Energy expenditure of transfemoral amputees walking on a horizontal and tilted treadmill simulating different outdoor walking conditions

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Abstract

Background and aim: Transfemoral amputees often report that walking on tilted pavements or in terrain with the prosthesis on the highest side is quite strenuous. This study investigates the energy expenditure of transfemoral amputees (n=8) walking on altered treadmill positions simulating different outdoor walking conditions.

Method: Oxygen uptake at self selected speed of gait was measured during walking at three different treadmill positions: (I) Horizontal treadmill, (II) 3 % tilt in the sagittal plane and (III) 3 % tilt in both the sagittal and frontal plane of the treadmill.

Results: The difference in oxygen uptake between position I and II was in median 4,3%, and 16,4% between position II and III ($p \leq 0,05$ for all comparisons). The subjects utilized about 50% of their $VO_{2\ max}$ when walking in position I and II while energy expenditure increased to about 60% of the amputees VO_{2max} when walking in position III.

Conclusion: Transfemoral amputees use significantly more energy when walking on a moderately tilted surface in the frontal plane compared to walking with a tilt in the sagittal plane only. The prosthetic leg becomes functionally too long when the walking surface is tilted sideways, and the transfemoral amputees adopt a more energy consuming gait pattern.

Introduction

Being able to walk in different terrains has been pointed out as important by the transfemoral amputees (1). For healthy individuals walking on flat ground requires only a modest effort. Ambulation with transfemoral prosthesis is significantly more energy consuming at all walking speeds compared to non-amputees (2). It is also reported that the more proximal the amputation level, the greater the physical exertion of walking (2-5). Consequently, the level of energy expenditure required to perform normal physical activities may limit the transfemoral amputees' activity level and the type of activities they can participate in (6).

When transfemoral amputees walks on pavements or in rising terrain where the ground is tilting sideways with the highest side under the prosthetic foot, they often modify their gait pattern and adopt to gait deviations such as circumduction, hip-hiking and vaulting due to the prosthetic leg becoming functionally too long (7, 8). Inability to adapt to tilted surfaces can be a result of several factors, i.e. reduction in hip flexion due to a weakened muscle apparatus after the amputation or restrictions from the prosthetic socket, lack of optimal knee flexion and timing in the prosthetic knee joint, and total loss of active ankle dorsiflexion in the prosthetic foot (8). Walking in rising and tilting terrain is often mentioned by the transfemoral amputee to be particularly strenuous when walking with their prosthesis outdoor. One possible explanation is that transfemoral amputees utilize more energy walking on uneven and tilted surfaces compared to walking on flat grounds due to the described gait deviations.

The authors have not been able to find any publications addressing this issue. An interesting question is whether minor tilts of the walking surface give significant differences in the energy expenditure for transfemoral amputees?

This study therefore investigate the energy expenditure (oxygen uptake; VO_2 ml kg^{-1} min^{-1}), the walking economy (VO_2 ml kg^{-1} $meter^{-1}$) and ratings of perceived exertion (Borg Cr 10 test), amongst transfemoral amputees during walking on a motorized treadmill (9). Due to the, practical difficulties obtaining reliable measurements of energy expenditure and walking economy in a field setting, it was chosen to simulate outdoor walking situations in a controllable laboratory setting. A treadmill was randomly set in three different positions; a horizontal position (position I), a position with inclination (position II) and a position with both inclination and sideways tilt with the prosthesis at the highest side (position III).

The maximal aerobic capacity (Vo_{2max}) was measured for each individual to investigate what proportions they use of their total capacity when walking in the three different treadmill positions.

The ratio between carbondioxide (VCO_2) production and the oxygen (VO_2) consumption, the “respiratory exchange ratio” (RER) was also calculated under the different treadmill positions. RER is an indicator of which energy substrate (carbohydrate or fat), that supply the body with energy under different types of physical activity, and consequently it is interesting to investigate which energy substrate is the dominant energy source during ordinary walking with a modest inclination and sideways tilt.

The authors are not aware of any studies that have investigated differences in energy expenditure and walking economy by manipulating the actual walking conditions by sideway tilt and inclination on a treadmill, nor are we aware of studies of the maximal oxygen uptake (VO_{2max}) of transfemoral amputees following an incremental gait protocol carried out on a treadmill.

Thus, the research question of the present study is:

Are there any differences in energy expenditure and walking economy during walking with transfemoral prosthesis on a horizontal treadmill and a treadmill moderately tilted in the sagittal and frontal plane?

