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The relationship between relative aerobic load, energy cost, and speed of walking in individuals post-stroke

Ilse Blokland^{a,b,*}, Arianne Gravesteyn^a, Matthijs Busse^a, Floor Groot^d, Coen van Bennekom^{b,c}, Jaap van Dieën^a, Jos de Koning^a, Han Houdijk^{a,b,e}

^a Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, the Netherlands

^b Helimare Research and Development, Wijk aan Zee, the Netherlands

^c Coronel Institute of Occupational Health, Amsterdam University Medical Center, University of Amsterdam, Amsterdam, the Netherlands

^d Sport- en BeweegKliniek, Haarlem, the Netherlands

^e University of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, Groningen, the Netherlands

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ABSTRACT

Background: Individuals post-stroke walk slower than their able-bodied peers, which limits participation. This might be attributed to neurological impairments, but could also be caused by a mismatch between aerobic capacity and aerobic load of walking leading to an unsustainable relative aerobic load at most economic speed and preference for a lower walking speed.

Research question: What is the impact of aerobic capacity and aerobic load of walking on walking ability post-stroke?

Methods: Forty individuals post-stroke (more impaired $N = 21$; preferred walking speed (PWS) < 0.8 m/s, less impaired $N = 19$), and 15 able-bodied individuals performed five, 5-minute treadmill walking trials at 70 %, 85 %, 100 %, 115 % and 130 % PWS. Energy expenditure ($\text{mlO}_2/\text{kg}/\text{min}$) and energy cost ($\text{mlO}_2/\text{kg}/\text{m}$) were derived from oxygen uptake ($\dot{V}\text{O}_2$). Relative load was defined as energy expenditure divided by peak aerobic capacity ($\%\dot{V}\text{O}_{2\text{peak}}$) and by $\dot{V}\text{O}_2$ at ventilatory threshold ($\%\dot{V}\text{O}_{2\text{VT}}$). Relative load and energy cost at PWS were compared with one-way ANOVA's. The effect of speed on these parameters was modeled with Generalized Estimating Equations.

Results: Both more and less impaired individuals post-stroke showed lower PWS than able-bodied controls (0.44 [0.19 – 0.76] and 1.04 [0.81 – 1.43] vs 1.36 [0.89 – 1.53] m/s) and higher relative load at PWS (50.2 ± 14.4 and 51.7 ± 16.8 vs 36.2 ± 7.6 $\%\dot{V}\text{O}_{2\text{peak}}$ and 101.9 ± 20.5 and 97.0 ± 27.3 vs 64.9 ± 13.8 $\%\dot{V}\text{O}_{2\text{VT}}$). Energy cost at PWS of more impaired (0.30 [0.19 – 1.03] $\text{mlO}_2/\text{kg}/\text{m}$) was higher than less-impaired (0.19 [0.10 – 0.24] $\text{mlO}_2/\text{kg}/\text{m}$) and able-bodied (0.15 [0.13 – 0.18] $\text{mlO}_2/\text{kg}/\text{m}$). For post-stroke individuals, increasing walking speed above PWS decreased energy cost, but resulted in a relative load above endurance threshold.

Significance: Individuals post-stroke seem to reduce walking speed to prevent unsustainably high relative aerobic loads at the expense of reduced economy. When aiming to improve walking ability post-stroke, it is important to consider training aerobic capacity.

1. Introduction

Individuals post-stroke walk slower compared to able-bodied individuals, which can lead to problems in participation [1,2]. When addressing walking ability, neurological factors such as reduced motor control, muscle weakness and spasticity, and concomitant biomechanical constraints, are often assessed. However, another reason for this

slow walking could be a high relative aerobic load caused by an increased energetic demand and a reduced aerobic capacity.

The peak aerobic capacity of individuals post-stroke is on average half that of age-matched able-bodied individuals [3]. In addition, their ventilatory threshold (VT), representing the upper limit of workloads that can be sustained for a prolonged period [4], is below the 10th percentile of able-bodied individuals [5–7]. Aside from a low aerobic

* Corresponding author at: De Boelelaan 1105, Amsterdam, 1081 HV, the Netherlands.

E-mail addresses: i.j.blokland@vu.nl, i.blokland@helimare.nl (I. Blokland).

