Optimizing Prosthetic Gait

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Peak oxygen consumption in older adults with a lower limb amputation

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Abstract

The objective of this study was to investigate whether the aerobic capacity of older adults who underwent a lower limb amputation is associated with the presence, cause (traumatic or vascular), and level of amputation (trans-tibial or trans-femoral). A total of 36 older subjects who underwent lower limb amputation and age-matched (n=21) able-bodied controls participated. All subjects were able to walk for a minimum of 4 minutes. Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured using open-circuit respirometry while performing a discontinuous, graded, one-legged, peak cycle exercise test. After correcting for age, body mass index, and sex, the multiple linear regression analysis revealed that subjects who underwent amputation had a 13.1% lower aerobic capacity compared with able-bodied controls ($p = .021$). Differentiation among etiologies revealed that subjects with a vascular amputation had a lower $\dot{V}O_{2peak}$ of 29.1% compared with able-bodied controls ($p < .001$), whereas traumatic amputees did not differ from able-bodied controls ($p = .127$). After correcting for etiology, no association between level of amputation and $\dot{V}O_{2peak}$ was found ($p = .534$). Older adults who underwent an amputation because of vascular deficiency had a lower aerobic capacity compared with able-bodied controls and people with a traumatic amputation. The level of amputation was not associated with $\dot{V}O_{2peak}$.

Introduction

The problems associated with regaining walking ability after undergoing lower limb amputation can be multidimensional and, amongst others, be related to poor prosthetic fitting, stump problems, impaired cognitive ability [184], problems on the non-amputated side, and reduced balance [216]. In addition, there is evidence suggesting that a low peak oxygen consumption can negatively influence walking ability [22, 24-25, 184]. Peak aerobic capacity is defined as the highest peak oxygen consumption obtained during maximal effort exercise [40], and is known to decline with age [115]. This decline can be severely aggravated in people with an amputation because of a perioperative period of limited physical activity [207] or comorbidities. As a result, differences might exist between individuals who underwent amputation because of trauma or because of vascular deficiency. Additionally, peak aerobic capacity might be influenced by the level of amputation. It has been shown that the higher the level of amputation the lower the walking distance [80] and activity level in daily life [184], which might result in a lower peak aerobic capacity [226].

Numerous studies have investigated the oxygen demand for walking with a prosthesis [78, 81, 110, 209, 226]. In contrast, only a limited number of studies have focused on the available aerobic capacity [216]. To assess physical fitness, direct measurement of the oxygen consumption during a maximal exercise test remains the preferred method in not only in young and elderly people [115], but also in people after lower limb amputation. Chin and colleagues (2002 and 2006) [24-25] report the physical fitness of older adults with an amputation because of vascular deficiency by determining the proportion of the predicted maximum oxygen uptake that was reached during a maximal exercise test. Others have used similar prediction equations to determine the physical fitness of people with an amputation by using data obtained during submaximal exercise testing [122, 133, 226]. However, the exercise mode needs to be adapted when testing people with an amputation, and the amputee population differs from controls with respect to physical limitations, comorbidity, medication intake, and age. Therefore, using general prediction equations to evaluate aerobic capacity is not viewed as a valid approach when reporting results on peak aerobic capacity in older people with a lower limb amputation [5].

Even though a maximal exercise test is the most reliable method to determine subjects' peak aerobic capacity, the impaired motor system, reduced muscle mass, comorbidities and local problems in the stump as well as the contralateral limb make standard graded exercise testing impossible. To overcome these difficulties, we previously developed a protocol that allows for the safe and reliable determination of the peak aerobic capacity of people with an amputation using a widely available cycle ergometer that is driven with the intact leg [229].

3

The aim of the present study was to investigate the $\dot{V}O_{2peak}$ of older adults who underwent a lower limb amputation because of trauma or vascular deficiency by using a discontinuous, graded, one-legged, peak cycle exercise test. It was hypothesized that people who underwent lower limb amputation would have a lower $\dot{V}O_{2peak}$ compared with controls, and that the lowest level would be found in the group with a vascular amputation. Additionally, it was hypothesized that the level of amputation would influence $\dot{V}O_{2peak}$, with a more proximal amputation relating to a lower $\dot{V}O_{2peak}$. Multiple linear regression analysis was used to determine to what extent the presence of an amputation, cause of amputation (traumatic vs vascular), or level of amputation (trans-tibial vs trans-femoral) was associated with $\dot{V}O_{2peak}$.