Materials and methods

Subjects

Eight healthy *s*ubjects volunteered to participate in this study. They were recruited through certified prosthetists in the east of Norway (n=5) and through advertisement in a magazine published by the Norwegian Association for Amputees (n=3). Characteristics of the subjects are shown in table 1. Inclusion criteria were to have a unilateral transfemoral amputation for at least 2 years for reasons other than vascular disease, being at an age between 20 and 65 years, and using the prosthesis on a daily basis. In order to assure that the subjects had a good prosthetic function and was physically capable of accomplishing the treadmill test, they also had to be able to walk continuously for at least 500 meters and be able to walk in moderately uneven terrain. None of the participants had musculoskeletal diseases or other conditions limiting their functional mobility.

TABLE 1:

Study design and procedure

An experimental design was chosen for the study, where each subjects responses to three different walking positions of a motorized treadmill (Woodway ELG70, Woodway, Germany), were compared in a random order (figure 1).

FIGURE 1:

Before inclusion the subjects answered two questionnaires: One about their health status, and one about their prosthetic usage and how they evaluated their physical fitness. Prior to data collection, the subjects walked for approximately 5 minutes on the treadmill to determine their self-selected speed of gait (10). The speed adopted by each individual was then monitored and utilized on the treadmill during all the following experimental situations. This study has been approved by the Regional Committee for Medical Research Ethics (REK) and the Norwegian Social Science Data Services (NSD). Written informed consent was obtained from all subjects.

Experimental situation

The sequence of testing started for all the subjects by measuring their maximal aerobic capacity (VO_{2max}) by a modified Naughton protocol (11). In short: The subjects started by walking on a horizontal treadmill at their self-selected speed for 10 minutes. Following this warm-up procedure, the inclination of the treadmill was increased by 3 % every 3 rd minute until exhaustion, while the speed was kept constant. In general, VO_{2max} was reached within 10-15 minutes following this protocol. After the VO_{2max} test, the subjects rested for a minimum of 30 minutes before the experiments in treadmill position I – II and III started. These tests were performed in a randomized order. In walking position I the subjects were walking on a horizontal treadmill. Position II was walking on a treadmill with 3 % inclination in the sagittal plane, and in position III the subjects were walking on a treadmill with 3 % inclination in the sagittal plane and 3 % tilt in the frontal plane with the prosthesis at the highest side. Three percent tilt in both planes is considered to be a very modest difference walking in terrain compared to walking on flat ground, even for a transfemoral amputee.

Measurements

Ventilatory (VE) and respiratory (VO_2,VCO_2) data during treadmill walking was collected during the last five minutes (steady state) of each experiment by a stationary ergospirometer (Sensor Medics Vmax229n, CA, USA). Heart rate was monitored by a Polar heart rate monitor (Polar Electro, Finland) and the Borg CR10 Scale was utilized to investigate the subjects' perceived exertion during the experiments (9). Between experiments, the subjects rested for 30 minutes to insure that they had resting heart rate and no muscle fatigue prior to the start of their next test.

Statistics

The data were analyzed by the SPSS version 16.0. The data was not normally distributed. Consequently descriptive statistics are given in median, min-max values and the Wilcoxon Signed Rank test was used to test for within group differences in oxygen consumption, walking economy, respiratory exchange ratio (RER) and Borg CR10 scores between experimental situations I, II and III. Spearman Rank Order test was utilized to analyse for correlations between variables. Statistical significance level was set at $p \leq 0.05$.

Results

Description of the subjects

Six of the eight subjects in the present study reported having hobbies that demanded physical activity. Six subjects reported that they walked at least 2000 m per day (table 1). All subjects except one stated that walking on tilted and uneven ground was difficult (data not shown).

Physiological responses during testing

The subjects' median (min-max) values following maximal exercise testing were for VO_{2max} 23.8 (18.3 - 43.0) ml kg^{-1} min^{-1}, for VE_{max} 52.5 (28.9 – 99.4) L min^{-1} , for HR_{max} 170 (148 – 196) beats min^{-1} , for RER_{max} 1.06 (0.97 – 1.10) and for $BORG_{max}$ 9.0 (5.0 – 10.0), indicating that VO_{2max} was achieved following the incremental treadmill protocol. The percentage of the subjects' maximal aerobic capacity (VO_{2max}) during walking in the three different treadmill positions is shown in table 2.