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capacity, individuals post-stroke experience a higher absolute aerobic load during walking (in $\text{mlO}_2/\text{kg}/\text{min}$) than able-bodied peers [8]. Factors that have been suggested to contribute to this higher load are increased co-contraction, an increase in external and internal mechanical work, decreased walking symmetry, and increased cost of balance control [9–11]. This implies that the absolute aerobic load relative to the aerobic capacity, i.e. the relative aerobic load of walking, is higher after stroke. Consequently, normal walking speed might require energy expenditure above sustainable limits. Hence, reducing walking speed might be a strategy to reduce relative aerobic load to sustainable levels.

Indeed, at their lower preferred walking speed (PWS), individuals post-stroke experience aerobic loads similar to able-bodied peers [12–15]. This slow walking speed, however, can be problematic in daily life, for example when trying to keep up with a partner or when participating in traffic. This may cause avoidance of walking, causing a vicious cycle in which reduced physical activity leads to a further decline in fitness, aggravating mobility problems [16].

Aside from practical consequences, slow walking speed may have another disadvantage, namely an increased energy cost. The energy required per unit distance, generally referred to as energy cost, shows a U-shaped relationship with speed. The PWS of able-bodied people is generally close to the most economic walking speed [13,17]. Post-stroke however, people seem to walk below their most economic speed, aggravating the difference in energy cost compared to able-bodied [9,18,19].

Several authors have highlighted the importance of the limited aerobic capacity in relation to aerobic load during walking post-stroke [11, 13,20], but only a limited number of studies reported relative aerobic load. It appears that aerobic capacity has been overlooked in stroke rehabilitation because it is traditionally linked to health and morbidity, but not to functioning. Furthermore, measuring cardiorespiratory fitness requires specialized equipment and qualified personnel. Relative aerobic loads of walking post-stroke between 45 and 65 % of peak aerobic capacity have been reported [21,22]. However, these studies did not include a control group, nor did they impose speeds below and above PWS, to investigate the concomitant effect on relative load and energy cost.

The goal of this study was to identify to what extent relative aerobic load and energy cost impact walking ability of individuals post-stroke. To this end, we compared relative aerobic load and energy cost at PWS between individuals post-stroke and able-bodied peers. Furthermore, we aimed to clarify the potential selection of PWS by investigating how these parameters change as a function of walking speed. To assess the effect of stroke severity on these parameters, we stratified the stroke group into more and less impaired individuals based on PWS. We hypothesized that individuals post-stroke walk slower and experience a similar or higher relative aerobic load than able-bodied controls at PWS. We also hypothesized that in individuals post-stroke, PWS is below their most economic walking speed. Consequently, we expected faster walking to reduce energy cost in individuals post-stroke, but at the expense of unsustainable relative load levels. We expected these effects to be larger in the more impaired individuals post-stroke.

2. Methods

Forty-five individuals post-stroke in clinical rehabilitation and fifteen age-, gender-, and BMI-matched able-bodied participants enrolled in this cross-sectional study. Individuals post-stroke were all referred for a routine cardiopulmonary exercise test (CPET).

Inclusion criteria for individuals post-stroke were: (1) >18 years of age, (2) Functional Ambulation Category (FAC) >2, indicating ability to walk without manual assistance. Exclusion criteria for all participants were (1) contraindications for CPET and/or exercise [24,25]; and (2) inability to execute study instructions. Control participants were excluded if they had a disorder influencing walking ability or a history of stroke or heart disease.

The Medical Ethical Committee of the VUMC (NL-64431.029.18) approved this study. Participants were fully informed about the study aim and protocol and signed written informed consent before participation.

2.1. Procedures

Participants performed the CPET and treadmill protocol on two days scheduled 2–14 days apart. Before testing, the Motricity Index [26] and FAC [27] were determined for individuals post-stroke. The following characteristics were retrieved from patient files: time since stroke, stroke characteristics (side, type, 1st or recurrent), days since admission, Beta Blocker use and Berg Balance Score [28,29].

2.1.1. Cardiopulmonary exercise test (CPET)

The CPET was performed on a cycle-ergometer under supervision of a physician. After 3-min rest and 3-min warming-up at 0 Watt, a ramp protocol based upon the estimated maximum exercise capacity of the participant was used. The test was stopped if cycling pace dropped below 50 rounds per minute, or if the physician deemed it unwise to continue. A 3-min cooling-down phase followed.

2.1.2. Treadmill walking

The second measurement day, PWS was determined on the treadmill, using a protocol previously described [31]. Then, participants performed five, five-minute treadmill-walking trials at different speeds in a randomized order; 70 %, 85 %, 100 %, 115 % or 130 % PWS. Participants could use the handrail on either side of the treadmill if needed. This condition was kept similar between trials within each participant. Seated rest between trials was at least five minutes to ensure return to resting metabolic values.