Methods

Subjects

Potential subjects for this study underwent prosthetic rehabilitation after lower limb amputation between January 1992 and March 2009, and were currently known by the rehabilitation physician or prosthetist to walk with their prosthesis. From this list only those subjects were selected who (1) were aged between 50 and 75 years at the time of the study; (2) had undergone a unilateral amputation of the lower limb at the level of the lower leg (trans-tibial) or upper leg (trans-femoral); (3) had a time since amputation longer than one year; and (4) were able to ambulate for at least 4 minutes. Exclusion criteria were absolute contraindication for exercise [143, 146], impairment of cognitive function, and neurological problems. Before participation, all subjects underwent clinical screening by a physician.

A total of 37 subjects with a lower limb amputation agreed to participate. One subject showed abnormalities on the resting electrocardiogram (ECG) and complained of chest pain, and was excluded from the study. Of the remaining 36 subjects, 26 had amputations after trauma, with 16 subjects having amputations at the trans-tibial level and 10 at the trans-femoral. Of the 10 subjects who had amputations because of vascular deficiency 7 had amputations at the trans-tibial level and 3 at the trans-femoral level. An additional group of 21 able-bodied older controls (aged between 50 and 75 y) were recruited through an advertisement in a local newspaper. After both verbal and written clarification of the test protocol, subjects gave written informed consent. This study carried the approval of the Medical Ethical Review Board of the VU University Medical Centre in Amsterdam.

Exercise protocol

Before exercise, a resting ECG was performed and the blood pressure was recorded. The $\dot{V}O_{2peak}$ was determined using a graded, discontinuous, one-legged, exercise test, for which the feasibility and validity for this population had previously been verified [229]. During this test, subjects cycled with their nonamputated leg on an electronically braked cycle ergometer (Lode Corival, Lode BV, Groningen, The Netherlands), whereas in the able-bodied control group the exercising leg was randomly assigned. The graded peak exercise test was executed using a discontinuous protocol: each exercise phase lasted 90 seconds and was followed by 30 seconds of rest. After familiarization, start workload and increment steps were individually determined to ensure a test duration between 8 and 12 minutes [229]. Throughout the duration of the test, subjects were verbally encouraged. The test was ended when either pedaling frequency dropped below 50 revolutions per minute, a further rise in workload did not lead to an increase in oxygen uptake, irregularities on the ECG or extreme blood pressure alternations were noted, or when subjects indicated that they wanted to stop. The test protocol is described in more detail elsewhere [229]. Subjects were asked to refrain from drinking coffee and eating large meals on the day of the test, and not to be involved in excessive exercise in the 24 hours preceding the test.

Measurement

During the test, oxygen consumption was measured breath-by-breath using open-circuit respirometry (Oxycon Delta, CareFusion, Houten, The Netherlands). Breath-by-breath variability was attenuated using a three-breath smoothing average filter. The $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$), peak respiratory exchange ratio (RER_{peak}) and peak heart rate (HR_{peak}, $beats \cdot min^{-1}$) were determined as the highest value attained during the last or penultimate exercise phase. Predicted maximal heart rate was calculated using the equation proposed by Tanaka and colleagues (2001) [201], and used to determine the percentage of predicted maximal heart rate ($HR_{\%predicted}$) reached during the test. Peak power output (W) was determined as the highest workload completed by the subject. Body weight was determined as the total weight of the subject excluding the weight of the subjects' prosthesis.