TABLE 2:

The average oxygen uptake (ml kg^{-1} min^{-1}) when walking at self selected speed in position III was significantly higher compared to the oxygen uptake in position I and II, the difference being 20,7 % from position I to III, 16.4 %, from position II to III and 4,3 % from position I to II, respectively ($p \leq 0.05$ for all comparisons).

Walking economy and respiratory exchange ratio (RER)

The oxygen cost of walking per meter distance (ml kg^{-1} m^{-1}), when walking in position III, was 27.3 % higher compared to the oxygen cost walking in position I ($p \leq 0.05$). The oxygen cost was 9.1 % higher in position II compared to position I ($p \leq 0.05$) and 16.7 % higher in position III compared to position II ($p \leq 0.05$). The relationship between the walking economy at different treadmill positions and the subjects self selected speed of walking is shown in figure 2.

FIGURE 2:

There was no association between the subjects´ VO_{2max} and the walking economy during treadmill walking, demonstrating that the walking economy of transfemoral amputees is determined by other factors than the *maximal* aerobic capacity. There was, however, a statistically significant correlation between VO_{2max} (ml kg^{-1} min^{-1}) and self reported daily walking distance of $r = 0.61$ ($p \leq 0.01$), demonstrating a good relationship between the subjects maximal aerobic capacity and their ability to walk long distances.

Respiratory exchange ratio (RER) was found to be significantly higher in position II and III compared to position I (both comparisons, $p \leq 0.05$) and carbohydrate was the preferred energy substrate during walking in all positions.

Discussion

Our study show that it is significantly more energy consuming for transfemoral amputees` to walk on a treadmill with a small inclination and sideways tilt compared to walking on a horizontal treadmill. Furthermore the results confirm that it is more energy consuming to walk on a small sideways tilt with the highest side under the prosthetic foot compared to walking on a small inclination.

This is also supported by the subjects' ratings of perceived exertion and the heart rate data. A possible explanation for this increase in oxygen consumption may be that the prosthetic leg becomes functionally too long during treadmill walking with a sideways tilt. The amputee is not able to increase the flexion of the hip and knee, and utilize an active plantar and dorsal flexion of the foot according to the needs for walking under these circumstances. Thus, transfemoral amputees are forced to modify their gait pattern and adopt to gait deviations like circumduction, hip-hiking and vaulting to be able to move forwards. These gait deviations has been shown to be very energy consuming (7, 8).

To place these findings into a more comprehensive perspective it is interesting to compare the oxygen consumption of our group of transfemoral amputees during treadmill walking to that of able- bodied persons. In this respect, Waters and Mulroy (2004), describes the mean percentage of VO_{2max} in normal walking on a horizontal surface for able-bodied in approximately the same age group as our subjects,

(age 20 – 59), to be in average 31% (2). The average for our test group was about 50 %. The able bodied subjects in the study of Waters and Mulroy (2004) walked at a controlled walking speed of 1, 3 m sec^{-1} which is well above the average speed in our test group, being 0, 78 $msec^{-1}$.

Knowing that energy consumption increase with speed of gait, we can conclude that walking with a prosthesis is quite energy consuming, and that the transfemoral amputees use a higher proportion of their maximal aerobic capacity at a lower speed of gait compared to non amputees during ordinary walking on a horizontal walking surface. These findings are supported by earlier studies (3).

The average VO_{2max} of the subjects in the present study was ~24 ml kg^{-1} min^{-1}. This is considerably lower than average values for able-bodied subjects with similar age and gender (12). In this respect, we are aware of only one other study that have investigated the VO_{2max} of transfemoral amputees, and the values reported in the present study is about 25 % higher than in the study of Chin et al (13). Thus, it is quite possible that the subjects in the present study were more fit than the group of amputees in the previous mentioned study (13).

The differences in VO_{2max} values between our study and the study of Chin et al may also partly be explained by dissimilar test protocols used on the subjects. In their study, Chin et al. (2002) used one legged reclining bicycle ergometry, while the present study used treadmill walking with progressively increasing inclination.

In general, VO_{2max} increases with magnitude of active muscle mass (14), therefore it may be that one legged cycling which presumably activates less muscle mass than treadmill walking, underestimates the VO_{2max} of transfemoral amputees. This indicates the need for a standard protocol for VO_{2max} testing of transfemoral amputees.