2.1.3. Data acquisition

Breath-by-breath gas exchange (Jaeger Oxycon Pro, Vyair, Hoechst, Germany) and arterial oxygen saturation were continuously measured during CPET and walking trials. Immediately after the CPET ramp phase and after each walking trial, rating of perceived exertion (RPE) was recorded on a modified Borg scale (6–20) [30].

2.2. Data analysis

Aerobic capacity was determined from CPET data. This has been shown to be feasible and reliable in individuals post-stroke [32,33]. The maximum of the 30-second averaged $\dot{V}\text{O}_2$ was considered peak oxygen uptake ($\dot{V}\text{O}_{2\text{peak}}$). $\dot{V}\text{O}_{2\text{peak}}$ was considered valid when a participant reached two out of three following criteria: respiratory quotient >1.1 (>1.0 for participants over 65 years of age [34,35]), maximum heart rate >85 % of predicted maximum, and RPE >15.

Oxygen uptake at ventilatory threshold ($\dot{V}\text{O}_{2\text{-VT}}$) was used as an additional measure of aerobic capacity. $\dot{V}\text{O}_{2\text{-VT}}$ expresses the exercise intensity that can be sustained for long duration without involvement of anaerobic metabolism and has been suggested to be a more specific measure of endurance for individuals post-stroke [5]. Two assessors determined VT following the V-slope method [36]. A plot of the ventilatory equivalents and respiratory quotient over time was presented after V-slope assessment, to allow the assessor to adjust the time point of VT if needed. If the two assessors did not agree on the $\dot{V}\text{O}_{2\text{-VT}}$ within 100 mL/min they conferred to reach consensus.

For the walking trials, a steady-state $\dot{V}\text{O}_2$ was confirmed visually. Energy expenditure (in $\text{mlO}_2/\text{kg}/\text{min}$) was determined by averaging $\dot{V}\text{O}_2$ during the last two minutes of each trial. Energy cost (in $\text{mlO}_2/\text{kg}/\text{m}$) was calculated by dividing energy expenditure by walking speed. Relative aerobic load was defined as energy expenditure divided by $\dot{V}\text{O}_{2\text{peak}}$ ($\%\dot{V}\text{O}_{2\text{peak}}$) or $\dot{V}\text{O}_{2\text{-VT}}$ ($\%\dot{V}\text{O}_{2\text{-VT}}$) respectively.

2.3. Statistical analysis

Data were analyzed using SPSS (IBM SPSS Statistics version 25.0, IBM Corp.) and checked for normality using visual inspection, skewness and kurtosis inspection and the Kolmogorov-Smirnov and Shapiro-Wilk tests. When the assumption of normality was violated, non-parametric equivalents of statistical tests were used. A p -value <0.05 was considered significant.

Since previous studies showed that the relationship between speed and energy cost in individuals post-stroke depends on the level of impairment [18], the group was split based on preferred walking speed: a less impaired group, (PWS >0.8 m/s) and a more impaired group (PWS ≤ 0.8 m/s) [37].

The potential differences between groups in relative aerobic load and energy cost at PWS were assessed with one-way ANOVA's. Significant main effects were followed up by post-hoc Bonferroni testing.

The relationships between walking speed and energy cost and between walking speed and relative aerobic load for all groups were described using Generalized Estimating Equations (GEE). GEE is a group-based approach that takes the dependency of observations within individuals into account. The following equation was used to model the relationship between speed and metabolic parameters:

$$\text{Dependent variable} = \beta_0 + \beta_1 * v + \beta_2 * G1 + \beta_3 * G2 + \beta_4 * G1 * v + \beta_5 * G2 * v + \beta_6 * v^2 + \beta_7 * G1 * v^2 + \beta_8 * G2 * v^2$$

In this equation v represents walking speed ($\text{m}\cdot\text{s}^{-1}$), $G1 = 1$ represents the more impaired stroke group and $G2 = 1$ represents the less impaired stroke group. The quadratic component was introduced since previous studies found a partly quadratic relation between speed and both relative aerobic load and energy cost [18,38]. Non-significant interaction parameters were removed from the final equations.

