cushioned heel (SACH) foot; a general-purpose energy storing and return (ESAR) foot, which utilized a carbon fiber keel and ankle; and a running-specific ESAR foot, which utilized a carbon fiber C-shaped keel but was heelless. During walking for TFA, at both fixed speeds and self-selected walking speeds (SSWS), no significant differences were observed for energy costs (VO_2 , gait economy, gait efficiency (GE)) among the three prosthetic feet conditions. However, at SSWS, TFA patients demonstrated significantly improved speed with the general-purpose ESAR foot and running-specific ESAR foot compared to the SACH foot (7% and 9% respectively).

Studies reporting the effects of prosthetic foot components on energy costs and ambulatory performance for TFA patients during running are very limited. In their study, Mengelkoch et al. (2) reported that TFA patients were not safely able to utilize the SACH foot during running. They observed that TFA participants were able to run at speeds up to their self-selected running speeds (SSRS) using the general purpose ESAR foot and the running-specific ESAR foot. At SSRS, the speed deemed comfortable for sustained distance running, GE was similar for TFA subjects using the general-purpose ESAR foot and the running-specific ESAR foot. However, a functional difference was that SSRS was significantly slower using the general-purpose ESAR foot (13%) compared to the running-specific ESAR foot. Another important observation from this study was that TFA participants were only able to run at speeds greater than SSRS using the running-specific ESAR foot. These researchers recommended that clinicians should recommend and prescribe a running-specific ESAR foot for TFA runners interested in performing more vigorous distance-type running (i.e., for exercise and running competition).

It has been observed that some TFA distance runners prefer to run with a prosthesis that has a non-articulating knee joint (i.e., a no-knee condition, in which a straight pylon attaches to the prosthetic socket and foot components). Anecdotally, it has been suggested that, during running, increased energy may be required for TFA patients to control the prosthetic articulating knee to prevent it from buckling, compared to a prosthesis with a non-articulating knee joint (3). Previously, a preliminary study compared VO_2 peak attained during running for two TFA runners utilizing both a conventional running prosthesis with an articulating knee mechanism and a prosthesis that had a non-articulating knee joint (3). Results were mixed in that VO_2 peak was higher for one subject using the prosthesis with an

articulating knee mechanism and one subject using the prosthesis that had the non-articulating knee joint. However, both subjects were able to run longer and attained faster speeds using the prosthesis that had the non-articulating knee joint. Based on their results, these researchers suggested that a prosthesis with a non-articulating knee joint may be more energy efficient for TFA runners. However, this study had several limitations. It utilized only two subjects, did not specify an accommodation period for TFA patients to utilize each type of prosthesis, performed the maximal exercise tests for both prostheses with only a 30 min rest between tests, and did not include information concerning ratings of perceived exertion during testing or subjective preference for running with each type of running prosthesis.

Given the limitations in the study by Wening et al. (3), the purpose of this study was to further examine potential bioenergetic differences for TFA patients utilizing a conventional running prosthesis with an articulating knee mechanism versus a running prosthesis that has a non-articulating knee joint.

METHODS

Subjects

Two male and two female ($n = 4$) unilateral TFA runners with amputation due to non-vascular causes were recruited (Table 1). Participants were healthy recreational runners (K4, Medicare Functional Classification Level), age 45 years, who performed run training 3 to 5 d-week⁻¹ for 30 min-d⁻¹ for 1 year. The study was conducted in accordance with ethical standards recommended by the Belmont Report (4). The study protocol was approved by the University of South Florida's Institutional Review Board, and each study participant provided written informed consent.

Study design

The study utilized a two-period repeated measures crossover experimental design. Each TFA participant was tested with two prosthetic knee conditions (Figure 1). Condition 1: The participant's usual running prosthesis was used with an articulating knee mechanism. All TFA runners utilized the same articulating knee mechanism, and all TFA participants utilized a running-specific ESAR foot, but the manufacturer differed among subjects (Table 2). Condition 2: The participant's usual running prosthesis fitted with a pylon (non-articulating knee condition, also called no-knee condition) of sufficient length to replace their preferred articulating knee mechanism. Subjects were then given a one-month accommodation period to train and exercise with the non-articulating knee condition prior to assessment. To ensure the assignment of the order of testing for the two prosthetic knee conditions was balanced and randomized, a block randomization method was used (5,6). Subjects acclimated to both conditions then tested with each prosthetic configuration on separate days in random order.

