JRRD
Volume 49, Number 8, 2012
Pages 1255–1260

Energy consumption during prosthetic walking and physical fitness in older hip disarticulation amputees

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Abstract—The objective of this study is to investigate energy consumption during prosthetic walking and physical fitness in older hip disarticulation (HD) subjects and to examine the ambulatory outcome in a community setting. The subjects were seven unilateral HD amputees with an average age of 67.7 +/– 3.9 yr. Energy consumption was measured during prosthetic walking at each individual's comfortable walking speed (CWS) by means of a portable telemetric system. An incremental exercise test was performed to evaluate fitness. The average CWS for the subjects was 30.5 +/– 9.6 m/min. The average oxygen consumption rate at each CWS was 18.3 +/– 2.4 mL/kg/min, and the average oxygen cost was 0.639 +/– 0.165 mL/kg/m. The maximum oxygen uptake during exercise as a proportion of predicted maximum oxygen uptake (%VO_2max) for the subjects was 57.2 +/– 11.1. Five subjects continued prosthetic walking on return to their communities. Two subjects abandoned prosthetic walking. The %VO_2max for the five who continued prosthetic walking after discharge ranged from 55.8 to 72.0. The subjects who abandoned prosthetic walking had lower %VO_2max of 43.3 and 44.2. Energy consumption during prosthetic walking at CWS seemed not to be excessive. Older HD amputees in good physical condition were able to successfully walk with a prosthesis in a community setting. A lower level of fitness appears to make community walking prohibitive.

Key words: comfortable walking speed, community, energy consumption, hip disarticulation, older amputee, physical burden, physical fitness, physical performance, prosthesis, rehabilitation.

INTRODUCTION

The low success rate for prosthetic walking among older hip disarticulation (HD) amputees is usually considered to be a result of the weight of the prosthesis itself and the increased energy consumption required for walking [1–3].· However, the advent in recent years of modular endoskeletal types of lower-limb prostheses has reduced prosthesis weight, thereby reducing the physical burden of prosthetic walking to some extent. But the increase in energy consumption during prosthetic walking in a person with a high amputation level is extreme and unavoidable [4–8]. In general, the underlying diseases leading to HD are malignancy, severe infections, and/or ischemia [2,9]. All subjects have serious diseases and undergo a deconditioning process that begins before their surgery and continues after. Young HD amputees with no serious underlying disease may recover from a deconditioned state relatively easily, giving them high probability of success in prosthetic walking [1–2,10–11].

Abbreviations: %VO_2max = maximum oxygen uptake during exercise as a proportion of predicted maximum oxygen uptake, CWS = comfortable walking speed, HD = hip disarticulation, VO_2 = oxygen uptake.

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http://dx.doi.org/10.1682/JRRD.2011.04.0067

In contrast, most older HD amputees have various coexisting conditions in all parts of their bodies, which add to the physiological deterioration brought about by age. They therefore experience difficulties recovering from their deconditioned state and maintaining the physical fitness required to walk with a prosthesis. Indeed, many researchers have reported that a level of physical fitness sufficient to meet the energy demands of prosthetic walking is required for practical success [12–14]. To our knowledge, besides our previous research, no other research specified the level of fitness needed for walking with a prosthesis. Our previous research demonstrated that the maximum oxygen uptake during exercise as a proportion of predicted maximum oxygen uptake (%VO_2max) value of 50 to 60 is a valid level of fitness required for an older transfemoral patient to walk with a prosthesis [15–16].

However, there have been very few reports investigating the energy consumption required for older HD amputees to walk with prostheses [3]. To the best of our knowledge, there have been no reports evaluating the physical fitness of such subjects, and thus, a deficiency in clinical information available for use in the rehabilitation of older HD amputees exists. The aim of this research was to investigate energy consumption during prosthetic walking, physical fitness, and ambulatory outcome in a community setting.