3. Results

Five out of 45 individuals post-stroke did not finish the protocol: two found the mask too uncomfortable, one found the protocol too tiring, one participant could not perform the protocol in time and one participant could not participate due to a fall. Twenty-one post-stroke individuals were allocated to the more impaired group, 19 to the less impaired group.

Eleven participants from the more impaired stroke group did not reach $\dot{V}\text{O}_2\text{peak}$ according to our criteria and were therefore not included in the analysis of $\% \dot{V}\text{O}_2\text{peak}$. All participants were included in the analysis of $\% \dot{V}\text{O}_2\text{-VT}$. The groups did not differ in age, gender or BMI (Table 1). As expected, the aerobic capacity of individuals post-stroke was significantly lower than that of able-bodied. No significant difference in aerobic capacity was found between stroke groups.

3.1. Relative load and energy cost at PWS

In line with our hypothesis, PWS was significantly different between groups ($\chi^2 = 42.9$, $p < 0.000$, Table 2). PWS of the control group was higher than both stroke groups ($U = 0.0$, $p < 0.000$ and $U = 42.5$, $p < 0.001$ respectively). Also in line with our hypothesis, we found a main effect of group on both $\% \dot{V}\text{O}_2\text{peak}$ at PWS ($F(2,20.8) = 8.571$, $p = 0.002$) and $\% \dot{V}\text{O}_2\text{-VT}$ at PWS ($F(2,33.9) = 14.146$, $p = 0.000$). The $\% \dot{V}\text{O}_2\text{peak}$ for both the more impaired ($50.2[14.4] \%$) and the less impaired stroke group ($51.7[16.8] \%$) was significantly higher than that of the control group ($36.2[7.6] \%$ $\dot{V}\text{O}_2\text{peak}$), ($p = 0.007$ and $p = 0.047$ respectively). The same was true for $\% \dot{V}\text{O}_2\text{-VT}$; both the more impaired ($101.9 \pm 20.5 \%$ $\dot{V}\text{O}_2\text{-VT}$) and the less impaired stroke group ($97.0 \pm 27.3 \%$ $\dot{V}\text{O}_2\text{-VT}$) had a significantly higher relative load than the control group ($64.9 \pm 13.8 \%$ $\dot{V}\text{O}_2\text{-VT}$), (both $p = 0.000$). No significant

Table 1
Group characteristics.

	More impaired individuals post-stroke (N = 21)	Less impaired individuals post-stroke (N = 19)	Control (N = 15)
Age (years)	58.5 (11.4)	57.7 (13.9)	59.4 (6.3)
Gender (M/F) (%M)	12/9 (57 %)	16/3 (84 %)	12/3 (80 %)
BMI	26.4 (4.1)	26.8 (3.5)	25.1 (3.9)
$\dot{V}\text{O}_2\text{peak}$ (ml/kg/min)	20.0 (4.4) (N = 10) ^a	23.3 (7.9) ^a	33.9 (8.1)
$\dot{V}\text{O}_2\text{-VT}$ (ml/kg/min)	9.5 (2.1) ^a	12.1 (3.4) ^a	19.0 (5.4)
Time since stroke (days)	37.2 [11–232]	24.4 [7–53]	
Time since admission (days)	14 [2–96]	8 [2–46]	
Side of stroke (left/right/other)	9/8/4	8/8/3	
Stroke type (ischemic/hemorrhagic)	17/4	13/6	
1 st /recurrent stroke	17/4	18/1	
Walking aid in daily life (y/n)	12/9	1/18	
Handrail hold on treadmill (y/n)	13/8	6/13	0/15
Charlston Comorbidity Index (0/1/2/3)	12/3/2/4	14/4/0/1	
Beta block medication (y/n)	7/14	6/13	
Motricity Index lower extremity	80 [14–92]	91 [73–100]	
upper extremity	83 [28–100]	100 [55–100]	
Functional Ambulation Category (3/4/5)	76 [0–100]	91 [55–100]	
Berg Balance Score	3/13/5	1/2/16	
	41 [24–56] ^b	4 [13–56]	

Values are presented as mean (standard deviation) or median [range] respectively. ^a Significantly different from control group ^b Significantly different from less impaired stroke group.

Table 2
Relative load and energy cost at PWS.