Statistical analysis

All data were analyzed using a computerized statistical package (Version 16.0; Spss Inc. Chicago, IL, USA). Differences between groups in subject characteristics and outcome parameters were analyzed using a one-way analysis of variance, with a Bonferroni post hoc test to control for the multiple comparison. A

Pearson chi-square test was performed to determine whether the allocation to the different groups was independent of sex. To study whether $\dot{V}O_{2peak}$ was associated with the presence of an amputation, cause of amputation, and level of amputation, a multiple linear regression analysis was performed in which $\dot{V}O_{2peak}$ was the dependent variable and the possible influencing factors were the independent variables. As age, body mass index (BMI) and sex are independently related to $\dot{V}O_{2peak}$ [221], these three parameters were entered as confounders in the model. Visualization of the residuals of the regression model revealed skewness; therefore, $\dot{V}O_{2peak}$ was natural log-transformed to improve model fit. The linear equations determined by the multiple regression analysis had the following general form:

$$\ln(\dot{V}O_{2peak}) = \beta_0 + \beta_a \cdot age_i + \beta_b \cdot BMI_i + \beta_c \cdot sex_i + \sum_{j=1}^{m} \beta_j \cdot X_j + \varepsilon \qquad (1)$$

where the coefficients β_0, β_a, β_b and β_c are constants representing the coefficients associated with the confounding independent variables age, BMI, and sex, respectively, and ε indicates the random error. Subscript i indicates the subject. β_j is the coefficient associated with the independent variable of interest (X_j). The m represent the number of independent variables of interest entered in the model. Four models were constructed. The first model was used to determine whether the presence of an amputation was associated with $\dot{V}O_{2peak}$. This variable (amputation [yes/no]) was entered as an independent dummy variable in the first model (n = 57). To further determine whether differences in $\dot{V}O_{2peak}$ between people with an amputation and able-bodied controls could be explained by a difference in the cause of amputation, a second model was constructed with two dummy variables (traumatic [yes/no] and vascular [yes/no], n = 57). A similar third model was constructed with both levels of amputation (trans-tibial [yes/no] and trans-femoral [yes/no]) as independent variables (n = 57). To gain

Table 1. Subjects' characteristics.

	overall	control n = 21	traumatic n = 26 (TT = 16, TF = 10)	vascular n = 10 (TT = 7, TF = 3)
Age (years)	61.7 (6.1)	60.8 (5.9)	60.7 (5.6)	66.3 (5.9) *†
Sex (men/women)	40/17	14/7	18/8	8/2
Bodyweight (kg)	81.1 (15.0)	81.1 (14.3)	78.2 (12.5)	93.4 (17.9) *†
BMI ($kg \cdot m^{-2}$)	26.8 (4.8)	25.7 (3.7)	25.4 (3.6)	30.2 (7.1) *†
Years since amputation	n/a	n/a	36.2 (20.7)	3.8 (3.6) †

NOTE. Values are mean ± SD or n. Bodyweight is the weight of the person minus the weight of the prosthesis.
Abbreviations: n/a, not applicable; TF, trans-femoral; TT, trans-tibial.
* Significantly different from controls (p < .05).
† Significantly different from people with a traumatic amputation (p < .05).

insight into the possible effects of an uneven distribution of both cause and level of amputation among the different amputation groups, a final regression analysis (model 4, n = 36) was performed in which both the cause (traumatic or vascular) and level (trans-tibial or trans-femoral) were entered as independent dummy variables. For each associated independent variable, the percentage difference in $\dot{V}O_{2peak}$ was calculated when the independent variable is changed by one unit.

Results

The people with a vascular amputation were older ($p = .027$) and had a higher body weight ($p = .021$) and BMI ($p = .013$) compared with the people with a traumatic amputation and able-bodied controls. No differences between the latter two groups were found. Time after amputation differed significantly between amputee groups ($p < .001$). The allocation of subjects to the different groups was independent of sex ($\chi 2 = 0.596$, $p = .742$; Table 1). All subjects successfully completed the exercise test to exhaustion and all but four subjects reached RER_{peak} values of > 1.1, with a mean ± SD value over all subjects of 1.3 ±0.1 (Table 2). Peak power output was significantly lower in the group with a vascular amputation ($p < .001$). HR_{peak} was also lower in the vascular group; however, when expressed as a $HR_{\%predicted}$ [201] no differences were found ($p = .085$) among groups.