Exercise Testing Procedures

For exercise testing, participants reported to the laboratory in the morning following a minimum 8 h fasting period and having refrained from exercise for approximately 48 h. Participants performed peak effort exercise testing for each test condition using an

incremental treadmill (*Quinton TM65™*, Cardiac Science, Waukesha, WI, USA) walking and running protocol. Testing began at $0.67 \text{ m}\cdot\text{s}^{-1}$ at a 0% grade. Speed increased every 2 min by $0.233 \text{ m}\cdot\text{s}^{-1}$. Approximately 48 to 72 h prior to testing, participants came to the laboratory for a treadmill familiarization session. At familiarization, individual SSWS & SSRS were determined for the given prosthetic knee condition and programmed into the subjects' respective exercise tests.

Measurements

Heart rate (HR) and VO_2 were measured continuously by telemetry and breath-by-breath gas exchange analysis (COSMED K4b²™, Rome, Italy). Calibration was performed immediately prior to testing according to manufacturer specifications. Flow volume measures were calibrated using a 3 L syringe and gas analyzers were calibrated to known gas mixtures. Body weight measurements without prosthesis were used for VO_2 ($\text{ml O}_2\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) measurements relative to body weight. During each minute of exercise testing and at peak exercise, participants rated perceived exertion (RPE) using the Borg scale (6 to 20) (7). Upon concluding exercise testing with both prosthetic knee conditions, participants were asked to subjectively rank the two prosthetic conditions by which was most preferred.

Data Analysis

Data were verified for accuracy, completeness, and normality. Parametric tests were selected and applied when appropriate; otherwise, non-parametric equivalent tests were used to compare responses between the two prosthetic knee conditions. It was expected that, during running, TFA participants would have variable speed/stage end-points of exercise tolerance for each prosthetic knee condition. Thus, some missing data for the TFA participants for the two prosthetic knee conditions was anticipated. We selected, *a priori*, the “last observation carried forward” method as our intention-to-treat strategy for imputation of missing data (8). Statistical analyses were performed using IBM SPSS software (v22, Armonk, NY, USA). For all procedures, statistical significance was $p < 0.05$. Values are reported as means $\pm$ standard deviation (SD).

RESULTS

Mean VO_2 for five of eight speeds, represented as the shaded region (speeds 1.12 to $2.01 \text{ m}\cdot\text{sec}^{-1}$) in Figure 2, were significantly greater ($p = 0.05$) for the non-articulating knee (no-knee) condition, indicating the non-articulating knee condition cost more energy to use at these speeds. Mean HR for five of eight speeds, represented as the shaded region (speeds 1.34 to $2.24 \text{ m}\cdot\text{sec}^{-1}$) in Figure 3, were significantly greater for the non-articulating knee condition, also indicating the non-articulating knee condition cost more energy to use at most speeds. Mean RPE was not significantly different between the two prosthetic knee conditions. However, as seen in Figure 4, there was a trend in which RPE was higher for the non-articulating knee condition at six of eight speeds, which suggests more effort was needed at most speeds with the non-articulating knee condition. Differences in gait speeds between the two prosthetic knee conditions are shown in Figure 5. There were no significant differences between the two prosthetic knee conditions for SSWS, SSRS, or maximal speed

attained. However, a trend emerged whereby use of the articulating knee condition resulted in faster SSWS, SSRS, and maximal speed. All four TFA participants subjectively ranked the prosthesis with the articulated knee condition as their most preferred running prosthesis.

DISCUSSION

The results in this study differ from those reported by Wening et al. (3). In that study, they tested two TFA runners and reported only on their end of exercise data. They reported VO_2 peak was higher for one subject using the prosthesis with an articulating knee mechanism and one subject using the prosthesis that had the non-articulating knee joint. However, both subjects were able to run longer and attained faster speeds using the prosthesis that had the non-articulating knee joint. In the current study, we compared VO_2 , HR, and RPE data at eight fixed ambulation speeds (walking & running) and SSWS and SSRS. We observed significant differences at most fixed speeds for VO_2 and HR, suggesting that energy costs were lower using the prosthesis with the articulated knee condition. For RPE, we observed a trend wherein, at most fixed speeds, RPE was lower using the prosthesis with the articulated knee condition, suggesting that less effort was required using that prosthesis. We also observed that there was a trend for SSWS, SSRS, and maximal speed attained to be faster for TFA subjects using the prosthesis with the articulated knee condition. Finally, all four TFA participants preferred ambulating with the prosthesis with the articulated knee condition.

