ORIGINAL ARTICLE

The Effects of Prosthetic Foot Design on Physiologic Measurements, Self-Selected Walking Velocity, and Physical Activity in People With Transtibial Amputation

Miao-Ju Hsu, PhD, PT, David H. Nielsen, PhD, PT, Suh-Jen Lin-Chan, PhD, PT, Donald Shurr, MA, PT, CPO

ABSTRACT. Hsu MJ, Nielsen DH, Lin-Chan SJ, Shurr D. The effects of prosthetic foot design on physiologic measurements, self-selected walking velocity, and physical activity in people with transtibial amputation. Arch Phys Med Rehabil 2006;87:123-9.

Objective: To investigate the physiologic differences during multispeed treadmill walking and physical activity profiles for the Otto Bock C-Walk foot (C-Walk), Flex-Foot, and solid ankle cushion heel (SACH) foot in people with transtibial amputation.

Design: A repeated-measures design with 3 prostheses.

Setting: Research laboratory.

Participants: Eight men with unilateral transtibial amputation.

Interventions: Not applicable.

Main Outcome Measures: Physiologic responses (energy expenditure, gait efficiency, exercise intensity, rating of perceived exertion [RPE]) during multispeed treadmill walking (53.64, 67.05, 80.46, 93.87, 107.28m/min) test were analyzed with 2-way repeated-measures analysis of variance (ANOVA). One-way ANOVA was employed to analyze foot-type differences for self-selected walking velocity (SSWV), and steps per day (daily activity). Analysis of covariance was used to analyze foot-type differences with SSWV as the covariable for the physiologic measurements.

Results: The C-Walk had a trend of improved physiologic responses compared with the SACH; however, no foot-type differences were statistically significant. Compared with the C-Walk and SACH, the Flex-Foot showed no significant differences in energy expenditure and gait efficiency, but significantly lower percentage of age-predicted maximum heart rate and RPE values.

Conclusions: The energy storing-releasing feet appeared to have certain trends of improved gait performance compared with the SACH; however, not many objective foot-type differences were significantly noted. Further studies with a larger sample size are suggested.

Key Words: Amputation; Heart rate; Oxygen consumption; Physical fitness; Prostheses and implants; Prosthesis design; Rehabilitation.

PEOPLE WITH TRANSTIBIAL amputation lose the ankle-foot complex and associated muscle function. Even though compensation is possible through the recruitment of substitute muscles at the ipsilateral and contralateral hips and knees,[1-4] research has shown that the gait of individuals with transtibial amputation is less efficient, requires increased energy expenditure, and produces a higher relative exercise intensity.[1,5,6] The study by Waters et al[7] of subjects with vascular and traumatic transtibial amputation showed that the subjects with vascular amputation expended 55% more $kcal\cdot kg^{-1}\cdot m^{-1}$ at the self-selected walking velocity (SSWV), and the subjects with traumatic amputation expended 25% more $kcal\cdot kg^{-1}\cdot m^{-1}$, compared with subjects with nonpathologic gait at SSWV. Prosthesis design has been a contributing factor to variations in these outcome parameters.

One of the most common energy-storing prosthetic feet currently available on the market is the Flex-Foot.[a] From a design perspective, the construction of the Flex-Foot provides dynamic function and allows energy to be stored through compression of an internal plate during heel contact and early stance with subsequent energy release during late stance and push-off.[8-10] The 1C40 Otto Bock C-Walk foot (C-Walk)[b] is among the newest energy-storing prostheses on the market. The main features of this prosthetic foot include the carbon fiber reinforced plastic spring elements (C-spring and base spring) and a control spring (fig 1).[11] Due to its unique design, the C-Walk is claimed to allow people with transtibial amputation to walk smoothly and comfortably at slow as well as higher walking speeds and also for use in recreational activities. Research on the interprosthesis comparison between the Flex-Foot and C-Walk is lacking.