METHODS

Subjects

Seven consecutive HD amputees were included in this study. Subjects were all patients who were hospitalized at our center for prosthetic fitting and training and had never been fitted with prostheses before. The inclusion criteria were (1) age older than 60 yr; (2) capability of prosthetic walking for at least 5 min at a constant pace on discharge; (3) absence of neurological, coronary, pulmonary, and mental disorders that impede ambulation; and (4) well-controlled medical conditions. The average age of the subjects was 67.7 ± 3.9 yr (6 women, 1 man). The cause of amputation was malignancy in six cases and postoperative infection following joint replacement in one. None of the subjects had amputations because of vascular disease. Amputations had been performed by doctors at other institutions, and subjects were referred to our center for rehabilitation. Subject 4 had a medical history of stable angina and diabetic mellitus, but no severe coexisting medical conditions affecting prosthetic rehabilitation process were observed in the other subjects.

All subjects had been fitted with endoskeletal HD prostheses at our center. The characteristics of subjects and types of temporary prostheses prescribed are shown in **Table 1** and **Table 2**, respectively.

Evaluation of Fitness

HD amputees were subjected to a one-leg cycling test driven by their nonamputated leg. This test was conducted 1 day before the subjects began prosthetic rehabilitation. This method has already been reported in Chin et al. [17]. A cycle ergometer (Angio WLP-300ST, Lode; Groningen, the Netherlands), which can be used from a supine position, was used. The tests were conducted with the subjects seated with their upper bodies reclining at an angle of approximately 45°. This incremental exercise test began with 3 min of unloaded pedaling, followed by incremental increases of 10 W/min until the subject's self-assessed maximum load

Table 1.
Characteristics of subjects.

Subject	Sex	Age (yr)	Weight (kg)	Height (cm)	Cause of Amputation	Time Between Amputation and Prosthetic Fitting (wk)
1	M	61	60	160	Tumor	13
2	F	69	42	153	Tumor	8
3	F	71	43	158	Tumor	11
4	F	67	51	155	Infection	26
5	F	65	44	155	Tumor	7
6	F	68	68	159	Tumor	10
7	F	73	50	154	Tumor	19

F = female, M = male.

Table 2.
Types of prostheses prescribed.

Subject	Prosthesis			Mass of Prosthesis (kg)
	Hip Joint	Knee Joint	Foot	
1	Stride Control	Pneumatic	Single Axis	4.0
2	Stride Control	Pneumatic	Single Axis	4.0
3	Stride Control	Pneumatic	Single Axis	4.0
4	Stride Control	Manual Knee Lock	Single Axis	3.6
5	Stride Control	Pneumatic	Single Axis	4.0
6	Stride Control	Pneumatic	Single Axis	4.0
7	Stride Control	Pneumatic	Single Axis	4.0

was reached. The test subjects were directed to turn the pedals 60 times per minute. Each subject drove the ergometer with his/her nonamputated leg. During exercise, respiratory gas was monitored with a respiromonitor (RM-300 system, Minato; Osaka, Japan) to measure oxygen uptake (VO_2). At the same time, electrocardiogram and heart rate were monitored by the Stress Test system (ML-5000, Fukuda Denshi; Tokyo, Japan), and cuff blood pressure was determined every minute using an autoelectrocardiometer (STPB-780, Colin; San Antonio, Texas).

The $\%VO_2max$ was used as an indicator of physical fitness. The predicted maximum VO_2 was calculated using the equation of Bruce et al. [18]. Predictions in milliliters per kilogram per minute were as follows:

1. Active men: $VO_2max = 69.7 – 0.612 \times$ (years of age)
2. Active women: $VO_2max = 44.4 – 0.343 \times$ (years of age).

Measurement of Walking Energy Consumption

After completion of prosthetic rehabilitation, we measured energy expenditure during ambulation. All subjects were capable of prosthetic walking for at least 5 min at a constant pace. The comfortable walking speed (CWS) of each subject was measured prior to testing. The general aspects of prosthetic rehabilitation in our center emphasized acclimatization to prosthetic use, bearing an adequate amount of body weight on the prosthesis, and correction of abnormal walking patterns. When amputees could overcome these problems and achieve a walking speed within a certain range that suited them using necessary ambulatory aid, prosthetic rehabilitation was completed.

The subjects first sat for 15 min before testing, and then they were instructed to walk at a comfortable speed. The test walk lasted 5 min. Each subject walked around a rectangular track with a circumference of 100 m. During the test walk, the subject's respiratory gas was measured by a portable telemetric system (subjects 1–4: K4 system, COSMED; Rome, Italy; subjects 5–7: V2000 system, Medical Graphics Co. Ltd; St. Paul, Minnesota) to obtain VO_2. The mean value of the last 2 min of the test walk was taken as the measurement value at that speed.