The primary limitation of this study was the small sample size and thus the generalizability; these findings may be limited to TFA runners with similar characteristics. Moreover, more thorough demographic (i.e., time since amputation), anthropometric (i.e., limb length), and history (i.e., exercise history) data could be gathered to facilitate better understanding regarding to whom the results would apply.

CONCLUSION

These findings suggest that, for trained TFA runners, a running prosthesis with an articulating knee prosthesis reduces ambulatory energy costs and enhances subjective perceptive measures compared to using a non-articulating knee prosthesis.

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Figure 1.
Running prostheses: (a) articulated knee prosthesis and (b) non-articulated knee prosthesis.

Figure 2. Differences in oxygen uptake (VO_2) during walking & running for TFA using a non-articulated knee prosthesis (no-knee) & an articulated knee prosthesis (knee). Transfemoral amputees (TFA). VO_2 at speeds 1.12 – 2.01 $\text{m} \cdot \text{sec}^{-1}$ (shaded region), were significantly greater ($p < 0.05$) for the non-articulating knee (no-knee) condition.

Figure 3. Differences in heart rate during walking & running for TFA using a non-articulated knee prosthesis (no-knee) & an articulated knee prosthesis (knee). Transfemoral amputees (TFA). Heart rate at speeds 1.34 – 2.24 m·sec⁻¹ (shaded region), were significantly greater ($p < 0.05$) for the non-articulating knee (no-knee) condition.

Figure 4. Differences in rating of perceived exertion (RPE) during walking & running for TFA using a non-articulated knee prosthesis (no-knee) & an articulated knee prosthesis (knee). Transfemoral amputees (TFA). No significant differences in RPE between knee conditions.

Figure 5.

Differences in self-selected walking speeds (SSWS), self-selected running speeds (SSRS), & maximal speeds (MAX) attained for TFA using a non-articulated knee prosthesis (noknee) & an articulated knee prosthesis (knee).

Transfemoral amputees (TFA). No significant differences in SSWS, SSRS and MAX between knee conditions.

Table 1

Physical Characteristics of Transfemoral Amputee Participants

Gender	n = 2 male, n = 2 female
Age (y)	28.5 ± 4.2
Height (cm)	173.6 ± 6.2
Weight (kg)	68.5 ± 23.4
Body Mass Index kg*m ⁻²	22.5 ± 7.0

All amputees were non-dysvascular.

Table 2

Characteristics of the Two Types of Running Prostheses

	Articulated Knee	Non-Articulated Knee
Socket	n = 2, ischial containment; n = 2, sub-ischial.	n = 2, ischial containment; n = 2, sub-ischial.
Suspension	n = 2, elevated vacuum; n = 2, suction.	n = 2, elevated vacuum; n = 2, suction.
Knee ^a .	n = 4, <i>Total Knee 2000</i> ® (Ossur, Reykjavik, Iceland)	n = 4, <i>Pylon</i>
Foot ^b .	n = 2, <i>Flex Run</i> ® (Ossur, Reykjavik, Iceland); n = 2, <i>Nitro</i> ® (Freedom Innovations, Irvine, CA, USA)	n = 2, <i>Flex Run</i> ® (Ossur, Reykjavik, Iceland); n = 2, <i>Nitro</i> ® (Freedom Innovations, Irvine, CA, USA)
Weight of Prosthesis (kg) ^c .	3.65 ± 0.40	3.05 ± 0.40

^aThe *Total Knee 2000* utilizes a mechanical hydraulic knee system.

^bThe *Flex Run* and *Nitro* prosthetic feet are running-specific, energy storing and return feet.

^cNo significant difference in the weight of the articulated knee prosthesis vs. the non-articulated knee prosthesis.