Physiologic assessment is an important aspect in evaluating efficacy of foot types. In gait studies of prosthetic foot types, the most commonly used physiologic variables include energy expenditure, gait efficiency, relative exercise intensity, and rating of perceived exertion (RPE). Gait efficiency has been defined as energy expenditure per distance traveled and is derived from the ratio of the oxygen consumption divided by the walking speed.[5,12] Measuring oxygen consumption requires expensive equipment and trained personnel, which are not always available. Therefore, heart rate and RPE have been used in many studies for physiologic monitoring. The exercise heart rate, expressed as a percentage of age-predicted maximum heart rate (%APMHR = [exercise heart rate/age-predicted maximum heart rate] × 100), has been used to indicate the relative exercise intensity during ambulation.[13]

Most investigations on assessing gait performance with various prostheses have been done in laboratory settings. Nevertheless, those tests fail to represent the lifestyle or the full

From the Institute and Faculty of Physical Therapy, National Yang Ming University, Taipei City, Taiwan (Hsu); Graduate Program in Physical Therapy and Rehabilitation Science, University of Iowa, Iowa City, IA (Nielsen, Shurr); and School of Physical Therapy, Texas Woman's University, Dallas, TX (Lin-Chan).

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Correspondence to Miao-ju Hsu, PhD, Institute and Faculty of Physical Therapy, National Yang Ming University, No.155, LiNong St 2 Sec, Pei-Tou District, Taipei City, Taiwan, e-mail: *mjhsu@ym.edu.tw*. Reprints are not available from the author.

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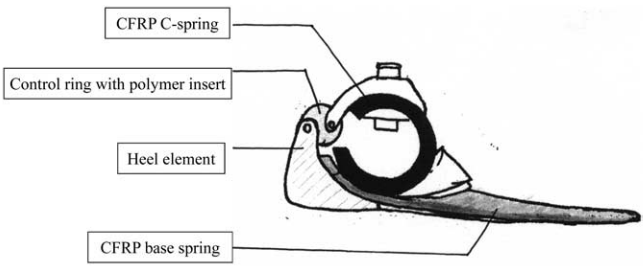

Fig 1. The basic structure of the C-Walk. Abbreviation: CFRP, carbon fiber reinforced plastic.

extent of the daily activities of people with transtibial amputation. The pedometer is a step-counter consisting of a miniature pendulum transducer that swings with each step and registers the number of steps on an internal counter. The pendulum mechanism is driven by oscillation of the pelvis during gait. The use of pedometers has shown promise in monitoring physical activity in various populations, including individuals with pathologic gait.[14-17] Pedometry may possibly be a useful tool to indicate the contrasts in physical activity levels due to the use of different types of prosthesis by individuals with transtibial amputation.

The purpose of this study was to investigate the physiologic differences in gait (energy expenditure, gait efficiency, exercise intensity, RPE) for the C-Walk, Flex-Foot, and solid ankle cushion heel (SACH) foot[b] during multispeed treadmill walking (53.64, 67.05, 80.46, 93.87, 107.28m/min, SSWV) in people with transtibial amputation. A secondary purpose involved pedometry determined foot-type comparisons of daily physical activity profiles. We hypothesized that the C-Walk and Flex-Foot were superior to the SACH foot on the parameters measured.

METHODS

We recruited eight men without significant medical problems other than unilateral traumatic transtibial amputation. Subjects had experience in prosthesis use for at least 1 year, were proficient walkers and had adequate exercise tolerance to achieve a treadmill walking speed of 107.28m/min without undue difficulty. The prestudy foot types of the subjects were 3 Flex-Foots, 2 ReFlex Vertical Shock Pylons, 1 SACH foot, 1 Flex-Walk, and 1 Icon-Allurion. We obtained written informed consent from each subject in accordance with the Human Subjects Review Committee of the College of Medicine at the University of Iowa prior to admittance into the study. Subjects were required to undergo 3 separate test sessions according to foot type (C-Walk, Flex-Foot, SACH foot). To ensure adequate prosthesis acclimation, subjects were asked to wear the relevant test foot for 4 weeks prior to laboratory testing.

