Optimizing Prosthetic Gait

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On the relationship between aerobic capacity and walking ability in older adults with a lower limb amputation

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Abstract

The objective of this study was to determine the relative aerobic load, walking speed and economy of older adults walking with a lower limb prosthesis, and to predict the effect of an increased aerobic capacity on their walking ability. A convenience sample of 36 older adults who underwent lower limb amputation due to vascular deficiency or trauma and 21 age-matched able-bodied controls participated. Peak aerobic capacity and the oxygen consumption while walking were determined. The relative aerobic load and walking economy were assessed as a function of walking speed, and a data-based model was constructed to predict the effect of an increased aerobic capacity on walking ability. Results showed that people with a vascular amputation walk at a substantial higher (45.2%) relative aerobic load than people with an amputation due to trauma. The preferred walking speed in both groups of amputees was slower than that of able-bodied controls, and it was below their most economical walking speed. We predicted that a 10% increase in peak aerobic capacity could potentially result in a reduction in the relative aerobic load of 9.1%, an increase in walking speed and it could lead to a 17.3% or 13.9%, and an improvement in the walking economy of 6.8% or 2.9%, for people after a vascular or traumatic amputation, respectively. Current findings corroborate the notion that, especially in people with a vascular amputation, the peak aerobic capacity is an important determinant for walking ability. The data provides quantitative predictions on the effect of aerobic training; however, future research is needed to experimentally confirm these predictions.

Introduction

Regaining or maintaining walking ability can be a challenge for people after undergoing lower limb amputation. Aside from problems with regards to pain, wounds or prosthetic fitting, walking with a prosthesis requires more metabolic energy than walking with two intact limbs [110, 116, 225]. The perceived exertion when walking can be aggravated when it coincides with a reduced aerobic capacity [71, 216, 226]. Unfortunately, the available aerobic capacity is known to reduce with age [73], and to be lower in older adults with a vascular amputation compared to age-matched controls [230]. Therefore, those most likely at risk of walking at an unfavorably high relative aerobic load (i.e. the aerobic energy requirement for walking relative to the available aerobic capacity) are the older adults with a vascular amputation.

When the relative aerobic load at a given walking speed exceeds a desirable limit, people can opt to reduce their walking speed, thereby reducing the metabolic energy expenditure [71]. Previous research has demonstrated that people with an amputation indeed lower their walking speed to such a degree that the metabolic energy expenditure per minute is equal to that of able-bodied controls [85, 114, 116-117, 169, 225-226]. There is, however, a tradeoff as reducing the walking speed will affect the ability to keep up with able-bodied peers and could result in a higher energy cost per distance traveled [44, 81, 116, 203]. The cost of walking is expressed as the energy expenditure per distance traveled and has a parabolic relationship with walking speed, with a minimum at a speed which is defined as the most economical walking speed [9, 28, 81, 240]. Able-bodied persons [28, 141] prefer to walk at, or close to, their most economical walking speed. By contrast, older adults with an amputation might not be able to walk at their most economical walking speed as that walking speed might coincide with an undesirably high relative aerobic load. Hence, a reduced peak aerobic capacity can influence walking ability as it can result in an increased relative aerobic load, reduced preferred walking speed and a reduced walking economy.

Whereas the notion that relative aerobic load is an important determinant of walking ability is recognized [107], it has been scarcely investigated in older adults walking with a lower limb prosthesis. Moreover, it is not known to what magnitude a reduced exercise capacity might affect walking effort, speed and walking economy, consequently possible effects of aerobic training on walking ability are unclear. The current study was designed to determine the relative aerobic load in a group of older adults walking with a prosthesis and a group of able-bodied controls, and establish the effect of etiology and level of amputation on relative aerobic load. In addition, we determined the relationship between relative aerobic load, walking economy and walking speed. Using the obtained results, we constructed a data-based model, to provide quantitative predictions of the potential effects of an increased peak aerobic capacity on the relative aerobic load, walking speed and walking economy.