	More impaired individuals post-stroke (N = 21)	Less impaired individuals post-stroke (N = 19)	Control (N = 15)
Preferred Walking Speed (m/s)	0.44 [0.19–0.76] ^{ab}	1.04 [0.81–1.43] ^a	1.36 [0.89–1.53]
Aerobic load at PWS (ml O ₂ /kg/min)	8.89 [7.1–12.3] ^{ab}	11.3 [7.1–13.8]	12.0 [8.9–13.8]
Relative aerobic load at PWS (% $\dot{V}\text{O}_2\text{peak}$)	50.2 (14.4) (N = 10) ^a	51.7 (16.8) ^a	36.2 (7.6)
Relative aerobic load at PWS (% $\dot{V}\text{O}_2\text{-VT}$)	101.9 (20.5) ^a	97.0 (27.3) ^a	64.9 (13.8)
Energy Cost at PWS (ml O ₂ /kg/m)	0.30 [0.19–1.03] ^{ab}	0.19 [0.10–0.24] ^a	0.15 [0.13–0.18]

Values are presented as mean (standard deviation) or median [range] respectively. ^a Significantly different from control group. ^b Significantly different from less impaired stroke group.

differences in relative load at PWS were found between stroke groups.

As hypothesized, energy cost at PWS was significantly higher in the more impaired stroke group ($0.30[.19-1.03]$ ml/kg/m), compared to the less impaired group ($0.19[0.10-0.24]$ ml/kg/m, $p = 0.000$) and the

control group (0.15[0.13–0.18] ml/kg/m, $p = 0.000$, Table 2). Furthermore, energy cost at PWS in the less impaired stroke group was significantly higher than in the control group ($p = 0.000$).

3.2. Relative load as a function of walking speed

Relative aerobic load changed curvi-linearly with speed in all groups (Fig. 1). Significant group effects show that both $\% \dot{V}O_{2\text{peak}}$ and $\% \dot{V}O_{2\text{-VT}}$ were systematically higher for both stroke groups compared to able-bodied individuals (Table 3). For $\% \dot{V}O_{2\text{-VT}}$, the interactions between speed and the less impaired group, and speed [2] and the more impaired group were significant (Table 3).

3.3. Energy cost as a function of walking speed

At similar speeds, energy cost was higher for both stroke groups compared to able-bodied individuals (Fig. 2, Table 4). Energy cost decreased with speeds above PWS for both stroke groups. This effect was larger for the more impaired group. Able-bodied PWS was close to predicted minimal energy cost.

Figures presenting all individual relationships between energy cost and speed and relative aerobic load and speed are provided in the supplementary material.

4. Discussion

This study aimed to identify to what extent relative aerobic load and energy cost impact walking ability of individuals post-stroke. To this end, we compared relative aerobic load and energy cost of walking between individuals post-stroke and able-bodied individuals.

Table 3
GEE results relative load.

	β	Std. Error	95 % CI Lower limit	95 % CI Upper limit	p-value
Relative Load in $\% \dot{V}O_{2\text{peak}}$					
Speed	21.86	5.41	11.26	32.46	0.00*
More impaired group	38.40	6.11	26.43	50.38	0.00*
Less impaired group	24.36	5.03	14.50	34.22	0.00*
Speed ²	3.44	2.18	−0.82	7.70	0.11
Intercept	2.69	5.01	−7.13	12.51	0.59
Relative Load in $\% \dot{V}O_{2\text{-VT}}$					
Speed	9.72	12.78	−15.34	34.78	0.45
More impaired group	50.58	11.18	28.67	72.49	0.00*
Less impaired group	37.23	8.60	20.38	54.08	0.00*
Speed ²	15.20	4.69	5.99	24.40	0.00*
More impaired group * Speed	34.68	9.79	15.49	53.86	0.00*
Less impaired group * Speed ²	7.86	2.11	3.73	11.99	0.00*
Intercept	26.58	10.47	6.06	47.10	0.01*

As hypothesized, we found that relative aerobic load at PWS was higher for individuals post-stroke compared to able-bodied individuals, even though PWS was lowered in individuals post-stroke. At PWS, both more and less impaired individuals post-stroke walked at relative aerobic load values around 100 % of ventilatory threshold and 50 % of peak

Fig. 1. Relative load as a function of walking speed.

Relative aerobic load in $\% \dot{V}O_{2\text{peak}}$ (left panel) and $\% \dot{V}O_{2\text{-VT}}$ (right panel) in relation to walking speed for all groups. Lines represent the fit according to GEE analysis, which takes the dependency of observations within individuals over conditions into account. For each group, preferred walking speed (PWS) is represented by a dotted vertical line, the shaded area represents the standard deviation of PWS for this group. Individual data points are represented by downward pointing triangles (more-impaired stroke group), upward pointing triangles (less-impaired stroke group) and dots (control subjects) respectively. Note that the range of walking speeds differed between participants and groups since it depended on the PWS of the individual.