When correcting for age, BMI, and sex, the multiple linear regression model revealed that having a lower limb amputation was inversely associated with $\dot{V}O_{2peak}$ ($p = .021$, model 1). The presence of an amputation because of vascular deficiency was associated with a lower $\dot{V}O_{2peak}$ of 29.1% ($p < .001$), whereas a traumatic amputation was not significantly associated with a difference in

Table 2. Results for graded peak exercise test.

Peak values (mean ± SD)	overall	control n = 21	traumatic n = 26 (TT = 16, TF = 10)	vascular n = 10 (TT = 7, TF = 3)
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	27.2(9.2)	30.8 (10.3)	28.1 (6.7)	17.1 (4.1) *†
RER_{peak}	1.3(0.1)	1.3 (0.1)	1.3 (0.1)	1.2 (0.2) †
HR_{peak} ($beats \cdot min^{-1}$)	148.6 (19.8)	151.6 (16.5)	151.4 (20.5)	134.2 (21.0)
$HR_{\%predicted}$ (%)	89.9 (11.2)	91.6 (9.2)	91.2 (11.4)	82.9 (13.1)
P_{peak} (watt)	128.7 (40.2)	141.9 (36.3)	135.6 (36.9)	83.0 (22.1) *†

NOTE. Values are mean ± SD or n. Two traumatic and one vascular subject were using β-blockers and were therefore excluded in the calculation of HR_{peak} and $HR_{\%predicted}$.
Abbreviation: P_{peak}, peak power output; TF, trans-femoral; TT, trans-tibial.
* Significantly different from controls ($p < .05$).
† Significantly different from people with a traumatic amputation ($p < .05$).

3

Table 3. Multiple linear regression model.

Entered variables (X_i)		β-coefficients			F_{change}†(p)
		β_i (SE)	p	% change*	
Model 1 (n = 57)					5.66 (p = .021)
-amputation	yes(1)/no(0)	-0.140 (0.059)	.021	-13.1 %	
Model 2 (n = 57)					7.74 (p = .001)
-traumatic	yes(1)/no(0)	-0.086 (0.058)	.145	-8.2%	
-vascular	yes(1)/no(0)	-0.344 (0.087)	< .001	-29.1 %	
Model 3 (n = 57)					2.95 (p = .061)
-trans-tibial	yes(1)/no(0)	-0.156 (0.065)	.021	-14.4%	
-trans-femoral	yes (1)/no(0)	-0.113 (0.076)	.144	-10.7%	
Model 4 (n = 36)					5.16 (p = .021)
-cause	traumatic(1)/vascular(2)	-0.306 (0.098)	.004	-26.4 %	
-level	TT(1)/TF(2)	0.046 (0.074)	.534	4.7%	

NOTE. The parameters of interest entered in the multiple linear regression models are presented with corresponding values. The total model had the following general form: $\ln(\dot{V}O_{2peak}) = \beta_0 + \beta_a \cdot age_i + \beta_b \cdot BMI_i + \beta_c \cdot sex_i + \sum_{j=1}^{m} \beta_j \cdot X_j + \varepsilon$, where X_j represent the j-th entered variable of interest and age, BMI and sex were entered as confounders. Model 4 only included the two amputation groups.
Abbreviations: TT/TF, trans-tibial or trans-femoral; β_i, unstandardized beta coefficient; SE, standard error.
* The percentage change in $\dot{V}O_{2peak}$ when the independent variable is increased with one unit (e.g. those who underwent a lower limb amputation had a lower $\dot{V}O_{2peak}$ of 13.1%)

$\dot{V}O_{2peak}$ (p = .145, model 2; Table 3) compared with controls. The third model with level of amputation as independent dummy variables revealed that an amputation at the trans-tibial level was associated with a significantly lower $\dot{V}O_{2peak}$ (p = .021, model 3; Table 3). However, when entering cause and level of amputation (model 4), level of amputation failed to explain an additional significant proportion of the variance in $\dot{V}O_{2peak}$ in the amputee subjects (n = 36). In this analysis, having a vascular amputation was associated with a 26.4% decrease in $\dot{V}O_{2peak}$ (p = .004) compared with having an amputation because of trauma (model 4; see Table 3). To determine to what extent the association of cause of amputation with $\dot{V}O_{2peak}$ was related to the level of amputation, and vice versa, we added an interaction term (level*cause) to the fourth model. This interaction term was not significantly associated with the dependent variable (p = .488). Therefore, the association found between cause of amputation and $\dot{V}O_{2peak}$ seems to be independent of the level of amputation.