Several prosthetists were involved in fitting and alignment of the prostheses. However, the same prosthetist was responsible for all 3 tested feet for a respective subject. Each subject used a standard socket for all 3 tested prosthetic feet. General selection criteria for a prosthetic foot were based on the subject's foot size and body weight. For the Flex-Foot, in addition to foot size and body weight, impact level (high, medium, low) based on the subject's physical activity level was also considered. As a general reference, the Day Activity Score inventory[18] was used to evaluate the physical activity level of the subjects. The descriptive data of subjects are presented in table 1.

A 2-factor (speed, type of prosthesis) repeated-measures design involving multiple speed treadmill walking (53.64, 67.05, 80.46, 93.87, 107.28m/min, SSWV) was employed for the physiologic assessment of each prosthesis. The dependent physiologic assessment variables included energy expenditure (oxygen consumption [in $mL \cdot kg^{-1} \cdot min^{-1}$]), gait efficiency, relative exercise intensity, and RPE. Gait efficiency was calculated from oxygen consumption divided by speed ($[mL \cdot kg^{-1} \cdot min^{-1}]/[m/min] = mL \cdot kg^{-1} \cdot m^{-1}$). The relative exercise intensity was expressed as (%APMHR = [exercise heart rate/age-predicted maximum heart rate] $\times$ 100). A repeated-measures design was used for daily activity and SSWV assessments. The dependent variables included the pedometers' mean step counts per day and the SSWV. The foot-type testing order was nonrandomized.

All subjects attended a preliminary session, which included general orientation to test procedures, familiarization with the RPE scale, practice of treadmill walking, instructions on using the pedometer and recording the daily activity log, and instructions on completing all necessary paperwork. In addition to the practice session, 3 test sessions on separate days at 1-month intervals were required. Each subject tested a single prosthesis per test session. The C-Walk was scheduled on either the first or the second test session, as was the SACH. The test order of these 2 prosthetic feet was counterbalanced between the first and the second sessions. In response to subjects' interest in and suggestions on the Flex-Foot, subjects were recruited back for a third test session, which was the Flex-Foot test. To ensure acclimation to the specific prosthesis for testing purposes, the subject wore the prosthesis to be tested for the month prior to each test session. During the same period, the subject was given a light-weight, battery-operated Yamax Digiwalker pedometer,[c] which he used to count his daily number of steps. The pedometer was positioned slightly anterior to the crest of the iliac on the side of the amputation. The subject put on the pedometer as soon as he arose in the morning; at the end of each day, he recorded the total steps for the day and reset the pedometer to zero for use the next morning. The subject was asked to continuously record each day's total for 1 month. The data from the pedometer were averaged and expressed as steps per day. To ensure the correct use of the pedometer, telephone follow-up calls were done.

Each of the test sessions involved an SSWV treadmill test and a multiple speed treadmill walking test. A 20-minute recovery period was provided between the SSWV test and the multiple speed treadmill test.

Table 1: Descriptive Data for the Subjects

Variable	Mean ± SD	Range
Age (y)	36±15	20–64
Body weight (kg)	81.71±9.64	61.5–95.5
Height (m)	1.75±0.06	1.64–1.82
Stump length (m)	0.15±0.03	0.12–0.19
Prosthesis experience (y)	16.6±17.9	1–55
Mass of C-Walk (kg)*	1.67±0.39	1.18–2.4
Mass of Flex-Foot (kg)*	1.76±0.31	1.1–2.1
Mass of SACH (kg)*	1.75±0.35	1.23–2.4
Day Activity Scale (U)†	33.3±6.8	21–43

Abbreviation: SD, standard deviation.
*Refers to the entire prosthetic limb.
†Day Activity Scale scores[18] range from −70 to 50 with following categories: very high, >30; high, 10 to 29; average, −1 to 9; restricted, −40 to −10; inactive, <−40.