Fig. 2. Energy cost as a function of walking speed.

Energy cost in relation to walking speed for all groups. Lines represent the relationship for each group according to GEE analysis, which takes the dependency of observations within individuals over conditions into account. For each group, preferred walking speed (PWS) is represented by a dotted vertical line, the shaded area represents the standard deviation of PWS for this group. Individual data points are represented by downward pointing triangles (more-impaired stroke group), upward pointing triangles (less-impaired stroke group) and dots (control subjects) respectively. Note that the range of walking speeds differed between participants and groups since it depended on the PWS of the individual.

Table 4
GEE results energy cost.

Variable	β	Std. Error	95 % CI Lower limit	95 % CI Upper limit	p-value
Speed	−0.326	0.055	−0.433	−0.218	0.000*
More impaired group	0.680	0.050	0.582	0.777	0.000*
Less impaired group	0.024	0.021	−0.017	0.065	0.250
Speed ²	0.118	0.022	0.076	0.161	0.000*
More impaired group * Speed	−1.836	0.127	−2.085	−1.587	0.000*
More impaired group * Speed ²	1.276	0.096	1.087	1.465	0.000*
Intercept	0.366	0.037	0.294	0.439	0.000*

aerobic capacity. These values coincide with thresholds for exercise intensity that can be sustained over longer time intervals [4,24]. Able-bodied individuals stayed well below such thresholds. The GEE model reveals that when individuals post-stroke would increase their speed to the PWS of able-bodied, this would lead to unsustainable relative loads of 120 %, and 166 % of ventilatory threshold for the less and more impaired group respectively (Fig. 1). It is possible that individuals post-stroke will be limited by biomechanical and coordinative factors before they reach such speeds. However, many individuals in the post-stroke groups did walk in the range of the PWS of able-bodied when they walked at 130 % PWS. This implies that they have the biomechanical and coordinative ability to do so for a significant amount of time, but that they prefer a lower speed. On the other hand, to decrease relative load to values of able-bodied (65 % $\dot{V}O_2$ -VT), both groups would virtually stand still. Hence, it can be argued that, individuals post-stroke select a PWS that allows them to walk as fast as possible without surpassing acceptable relative load levels.

In line with our hypothesis, energy cost at PWS was higher for individuals post-stroke and highest in the more-impaired stroke group. Likely, this higher energy cost is partly due to the fact that the speed-energy cost curve is elevated for individuals post-stroke, indicating a less efficient walking pattern. This is in accordance with previous studies [8,19]. However, the high energy cost at PWS appears to be caused mostly by the fact that individuals post-stroke walked below their optimum speed concerning energy cost. Hence, while reducing walking speed limits relative load and prevents fatigue, this comes at the expense of increased energy cost, aggravating the mismatch between aerobic capacity and aerobic energy demand.

It has often been argued that people select their preferred walking speed such that energy cost is minimized [14,15,17]. When the cardiovascular system is not a limiting factor, as in able-bodied individuals, walking speed might indeed be optimized for energy cost. However, when the relative load of walking is high, as a consequence of low aerobic capacity or a high energy demand, walking speed seems to be lowered to limit the strain on the cardiorespiratory system at the expense of a higher energy cost. This has previously been observed for individuals with a lower limb amputation [38].

Both increasing aerobic capacity, by exercise training, or decreasing the aerobic load of walking, by improving efficiency, would decrease the relative aerobic load of walking. Macko et al. [21], showed that after an aerobic treadmill training program for individuals post-stroke, the relative aerobic load of walking decreased from 62 % to 50 % $\dot{V}O_{2peak}$, while walking speed increased. This indicates that individuals did not only reduce relative aerobic load, but also exploited the training effect to increase movement speed and likely, lower energy cost. It cannot be determined to what extent an improved economy, or an improved aerobic capacity contributed to this reduced relative load and increased speed. Nevertheless, it seems likely that improving aerobic capacity would make it possible to sustain a higher walking speed, which would in turn lead to a lower energy cost. Thus, for individuals post-stroke who

walk at a high relative aerobic load and concomitant high energy cost, it might be worthwhile to consider training aerobic capacity when addressing walking ability.