Methods

Subjects

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In total a convenience sample of 36 people, aged between 50 and 75 years with a unilateral lower limb amputation, participated in this study. Subjects had undergone amputation over one year prior to participation, and all were able to walk comfortably with their prosthesis for a minimum of four minutes. Of the 36 subjects, 26 had undergone amputation because of trauma, of which 16 at the trans-tibial and 10 at the trans-femoral level. The remaining 10 subjects had undergone amputation because of vascular deficiencies (7 trans-tibial and 3 trans-femoral). Subjects were ineligible for participation when they had any absolute contraindication for exercise [143], impairments of cognitive function, wounds on the stump or a history of musculoskeletal or neurological diseases other than the amputation that might affect test performance. Prior to participating all subjects with an amputation were examined by a physician. An additional group of 21 able-bodied controls participated. Informed consent was obtained and the study carried the approval of the Medical Ethical committee of the VU University Medical Center in Amsterdam.

Experimental procedure

All subjects visited the rehabilitation centre twice; visits were separated by a minimum of 1 day (mean = 5.3, sd = 4.4). Subjects were asked to refrain from drinking coffee and eating large meals on the test days, and were asked not to be involved in excessive exercise in the 24 hours preceding test days.

The oxygen consumption during walking was determined breath-by-breath using open-circuit respirometry (Oxycon Delta; CareFusion, Houten, The Netherlands) while walking on a treadmill (3m by 1m, ForceLink©, Culemborg, The Netherlands). After a familiarization period, preferred walking speed (PWS) was determined according to the method previously reported by others [139-141]. Subjects performed five walking trials at different walking speeds. Each of these trials lasted four minutes in order to allow steady state oxygen consumption to be attained. Subjects walked at PWS and at speeds 15 and 30 percent higher and lower than PWS. Imposing walking speeds relative to PWS was deemed essential due to large inter-individual differences in PWS. All trials were performed in random order, and were separated by 10 minutes of rest.

During the second visit peak aerobic capacity was measured using a graded one-legged cycle exercise test. The exercise test was performed using an electronically braked cycle ergometer (Lode Corival, Lode B.V., Groningen, The Netherlands). For a more detailed description of the exercise test and a validation of the protocol we refer to Wezenberg and colleagues (2012) [229].

Data analysis

During the walking trials, steady state oxygen consumption was determined as the mean value of oxygen consumed during the last minute of data collection. This value was then normalized for body weight in order to attain the energy expenditure during walking ($\dot{V}O_{2walking}$, $ml \cdot kg^{-1} \cdot min^{-1}$). Verification of steady state was done online by visual inspection of the oxygen consumption [209], and offline using the method previously described by Schwartz and colleagues (2007) [189]. Peak aerobic capacity ($\dot{V}O_{2peak}$, $ml \cdot kg^{-1} \cdot min^{-1}$) was determined as the highest value attained during the last or penultimate exercise phase during the graded exercise test. Relative aerobic load ($\dot{V}O_{2rel}$, %) was determined as the percentage of available $\dot{V}O_{2peak}$ that was used when walking. The oxygen cost of walking at preferred walking speed (C_{pws}, $ml \cdot kg^{-1} \cdot m^{-1}$) was determined as the measured oxygen consumption while walking at PWS divided by the preferred walking speed.

Relative aerobic load and oxygen cost as a function of walking speed

For all groups, stratified according to etiology, the relative aerobic load as a function of walking speed (v) was described using a second order polynomial function [9, 28],

$$\dot{V}O_{2rel} = \frac{\dot{V}O_{2walking}}{\dot{V}O_{2peak}} = a \cdot v^2 + b \cdot v + c \qquad (1)$$

Only subjects who were able to walk a minimum of three trials were included in this analysis. Similarly, a second polynomial function was fitted to describe the relationship between oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) and walking speed.