If we take our findings further and investigate the subjects walking economy (VO_2 ml kg^{-1} m^{-1}) we can see in this study that the average walking economy on a horizontal treadmill was 0.22 ml kg^{-1} m^{-1} for our subjects.

The walking economy of adult able bodied persons at self selected speed of gait is reported to be approximately 0.15 ml kg^{-1} m^{-1} (11) and this is comparable to unpublished data from our own laboratory. Consequently, on level ground and walking at their most economic and at preferred speed, transfemoral amputees consume in average about 47 % more oxygen per meter than able bodied subjects do. One would normally expect that a poor walking economy would restrict the subject's daily walking range, as femoral amputees probably would develop muscular fatigue earlier than able bodied persons. The average walking distance of the subjects in the present study was about 2000 m day^{-1}, which is about half the distance reported for able bodied American men and women (15). One subject with a VO_{2max} of 44 ml kg^{-1} min^{-1}, however, walked as much as 10 000 m day^{-1} and if we look at the correlation between the transfemoral amputees maximal aerobic capacity (VO_{2max}) and their daily walking distance we found a correlation coefficient of $r = 0.61$, demonstrating that the physical activity level of transfemoral amputees is an important factor for their ambulatory capacity. In this regard, we observe that the subjects walking economy improve with increasing speed of walking (figure 2). Thus, the slowest moving transfemoral amputees in the present study expend much more energy than the faster moving subjects. Interestingly, when the subjects' speed of gait is faster than approximately 0.8 m sec^{-1}, there is little difference in the walking economy between the subjects, regardless of their walking speed. In a clinical view, these findings might be partly explained by the prosthetic design chosen to the individual patient. If the prosthetic alignment or choice of components is not optimal, this will restrain the prosthetic users from walking with the gait pattern and the speed of gait that gives the best walking economy.

Regarding the energy consumption, it is also interesting to look at the relative contribution of fat and carbohydrate combustion to the energy expenditure during the subjects walking in position I, II and III. In position I, 58 % of the total energy demand was supplied by carbohydrate combustion, while by comparison, carbohydrate supplied only 47 % of the energy demand for able bodied subjects during level walking at their self selected speed of gait (10).

The transfemoral amputees' reliance on carbohydrate combustion increased when walking in position II and III, supplying 74 and 81 % of the total energy demand, respectively. Thus, transfemoral amputees must rely heavily on carbohydrate combustion during walking conditions that most able bodied subjects would characterize as only moderately strenuous. Since carbohydrate stores in skeletal muscle may be limited, a high rate of carbohydrate utilization may influence the endurance capacity of transfemoral amputees also during ordinary walking.

Clinically our findings indicate that the transfemoral amputee generally use a lot of energy even during ordinary walking. This is not novel knowledge, but the results from the present study also tell us that when this group of amputees walks on minor tilted terrain, they use a surprisingly large amount of their aerobic capacity. For example, most pavements are tilted much more than 3% indicating that the transfemoral amputee has a strenuous task walking under what could be called non-strenuous outdoor conditions. A solution to the problem we have investigated in this study might therefore be to avoid the increase in functional leg length that amputees experience under these walking conditions.

This might be overcome by making a prosthetic design for transfemoral amputees incorporating an adjustable leg length so that the amputee can choose to shorten the prosthesis in situations where it becomes functionally too long. It is also important that the choice of prosthetic components makes it possible for the amputees to walk in their self selected speed and with the optimal walking pattern providing the best walking economy.

Consequently, to achieve a better functional capacity during daily living, it is very important that the rehabilitation team together with the patient do a proper evaluation of the choice of prosthetic design, components and prosthetic alignment, having in mind the level of energy consumption for the individual patient. In parallel it should also be considered to take steps to increase the transfemoral amputees' cardiovascular fitness and muscle strength.

The main strength of this study is the experimental design where the different conditions the participants are exposed to are strictly controlled. The three conditions for an experiment are also met, including manipulation, randomization, and reducing intraindividual variation by the subjects being their own control. This gives a high internal validity (16). The fact that all our results point in one direction also strengthen the internal validity.

It is possible that our findings cannot be generalized due to the subjects being a group of fairly young/middle aged transfemoral amputees at good health and having the ability for prosthetic ambulation that exceeds basic demands.

At the same time the subjects are a very heterogeneous group of transfemoral amputees. It is therefore reason to believe that our results enlighten a problem that most likely will be even greater for the less healthy and older population of transfemoral amputees.