4.1. Study limitations

Since this study aimed to compare physiological parameters at and around PWS, we could not directly compare energy cost and relative aerobic load at similar speeds between groups. Furthermore, the imposed model on the relation between energy cost and walking speed did not fit this relationship for the more-impaired group very well. Therefore, the regression model for this group, especially the predicted minimum energy cost should be interpreted with caution. Advisably, future studies should impose equal absolute speed ranges over all groups to improve comparisons.

About half of individuals post-stroke used the handrail during their trials. We do not believe this to have changed our results, since handrail support likely only reduced energy cost or energy consumption on the treadmill [39] and the condition was kept similar within participants. Therefore, if handrail hold had any effect on our outcome parameters, it would have made the differences we found smaller.

The results of this study on treadmill walking cannot be translated directly to overground walking because differences in preferred walking speed and energy cost exist between these modalities [40]. However, it can be expected that the mechanism shown in this study does translate to overground walking; a high relative aerobic load potentially limits individuals post-stroke to walk faster and more efficiently.

A strength of this study is that we measured aerobic capacity via the gold standard: a maximal cardiopulmonary exercise test. Identical, standardized criteria for maximal effort were used for all groups, which led to a more reliable estimate of relative aerobic load compared to studies using prediction equations, and to a more complete estimate of the strain of walking compared to studies that only report absolute aerobic load. Furthermore, we included ventilatory threshold in our analyses of relative load. The ventilatory threshold was attained by all subjects and it might be a more relevant reference for aerobic strain as it represents the exercise intensity that can be sustained for a long duration.

5. Conclusion

Individuals post-stroke seem to reduce their walking speed to prevent unsustainable relative aerobic loads. This comes at the expense of reduced economy (i.e. higher energy cost). A higher aerobic capacity would decrease the relative aerobic load of walking, which would make it possible to increase walking speed and thereby improve economy. Therefore, when aiming to improve walking ability in individuals post-stroke, it is important to consider training aerobic capacity.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.gaitpost.2021.07.012>.