$$\dot{V}O_{2walking} = m \cdot v^2 + n \cdot v + p \qquad (2)$$

This function was then divided by walking speed to obtain the oxygen cost ($J \cdot kg^{-1} \cdot m^{-1}$) as a function of walking speed ($m \cdot s^{-1}$).

$$\text{oxygen cost} = \frac{\dot{V}O_{2walking}}{v} = m \cdot v + n + \frac{p}{v} \qquad (3)$$

Table 1. Subjects characteristics and outcome parameters (mean ± SD).

	control n = 21	traumatic n = 26 (TT = 16, TF = 10)	vascular n = 10 (TT = 7, TF = 3)
Age (years)	60.8 (5.9)	60.7 (5.6)	66.3 (5.9) *,†
Sex (men/women)	14/7	18/8	8/2
Bodyweight (kg)	81.1 (14.3)	78.2 (12.5)	93.4 (17.9) *,†
BMI	25.7 (3.7)	25.4 (3.6)	30.2 (7.1) *,†
Years since amputation	n/a	36.2 (20.7)	3.8 (3.6) †
PWS	1.25 (0.15)	0.98 (0.18)*	0.70 (0.21)*,†
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	30.8 (10.3)	28.1 (6.7)	17.1 (4.1)*,†
$\dot{V}O_{2walking}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	13.8 (2.1)	13.5(2.2)	12.2(2.5)
$\dot{V}O_{2rel}$ (%)	48.7 (14.6)	49.7 (10.7)	73.1 (13.1)*,†
C_{pws} ($ml \cdot kg^{-1} \cdot m^{-1}$)	0.18 (0.02)	0.24 (0.05)*	0.30 (0.07)*,†

Note: Bodyweight is the weight of the person minus the weight of the prosthesis.
Abbreviations: TT/TF, trans-tibial or trans-femoral; n/a; not applicable; PWS, preferred walking speed; $\dot{V}O_{2peak}$, peak aerobic capacity; $\dot{V}O_{2walking}$, energy expenditure while walking at PWS; $\dot{V}O_{2rel}$, relative aerobic load at PWS; C_{pws}, the oxygen cost of walking at PWS.
* Significantly different from controls ($p < .05$).
† Significantly different from people with a traumatic amputation ($p < .05$).

Model predictions

The potential effect of a given increase in $\dot{V}O_{2peak}$ on relative aerobic load, while maintaining the same walking speed, is found by multiplying the relative aerobic load with a factor x equal to the inverse of the fractional change in $\dot{V}O_{2peak}$. The potential effect of a given increase in $\dot{V}O_{2peak}$ on walking speed can be determined by multiplying Equation 1 with the factor x, and solving the equation for walking speed, while restricting the left side of the equation to the relative aerobic load measured at PWS. In other words, in this way we determined the change in walking speed when subjects would choose to walk at the same relative aerobic load as before but with a higher $\dot{V}O_{2peak}$. Finally, the corresponding effect on walking economy could subsequently be derived from the known relationship between oxygen cost and walking speed.

Statistics

All data were analyzed using a computerized statistical package (SPSS inc., Version 18.0; Chicago, Illinios). To evaluate whether the choice of PWS and $\dot{V}O_{2walking}$, $\dot{V}O_{2rel}$ and C_{pws} at PWS (dependent variables) were influenced by the presence of an amputation, cause of amputation and level of amputation (independent variables) multiple linear regression analyses were performed. For each dependent variable a model was constructed to identify whether an association between the dependent variable and the presence of an amputation exists. An additional model, which included only the subjects with an amputation, was constructed to determine the association between the dependent variables and both etiology and level of amputation. Age, BMI and sex were added as confounders in all regression models. After analysis of the initial constructed model we decided to natural log transform the dependent variable to improve the model fit. Prior to interpretation of the data, case-wise diagnostics and normality analysis were performed on all constructed models.

Results

The subject characteristics, stratified according to etiology, are shown in Table 1. The multiple linear regression analyses revealed that both etiology (p = .033) and level of amputation (p = .006) were negatively associated with PWS; with a more proximal and vascular amputation resulting in the lowest walking speed (Table 2).