Evaluation of Prosthetic Walking Capacity

It was difficult to define a precise prosthetic walking capacity in a community setting. Subjects were permitted to use any necessary ambulatory aid. In this study, an HD subject walking outside in individual home environments with a prosthesis after discharge was defined as a community ambulator. Prosthetic walking capacity in a community setting was assessed through in-person interviews 1 month after discharge.

RESULTS

The average CWS for the subjects was 30.5 ± 9.6 m/min (0.5 ± 0.1 m/s). The average oxygen consumption rate value at each CWS was 18.3 ± 2.4 mL/kg/min, and the average oxygen cost value at each CWS was 0.639 ± 0.165 mL/kg/m. The $\%VO_2max$ value for the subjects was 57.2 ± 11.1. The results of metabolic measurements for each subject are shown in **Table 3**. Subjects 1 and 4 abandoned prosthetic walking. All other subjects continued prosthetic walking upon return to their communities after discharge.

DISCUSSION

The success rate for prosthetic walking in older lower-limb amputees declines as the level of amputation becomes more proximal [5–6,12,19]. One of the main reasons for this is that energy consumption during prosthetic walking increases when the amputation level becomes more proximal. Reports by various researchers state that the energy consumption, expressed as an oxygen consumption rate (per unit time), of transfemoral amputees during prosthetic walking was 11.7 to 14.0 mL/kg/min [20–23]. In an investigation of energy consumption in eight HD cases with an average age of 36.7 yr, Nowroozi et al. reported an average

Table 3.
Results of metabolic measurements for each subject.

Subject	CWS (m/min)	Oxygen Consumption Rate ± SE (mL/kg/min)	Oxygen Cost ± SE (mL/kg/m)	$\%VO_2max$
1	30	18.0 ± 0.8	0.600 ± 0.151	44.2
2	35	20.5 ± 1.2	0.587 ± 0.037	55.8
3	27	18.3 ± 2.1	0.679 ± 0.078	56.5
4	17	13.9 ± 0.8	0.822 ± 0.052	43.3
5	47	20.4 ± 2.3	0.435 ± 0.049	59.6
6	23	20.1 ± 1.4	0.878 ± 0.062	69.6
7	35	16.6 ± 0.5	0.475 ± 0.057	72.0

$\%VO_2max$ = maximum oxygen uptake during exercise as a proportion of predicted maximum oxygen uptake, CWS = comfortable walking speed. SE = standard error of the mean.

oxygen consumption rate of 11.1 mL/kg/min and an average oxygen cost of 0.237 mL/kg/m at the average CWS of 47.4 m/min (0.79 m/s) [1]. McAnelly et al. reported on the energy consumption of a 73 yr old HD patient [3]. That report put the oxygen consumption rate at 11 mL/kg/min and the oxygen cost at 0.52 mL/kg/m at the patient's CWS of 21.0 m/min (0.35 m/s).

Since oxygen cost is the volume of oxygen consumption per unit distance and body weight and can be regarded as the true expression of energy consumption, oxygen cost was used to compare subjects in this study with those in previous reports. The subjects' average oxygen costs were not substantially different from that reported by McAnelly et al. [3], which is natural because the subjects' ages and CWSs were very similar. However, the subjects' average oxygen costs were 2.6 times higher than that reported by Nowroozi et al. [1], indicating a great increase in energy consumption. This disparity occurred because subjects were much younger and CWS was faster in Nowroozi et al.'s study [1]. These figures clearly show the inefficiency of older HD patients' prosthetic walking in terms of energy consumption.

Amputees are able to modify their walking speed in line with their own physical fitness in order to minimize the energy consumption involved in prosthetic walking [1]. Morey et al. reported that peak VO_2 was most strongly associated with physical performance in the elderly, and gave 18 mL/kg/min as a guideline oxygen consumption rate for the minimum exercise needed for the performance of daily tasks in the elderly aged 65 to 90 yr [24]. The subjects in this research had an average oxygen consumption rate of 18.3 mL/kg/min for prosthetic walking at CWS, which roughly corresponds with Morey et al.'s suggestions. Therefore, when older HD subjects walk at their own CWS, energy required for prosthetic walking seemed not to be an excessive physical burden.