Conclusion

Our results confirm that transfemoral amputees with good functional ability at different ages and no cardiovascular disease use significantly more energy when walking with self selected speed on a moderately tilted treadmill in two planes compared to walking on a horizontal treadmill. It is also shown that the subjects use a great proportion of their maximal aerobic capacity (Vo_{2max}).

This indicates that being a transfemoral amputee trying to walk under what would be normal outdoor conditions for an able-bodied person, is very energy consuming. Despite that the subjects reported that they considered themselves of being generally physical fit, the measured Vo_{2max} was found to be lower than for able bodied persons with similar age and gender.

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Table 1: Characteristics of eight subjects with transfemoral amputation

Subjects (Gender)	Age, yrs	Height, cm	Weight, (kg) Incl. prosth.	Self rep. walking distance, m a day^{-1}	CWS #, m sec^{-1}	Years since amp.	Cause of amp.	Side of amp.
1 (F)	45	160	87	2000	0.90	36	Trauma	Left
2 (M)	61	172	84	2500	0.70	22	Cancer	Left
3 (M)	35	179	75	10000	1.20	35	Congenital	Left
4 (F)	49	176	72	1000	0.78	7	Cancer	Right
5 (F)	61	161	50	1500	0.52	21	Cancer	Right
6 (M)	54	180	83	2000	1.02	11	Infection	Left
7 (M)	22	180	125	4000	0.69	10	Cancer	Left
8 (F)	46	168	63	2000	0.78	32	Cancer	Left
Average	47.5	174	79	2000	0.78	21.5	-	-
min-max	22-61	160-180	50-125	10^3-10^4	0.52-1.20	7-36		

CWS = controlled walking speed

Table 2: Transfemoral amputees` physiological responses to treadmill walking in different positions; on a horizontal treadmill (Position I), with 3% inclination in the sagittal plane (Position II), with 3 % inclination in the sagittal plane and 3 % tilt in the frontal plane with the prosthesis at the highest side (Position lll).

	Position I Median (min-max)	**Position II** Median (min-max)	**Position III** Median (min-max)
Oxygen uptake ml kg^{-1} min^{-1}	*11.7 (10.5-13.0)*	*12.2 * (11.4-15.2)*	*14.2 $,# (12.8-16.8)*
Oxygen uptake in percent of VO_{2max}	*49.2 (30-56)*	*51.3* (35-64)*	*59.7 $,# (39-77)*
Walking economy ml kg^{-1} $meter^{-1}$	*0.22 (0.18-0.41)*	*0.24* (0.21-0.44)*	*0.28 $,# (0.23-0.47)*
Heart rate beats min^{-1}	*118 (109-140)*	*113 (103-139)*	*132 $,# (113-156)*
Borg score	*2.5 (1.5-3.5)*	*3.0 (1.5-4.5)*	*5.3 $,# (3.0-7.0)*
Respiratory exchange ratio	*0.87 (0.81-0.95)*	*0.92* (0.85-0.98)*	*0.94 $,# (0.83-1.0)*
Percent energy derived from carbohydrate	*58 (63-16)*	*74* (49-6)*	*81$,# (56-0)*

* p≤ 0, 05; Pos I vs. Pos II, $ p≤ 0, 05; Pos I vs. Pos III # p≤ 0, 05; Pos II vs. Pos III