A trend can be noted indicating that the presence of an amputation might be associated with a higher relative aerobic load at PWS compared to able-bodied controls (p = .071). When entering only those subjects with an amputation and controlling for the difference in level of amputation, the regression analysis revealed that the presence of a vascular amputation resulted in a relative aerobic load at PWS that was 45.2 % higher than that of people with a traumatic amputation (p = .001). No association between relative aerobic load and the level of amputation was found (p = .803; Table 2).

The oxygen cost of walking (C_{pws}) was related to both etiology (p = .008) and level of amputation (p = .002), with a more proximal and vascular amputation resulting in the highest energy cost of walking at PWS (Table 2).

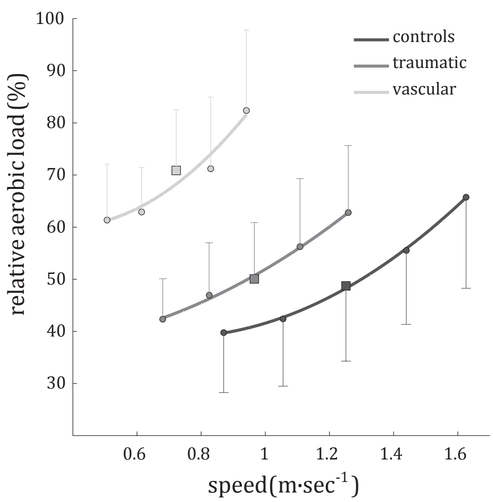

Figure 1. The relative aerobic load while walking at different walking speeds.

The Figure shows the mean values found for the able-bodied controls and the subjects walking with a lower limb prosthesis grouped according to etiology. The vertical bars represent the standard deviation. Squares represent the averaged preferred walking speed.

Table 2. Multiple linear regression models

	PWS ($m \cdot sec^{-1}$)				$\dot{V}O_{2walking}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)				$\dot{V}O_{2rel}$ (%)				C_{pws} ($ml \cdot kg^{-1} \cdot m^{-1}$)			
	F_{change}	R^2	β (p)	%change (95%CI)	F_{change}	R^2	β (p)	%change (95%CI)	F_{change}	R^2	β (p)	%change (95%CI)	F_{change}	R^2	β (p)	%change (95%CI)
Model 1 (n=57)	39.5 (p<.001)	.802			.4 (p=.517)	.052			3.4 (p=.071)	.658			27.7 (p<.001)	.659		
Amputation *(yes/no)*			-0.310 (p<.001)	-26.7% (-33.6, -19.0)			-0.029 (p=.517)	n/a.			0.116 (p=.071)	12.3% (-1.0, 27.3)			0.281 (p<.001)	32.5% (19.0, 47.5)
Model 2 (n=36)	6.6 (p<.001)	.797			.5 (p=.639)	.619			7.4 (p=.002)	.705			9.3 (p=.001)	.679		
-etiology *trau(1)/vasc(2)*			-0.191 (p=.032)	-17.4% (-30.5, -1.7)			0.059 (p=.435)	n/a.			0.373 (p=.001)	45.2% (19.0, 77.3)			0.250 (p=.008)	28.4% (7.5, 53.4)
- level of amputation *TT(1)TF(2)*			-0.187 (p=.006)	-17.1% (-27.1, -5.6)			0.032 (p=.576)	n/a.			-0.018 (p=.803)	n/a.			0.219 (p=.002)	24.5% (8.9, 42.2)

Note: For all four dependent variables a regression analysis was performed. In addition to the entered variables presented here, age, BMI and sex were added as confounders. Whereas Model 1 contains also the able bodied control group, Model 2 only included subjects with a lower limb prosthesis.
Abbreviations: trau/vasc, traumatic or vascular; TT/TF, trans-tibial or trans-femoral; n/a; not applicable; PWS, preferred walking speed; $\dot{V}O_{2walking}$, energy expenditure while walking at PWS; $\dot{V}O_{2rel}$, relative aerobic load at PWS; C_{pws}, the oxygen cost of walking at PWS; F_{change}, the F test statistics for the model with respect to the basic model with only age, BMI and sex included; R^2, the explained variance; β, unstandardized beta coefficient; %change, the percentage change in the dependent variable when the independent variable is increased with one unit, 95% confidence intervals are given.