In this study, five subjects continued prosthetic walking upon return to their communities after discharge. However, two subjects abandoned prosthetic walking. The $\%VO_2$max value for the five who continued to use their prostheses after discharge ranged from 55.8 to 72.0. We have previously reported that $\%VO_2$max value of 50 to 60 is a valid guideline for the physical fitness required for elderly transfemoral amputees to walk independently [15–16]. Of the elderly transfemoral amputees with $\%VO_2$max values more than 50, 93.7 percent (30/32) were able to walk independently [16]. The values for the physical fitness of those who continued prosthetic walking in a community setting are close to the guideline. In general, the vast majority of older HD subjects have comorbidities that are associated with a lower physical state. In this study, none of the participants had amputations because of vascular disease, and the prevalence of comorbidities in these five subjects was low. Thus, older HD subjects who are in good physical condition and have few comorbidities appear to be rehabilitative and can be community ambulators. On the other hand, subjects who abandoned the prosthesis had lower $\%VO_2$max values of 43.3 and 44.2. Subject 4 was suffering from a postoperative infectious reaction for a long time following hip joint replacement before amputation surgery. In addition, because of coexisting heart disease and diabetic mellitus, it was not easy for her to recover from a deconditioned state despite spending more time in rehabilitation than other subjects. As a result, subject 4 needed a different type of prosthesis (manual lock knee) and had dramatically lower CWS. On the other hand, subject 1 had no serious coexisting condition and no particular medical history that would prevent adequate recovery of fitness. His physiological deterioration might be the contributing factor. Because of their lower $\%VO_2$max, both subjects were using a high percentage of their total capacity. Thus, a low level of physical ability may make walking prohibitive in older HD subjects.

Burger et al. and Schoppen et al. previously demonstrated that the ability to balance on one leg on the unaffected limb was the most important factor for prosthetic ambulatory success [25–26]. In terms of ability of balance, there was no significant difference among all subjects.

Van der Windt et al. suggested studying the energy cost during walking in amputees after assessment of maximum exercise capacity [10]. The present study is the first investigation attempting to clarify the physical fitness and energy consumption during prosthetic walking in older HD subjects. Since prosthetic rehabilitation of older HD subjects is a specialized area, sample size was small. This is a weakness in this study, and care should be taken in generalizing these results. However, our preliminary study demonstrated that energy consumption required for prosthetic walking at each CWS seemed not to be excessive and suggested that older HD subjects in good physical condition appeared to have the potential to be community ambulators.

CONCLUSIONS

This research showed the inefficiency of older HD amputees' prosthetic walking in terms of energy consumption. Although small sample size is a weakness in this study, this research demonstrated older HD amputees in good physical condition and with a low prevalence of comorbidities were able to successfully walk with a prosthesis in a community setting. We suggest that physical fitness of around 60%VO_2max is necessary for older HD amputees to successfully walk. Because of lower %VO_2max, HD amputees were using a high percentage of their total capacity. Thus, a low level of physical ability may make walking prohibitive in older HD amputees.

ACKNOWLEDGMENTS

Author Contributions:
Study concept and design: T. Chin.
Acquisition of data: T. Chin.
Analysis and interpretation of data: T. Chin, T. Iguchi.
Drafting of manuscript: T. Chin.
Critical revision of manuscript: R. Kuroda, T. Akisue, M. Kurosaka.
Financial Disclosures: The authors have declared that no competing interests exist.
Funding/Support: This material was unfunded at the time of manuscript preparation.
Institutional Review: Informed consent was obtained from each subject. The study methods were approved by our local institutional review board.
Participant Follow-Up: The authors plan to notify subjects whose contact information is available of the publication of this article.

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Submitted for publication April 6, 2011. Accepted in revised form January 9, 2012.

This article and any supplementary material should be cited as follows:
Chin T, Kuroda R, Akisue T, Iguchi T, Kurosaka M. Energy consumption during prosthetic walking and physical fitness in older hip disarticulation amputees. J Rehabil Res Dev. 2012;49(8):1255–60.
http://dx.doi.org/10.1682/JRRD.2011.04.0067