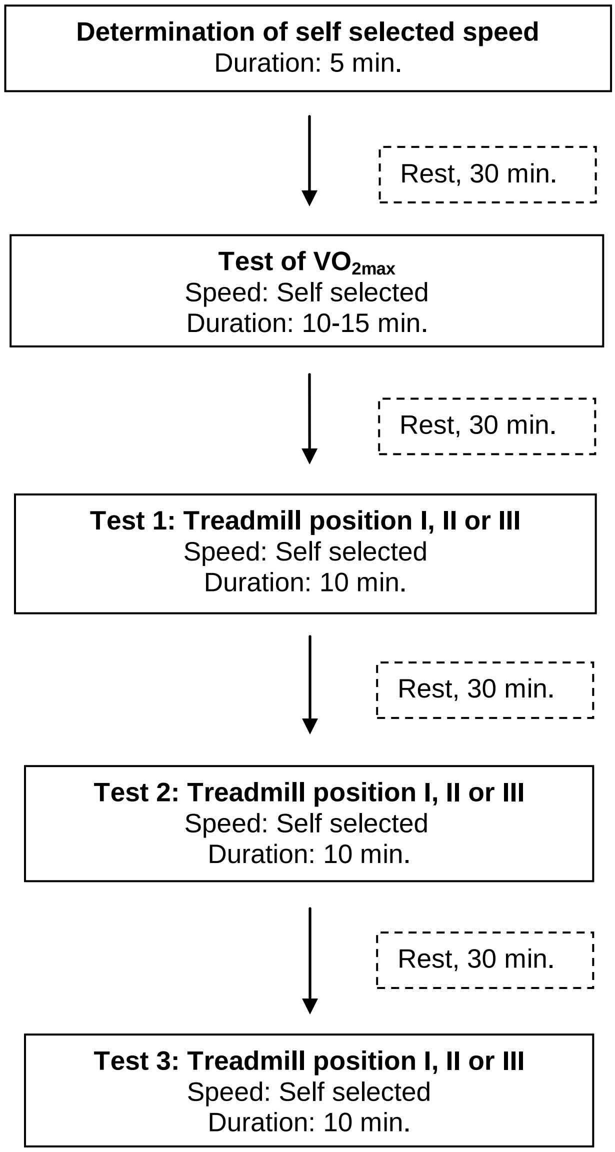

Figure 1: Experimental procedure

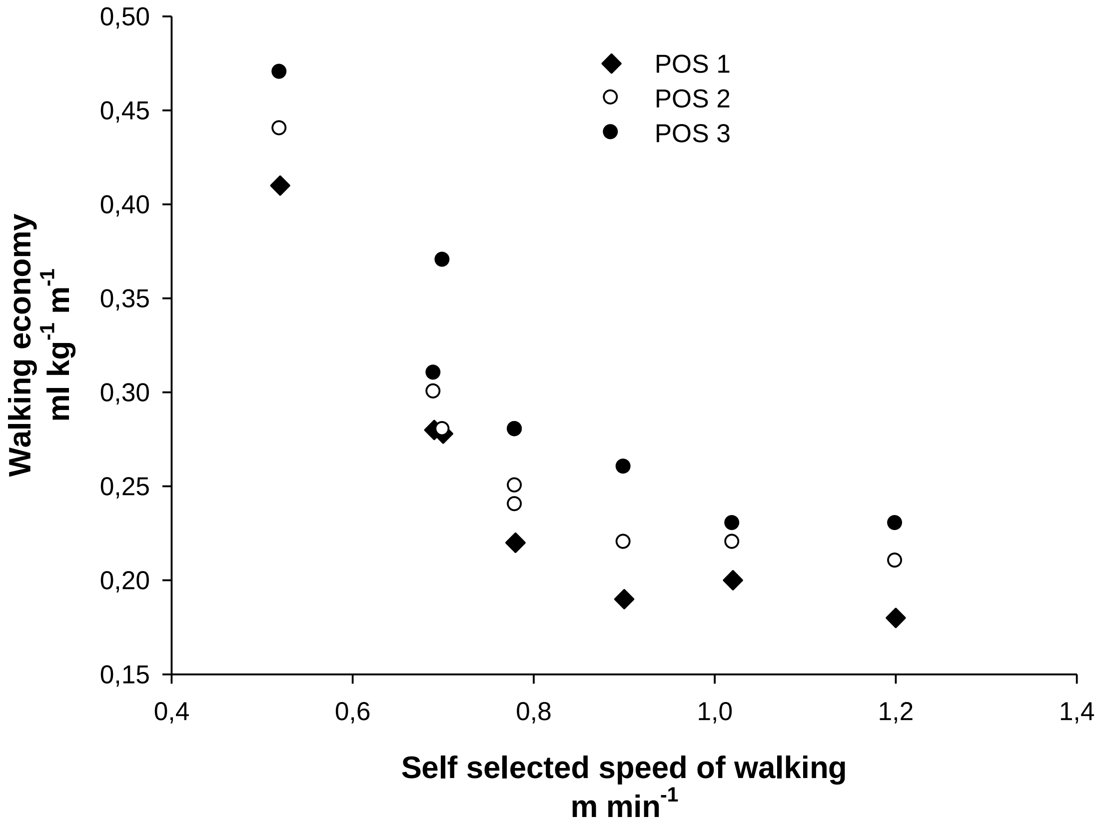

Figure 2: Relationship between walking economy and walking speed during different walking conditions for transfemoral amputees