Relative aerobic load and oxygen cost as a function of walking speed

One participant with a traumatic and two with a vascular amputation were unable to complete a minimum of three speeds and were omitted in the analysis. For the remaining subjects, averaged relative aerobic load increased curvilinear with walking speed (Figure 1). The curvilinear relationship was shifted to the left for people with an amputation. An additional shift upwards was found in people with a vascular amputation. Figure 1 also shows that people with a traumatic amputation were able to walk at the same relative aerobic load as able-bodied controls but at a lower walking speed, this in contrast to people with a vascular amputation. The relative aerobic load while walking at PWS was only associated with etiology and not with the level of amputation (Table 2). However, it is important to acknowledge that the choice of PWS was related to the level of amputation; subjects with a trans-femoral amputation chose to walk at a lower PWS than subjects with a trans-tibial amputation. Consequently, people with a trans-femoral amputation walk at the same relative aerobic load as people with a trans-tibial amputation but attain this relative aerobic load while walking slower.

For able-bodied controls the averaged most economical walking speed is close to their PWS, stated differently; the speed at which the cost of walking is the lowest is close to the PWS. Conversely, subjects with an amputation chose a PWS which was substantially lower than their theoretically most economical walking speed (Figure 2). Increasing the walking speed to match the most economical walking speed coincides with a higher effort for walking. This entails that participants with a traumatic amputation would need to walk at 60.5% and those with a vascular amputation at 109.3% of their peak aerobic capacity in order for them to walk at their theoretically most economical walking speed (Table 3).

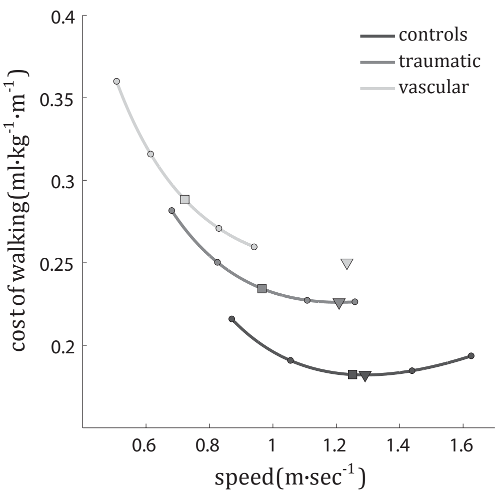

Figure 2. The relationship between the cost of walking and walking speed.

The values found for the able-bodied controls and the subjects walking with a lower limb prosthesis grouped according to etiology are shown. Squares represent the averaged preferred walking speed while the triangles represent the cost of walking while walking at the most theoretical economic walking speed. Only those subjects who were able to walk a minimum of three trials are included in the Figure.

Table 3. The relative aerobic load.

	At preferred walking speed	At theoretically most economic walking speed*	
	$\dot{V}O_{2rel}$ (%,SD)	$\dot{V}O_{2rel}$ (%)	% change needed in $\dot{V}O_{2peak}$
Controls (n = 21)	48.7 (14.4)	49.7	2.9
Traumatic (n = 25)*	50.1 (10.8)	60.5	19.2
Vascular (n=8)*	70.9 (11.6)	109.3	60.1

Note: The percentage change needed to walk at the most economical walking speed while maintaining the same relative aerobic load as measured during the preferred walking speed trial is presented in the last column.
* Only subjects who walked a minimum of three speeds were included in the analysis.