3

Discussion

We used a graded one-leg peak exercise test to determine the $\dot{V}O_{2peak}$ of people with a lower limb amputation. While controlling for the possible confounding effects of age, BMI, and sex, the multiple linear regression analysis revealed that people who underwent a lower limb amputation had, in general, a 13.1% lower aerobic capacity compared to controls. An additional analysis, differentiating between etiologies, revealed that people with a traumatic amputation did not differ from controls, whereas people with a vascular amputation had a significantly lower $\dot{V}O_{2peak}$ of 29.1%.

Chin and colleagues (1997, 2001 and 2002) [21-23] report values of $\dot{V}O_{2peak}$ between 18.0 and 20.1 $ml \cdot kg^{-1} \cdot min^{-1}$ for people with a traumatic amputation, which are lower than the values found in this study (28.1 $ml \cdot kg^{-1} \cdot min^{-1}$). A possible explanation might be a difference in time since amputation. In the studies by Chin and colleagues (2001 and 2002) [22-23] subjects underwent amputation more recently, which might explain the lower peak aerobic capacity found compared with our subjects. Pitetti and colleagues (1978) [171] studied seven young subjects with a traumatic amputation with an average time since amputation of 19 years and found that the average aerobic capacity increased from 23.1 to 29.4 $ml \cdot kg^{-1} \cdot min^{-1}$ after a 15-week training period. Remarkably, the values after training are comparable to the values found in the current study, even though subjects in the study by Pitetti and colleagues (1987) [171] were substantially younger.

The higher values found in the current study compared with those in the literature might imply that our traumatic amputees were extremely fit compared with previously studied subjects, but because none of the amputees were abnormally active, we deem this unlikely. A more plausible explanation might be that with the current set-up, we were able to stress the cardiopulmonary system to a larger extent and more closely approximate subjects' true maximal aerobic capacity. Compared to an upright bicycle, the recumbent bike used by Chin and colleagues (1997,2001 and 2002) [21-23] might have led to a reduced gravity-induced hydrostatic pressure, which could result in inadequate perfusion and oxygen delivery to the active muscles [62, 227]. Furthermore, the continuous protocol used by Chin and colleagues (1997,2001 and 2002) [21-23] might have caused premature feelings of local fatigue and consequently premature ending of the exercise test [21-23]. The notion that the cardiovascular system was stressed to its full potential in the current study is supported by the fact that the overall averaged RER_{peak} was 1.3 ± 0.1 indicating maximal aerobic effort.

Current findings corroborate the limited existing evidence and the intuitive notion that the aerobic capacity of people who have had lower limb amputation because of vascular deficiency is lower. The 29.1% lower $\dot{V}O_{2peak}$ might be explained by the fact that comorbidities, stump problems resulting from delayed wound healing, or persisting pain caused by claudication limit an active lifestyle [18, 184] and, consequently, lead to a lower $\dot{V}O_{2peak}$. In addition, people who undergo an amputation because of vascular deficiency might already have had a lower preoperative as a result of a sedentary life, smoking, or preexisting medical conditions [137]. To control for these influencing factors and to single out the effect of an amputation in this group of subjects, it would be of great value to in a future study to compare two group of subjects, both diagnosed with vascular deficiency, that differ only with respect to the existence of a lower limb amputation. With respect to the traumatic amputees, Chin and colleagues (2002) [23] found initial differences at the start of rehabilitation between able-bodied controls and traumatic amputees, but these differences disappeared after a 6 week aerobic training regimen. The traumatic amputees in the current study already walked with their prosthesis for a number of years, and were able to walk comfortably for at least 4 minutes. The familiar and correctly fitted prosthesis apparently enabled the traumatic subjects to adopt a relatively active lifestyle, resulting in an aerobic capacity similar to that of able-bodied controls.

Although a regression model with level of amputation entered as a dummy variable (model 3), revealed that subjects who underwent a trans-tibial amputation had a lower aerobic capacity compared to able-bodied controls and people with a trans-femoral amputation, this difference disappeared when a regression analysis was performed in which both cause and level were entered as independent variables (model 4). This might be explained by the fact that in the trans-femoral group, 23% of the subjects had amputations performed because of vascular deficiency, whereas in the trans-tibial group this was the case for 30% of the subjects. Therefore, the higher number of subjects with a vascular amputation in the trans-tibial group could explain the association between level and $\dot{V}O_{2peak}$ found in the third model.

The finding of no association between $\dot{V}O_{2peak}$ and the level of amputation was found was surprising and contrary to what has been reported by Waters and colleagues (1976) [226]. They state that a more proximal amputation is related to a lower predicted peak aerobic capacity. However, their findings were not substantiated by a statistical test. Moreover, Waters and colleagues (1976) [226] predicted the peak capacity based on data obtained during a fast-walking trial. Because walking efficiency differs between walking with a trans-tibial and a trans-femoral amputation [44], predicted oxygen consumption might not be reliably compared between both groups. The lack of an association between level of amputation and aerobic capacity suggests that in our population, the proposed limited activity level in people with a more proximal amputation was not related to a lower aerobic capacity. This could be because we included only proficient ambulators. Another explanation might be a lack of statistical power in the current study. However, interestingly, the percentage difference associated with the level of amputation (4.7%) is substantially smaller than that associated with the cause of amputation (26.4%). This may imply that in clinical practice, the level of amputation only marginally influences the $\dot{V}O_{2peak}$.

The observed influences of presence, cause, and level of amputation on $\dot{V}O_{2peak}$ were found after adjusting for the potential confounding effects of age, BMI and sex. Age, BMI and sex indeed explained a significant additional proportion of the total variance. When, for example, the confounders were excluded from the analysis in model 2, the adjusted explained variance decreased from 66.0% to 34.4% (data not shown). More importantly, part of the differences in average $\dot{V}O_{2peak}$ between controls and people with a vascular amputation, presented in Table 2, can be explained by the higher age and BMI in the latter group.

Study limitations

All subjects were relatively active, healthy older adults with an amputation who were able to walk for at least 4 minutes, thereby limiting generalization. However, we believe that the lower $\dot{V}O_{2peak}$ observed will only be aggravated in subjects of similar age who are currently inactive. Another limitation in the current study is the limited number of subjects with a vascular amputation and, specifically, the limited number of people who had a trans-femoral amputation in this group. This reduces the statistical power of this study and might conceal a potential association between $\dot{V}O_{2peak}$ and the level of amputation. However, differences that were observed were consistent and large enough to provide statistically significant results. Furthermore, matching the participants on age inevitably resulted in the group with a traumatic amputation having a longer time since amputation. This could be a confounding factor influencing the differences found in peak aerobic capacity between both amputation groups.

Conclusion

The present study investigated the aerobic capacity of older adults who were ambulatory prosthetic users by means of a discontinuous, graded, one-legged, exercise test in which a regular cycle ergometer was used. $\dot{V}O_{2peak}$ of vascular amputees was lower than that of able-bodied controls. After correcting for the confounding effects of age, BMI, and sex, $\dot{V}O_{2peak}$ of the vascular group was 29.1% lower than that of able-bodied controls. The traumatic amputees had a $\dot{V}O_{2peak}$ similar to that of able-bodied controls, and no effect of level of amputation was found. The lower aerobic capacity found in the vascular group, together with the higher aerobic demand when walking with a prosthesis [226], might influence the walking ability in those walking with a lower limb amputation [171] because of vascular deficiency. Although limited, some evidence indeed suggests that a relationship between walking ability and aerobic capacity exists [29, 184, 224]; a lower aerobic capacity has been claimed to result in lower walking ability [24-25]. Future research should focus on the question to what extent the lower aerobic capacity influences walking ability, and whether aerobic training can be beneficial in this respect.