Model predictions

Using the data-based model (Equation 1), we predict that for people with a vascular amputation to walk at a relative aerobic load similar to that of able-bodied controls (i.e. 48.7%) would require an increase in $\dot{V}O_{2peak}$ of 41.4%. When the aim is to walk at the theoretically most economical walking speed (while maintaining the same $\dot{V}O_{2rel}$), people with an amputation due to trauma would need to increase their $\dot{V}O_{2peak}$ by 19.2%, while those with an amputation due to vascular deficiency need to increase the $\dot{V}O_{2peak}$ by 60.1% (Table 3). In Figure 3 the relative changes in relative aerobic load, walking speed and cost of walking that can potentially be attained are depicted as a function of the percentage increase in $\dot{V}O_{2peak}$. A certain percentage increase in peak aerobic capacity will result in the same percentage difference in relative aerobic load for both etiologies. While the effect on walking speed and the associated cost of walking differs among etiologies.

Discussion

The principal finding of this study is that people with a lower limb amputation due to vascular deficiencies walked at a considerably higher $\dot{V}O_{2rel}$, despite walking at a much slower speed compared to able-bodied controls. People after traumatic amputation also walk slower; however, they are able to walk at a similar $\dot{V}O_{2rel}$ as the able-bodied controls. Both groups of amputees walked slower than their theoretically most economical speed.

In the current study the older able-bodied controls walked at a $\dot{V}O_{2rel}$ of 48.7% (Table 1); this value is in close agreement with previous published results for the same age group [71, 107, 121, 139]. The few studies that report values for

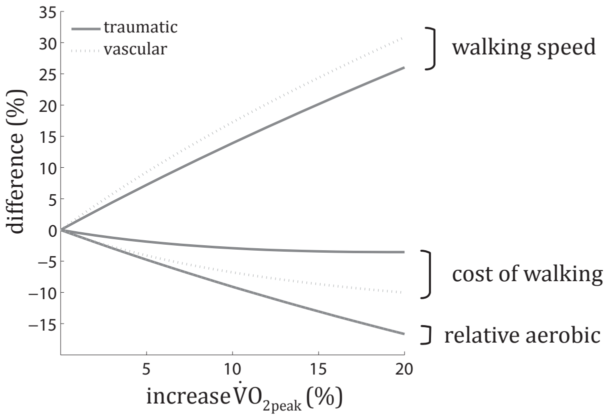

Figure 3. The effect of a percentage increase in peak aerobic capacity on relative aerobic load, walking speed and the cost of walking.

Values are expressed as percentage difference with respect to their original values. A certain percentage increase in peak aerobic capacity will result in the same percentage difference in relative aerobic load for both etiologies. The effect on walking speed and the associated cost of walking differs among the two amputee groups. Only those subjects who were able to walk a minimum of three trials are included in the Figure.

relative aerobic load in people with an amputation vary markedly (between 35 and 56%) [162, 226]. In contrast to the previous published studies [162, 226], which used prediction equations, we have used a graded peak exercise test [229]. This provided us with a more reliable and comparable estimation of the individual relative aerobic load while walking.

Relative aerobic load and oxygen cost as a function of walking speed

Aerobic capacity declines with age [73], consequently, healthy older subjects reduce their walking speed to ensure that $\dot{V}O_{2rel}$ remains within acceptable limits, thereby, reducing the feelings of fatigue during walking [31, 71, 139]. To walk at the same $\dot{V}O_{2rel}$, people with a traumatic amputation reduced their walking speed with 21.6% compared to that of able-bodied controls. Remarkably, for people with a vascular amputation to walk at a $\dot{V}O_{2rel}$ similar to controls seems not feasible as this would theoretically require speeds below zero (Figure 1).

For healthy able-bodied young [28] and old adults [141] the choice of walking speed is believed to be governed by the relationship between walking speed and walking economy. Our results support this as controls indeed walked at their most economic walking speed. However, both the subjects with a traumatic and vascular amputation generally did not (Figure 2). These findings are in agreement with some [44, 116], but not all studies [79, 81, 85, 103]. It can be hypothesized that for people with an adequate aerobic capacity the most economic walking speed can be reached within an acceptable level of $\dot{V}O_{2rel}$. Presumably, people with an adequate aerobic capacity, like young people with a traumatic trans-tibial amputation [78, 208, 226], the most economic walking speed can be reached at an acceptable level of relative aerobic load. While for other, and especially the older people with a reduced capacity, this seems not within reach. For these people, the choice of walking speed seems to be governed by the relative aerobic load rather than walking economy.

Potential effects of an improvement in aerobic capacity

The current data set was used to quantitatively predict the potential effect of an improvement in peak aerobic capacity on the walking ability in terms of relative aerobic load, speed and economy. The reported increases in peak aerobic capacity of people with an amputation after aerobic training vary between 27.2% and 41.2% [22-23, 170]. Whereas these training studies were limited to relatively young people with a traumatic amputation, improvements in aerobic capacity have been reported for older subjects with a wide range of pathologies [142], suggesting that aerobic capacity can also be increased in older deconditioned people with a vascular amputation. From Figure 3 it can be seen that a relatively modest increase in peak aerobic capacity of 10% can, theoretically, result in clinical relevant changes with regards to relative aerobic load (9.1% lower), speed (17.3% higher) and walking economy (6.8% lower cost of walking) in people after a vascular amputation, and somewhat more modest changes in people after a traumatic amputation. Hence, the current model shows that even small increases in peak aerobic capacity can result in substantial improvements in walking ability in term of relative aerobic load, speed and walking economy.

Alternatively to increasing the peak aerobic capacity, technological advancements have aimed at improving walking economy and, concomitantly, the relative aerobic load while walking. Although improvements in the field of prosthetics are promising, the current study underscores the importance that in order to allow a person to walk greater distances with less fatigue it is important to also look beyond the prosthetic innovations and optimize the physical capacity of the person walking with the prosthesis.

Study limitations

Information concerning the isolated effect of a potential increase in peak aerobic capacity can help to gain insight in the magnitude of change necessary when aiming to reduce the or increase the walking speed. However, there are some limitations with this approach. Firstly, it is important to realize that due to the large inter-individual variation, conclusions cannot be generalized to individual patients; it merely provides a quantitative description of an overall trend. Secondly, the novelty of this modeling approach is that we can alter one parameter (in this case $\dot{V}O_{2peak}$). However, in reality, there is no isolated effect of aerobic training on $\dot{V}O_{2peak}$ [171].

Previous research has shown that walking on a treadmill results in a lower PWS and is less economical in both healthy controls [36] and people walking with an prosthesis [209] compared to overground walking. Therefore subjects might have walked faster and more economical when tested while walking overground, however, conclusions drawn about the differences between groups will, most likely, remain the same.

Finally, a limitation in the current study is the small number and biased sample, especially with regards to the number of subjects with a vascular amputation. Furthermore, our set-up allowed us to only include subjects who could walk independently. Consequently, the participants selected in this study might have been biased to the physically fit which limits generalization of the results. Even though our results are evident, future research with larger groups will strengthen the conclusions.

Conclusion

To sum, people with a traumatic amputation walked at the same relative aerobic load as able-bodied controls but did so at a lower walking speed. People with a vascular amputation walked at an even slower speed, but nevertheless walked at a substantial higher relative aerobic load. Interestingly, both amputee groups chose a walking speed that was lower than the most economic walking speed.

The model predictions in this study indicate that improving $\dot{V}O_{2peak}$ through aerobic training can result in a clinically relevant reduction in relative aerobic load in people with a vascular amputation. Additionally, it can allow people to adopt a faster and more economical walking speed. Therefore, we propose that peak aerobic capacity ought to be considered as an important factor when aiming to improve the walking ability in people with an amputation. Future longitudinal studies are needed to empirically test the predicted effect of aerobic training on walking ability in older adults with a lower limb amputation.