References

- [1] H.L. Jarvis, S.J. Brown, M. Price, et al., Return to employment after stroke in young adults: how important is the speed and energy cost of walking? *Stroke* 50 (11) (2019) 3198–3204, <https://doi.org/10.1161/STROKEAHA.119.025614>.
- [2] P. Langhorne, J. Bernhardt, G. Kwakkel, Stroke rehabilitation, *Lancet* 377 (9778) (2011) 1693–1702, [https://doi.org/10.1016/S0140-6736\(11\)60325-5](https://doi.org/10.1016/S0140-6736(11)60325-5).
- [3] A.C. Smith, D.H. Saunders, G. Mead, Cardiorespiratory fitness after stroke: a systematic review, *Int. J. Stroke* 7 (6) (2012) 499–510, <https://doi.org/10.1111/j.1747-4949.2012.00791.x>.
- [4] M. Guazzi, V. Adams, V. Conraads, et al., Clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations, *Eur. Heart J.* 33 (23) (2012) 2917–2927, <https://doi.org/10.1093/eurheartj/ehs221>.
- [5] P. Boyne, D. Reisman, M. Brian, et al., Ventilatory threshold may be a more specific measure of aerobic capacity than peak oxygen consumption rate in persons with stroke, *Top. Stroke Rehabil.* 9357 (November) (2016) 1–9, <https://doi.org/10.1080/10749357.2016.1209831>.
- [6] J. Fujitani, T. Ishikawa, M. Akai, S. Kakurai, Influence of daily activity on changes in physical fitness for people with post-stroke hemiplegia, *Am. J. Phys. Med. Rehabil.* 78 (6) (1999) 540–544.
- [7] B. Vainshelboim, R. Arena, L.A. Kaminsky, J. Myers, Reference standards for ventilatory threshold measured with cardiopulmonary exercise testing: the fitness registry and the importance of exercise: a national database, *Chest* (2020) 1–7, <https://doi.org/10.1016/j.chest.2019.11.022>. Published online.
- [8] M.M. Platts, D. Rafferty, L. Paul, Metabolic cost of overground gait in younger stroke patients and healthy controls, *Med. Sci. Sports Exerc.* 38 (6) (2006) 1041–1046, <https://doi.org/10.1249/01.mss.0000222829.34111.9c>.
- [9] J.M. Finley, A.J. Bastian, Associations between foot placement asymmetries and metabolic cost of transport in hemiparetic gait, *Neurorehabil. Neural Repair* 31 (2) (2017) 168–177, <https://doi.org/10.1177/1545968316675428>.
- [10] H. Houdijk, N. Ter Hoeve, C. Nooijen, D. Rijntjes, M. Tolsma, C. Lamoth, Energy expenditure for balance control during upright standing in people after stroke, *Gait Posture* 30 (November 2009) (2009) S69, <https://doi.org/10.1016/j.gaitpost.2009.08.103>.
- [11] C. Detrembleur, F. Dierick, G. Stoquart, F. Chantaine, T. Lejeune, Energy cost, mechanical work, and efficiency of hemiparetic walking, *Gait Posture* 18 (2) (2003) 47–55, [https://doi.org/10.1016/S0966-6362\(02\)00193-5](https://doi.org/10.1016/S0966-6362(02)00193-5).
- [12] S. Kramer, L. Johnson, J. Bernhardt, T. Cumming, Energy expenditure and cost during walking after stroke: a systematic review, *Arch. Phys. Med. Rehabil.* 97 (4) (2015) 619–632, <https://doi.org/10.1016/j.apmr.2015.11.007>, e1.
- [13] R.L. Waters, S. Mulroy, The energy expenditure of normal and pathologic gait, *Gait Posture* 9 (3) (1999) 207–231, [https://doi.org/10.1016/S0966-6362\(99\)00009-0](https://doi.org/10.1016/S0966-6362(99)00009-0).
- [14] J.C. Selinger, M. Shawn, O. Connor, et al., Humans can continuously optimize energetic cost during walking report humans can continuously optimize energetic cost during walking, *Curr. Biol.* 25 (18) (2015) 2452–2456, <https://doi.org/10.1016/j.cub.2015.08.016>.
- [15] J.E.A. Bertram, Constrained optimization in human walking: cost minimization and gait plasticity, *J. Exp. Biol.* 208 (6) (2005) 979–991, <https://doi.org/10.1242/jeb.01498>.
- [16] I.G.L. van de Port, G. Kwakkel, I. Van Wijk, E. Lindeman, Susceptibility to deterioration of mobility long-term after stroke: a prospective cohort study, *Stroke* 37 (1) (2006) 167–171, <https://doi.org/10.1161/01.STR.0000195180.69904.f2>.
- [17] H.J. Ralston, Energy-speed relation and optimal speed during level walking, *Int. Zeitschrift für Angew. Physiol. Einschl. Arbeitsphysiologie* 17 (4) (1958) 277–283, <https://doi.org/10.1007/BF00698754>.
- [18] D.S. Reisman, K.S. Rudolph, W.B. Farquhar, Influence of speed on walking economy poststroke, *Neurorehabil. Neural Repair* 23 (6) (2009) 529–534, <https://doi.org/10.1177/1545968308328732>.
- [19] P. Zamparo, M.P. Francescato, G. De Luca, L. Lovati, P.E. di Prampero, The energy cost of level walking in patients with hemiplegia, *Scand. J. Med. Sci. Sports* 5 (6) (1995) 348–352, <https://doi.org/10.1111/j.1600-0838.1995.tb00057.x>.
- [20] F.M. Ivey, R.F. Macko, S. Ryan a, C.E. Hafer-Macko, Cardiovascular health and fitness after stroke, *Top. Stroke Rehabil.* 12 (1) (2005) 1–16, <https://doi.org/10.1310/GEEU-YRUY-VJ72-LEAR>.
- [21] R.F. Macko, G.V. Smith, C.L. Dobrovolsky, J.D. Sorkin, A.P. Goldberg, K.H. Silver, Treadmill training improves fitness reserve in chronic stroke patients, *Arch. Phys. Med. Rehabil.* 82 (7) (2001) 879–884, <https://doi.org/10.1053/apmr.2001.23853>.
- [22] M.C. Serra, E. Balraj, B.L. Disanzo, et al., Energy expenditure in chronic stroke, *Top. Stroke Rehabil.* 24 (1) (2017) 18–23, <https://doi.org/10.1080/10749357.2016.1183866>. Validating.
- [24] L.S. Pescatello, D. Riebe, R. Arena, American College of Sports Medicine. ACSM's Guidelines for Exercise Testing and Prescription, 9th ed., Lippincott, Williams & Wilkins, 2014.
- [25] P.D. Thompson, R. Arena, D. Riebe, L.S. Pescatello, ACSM's new preparticipation health screening recommendations from ACSM's guidelines for exercise testing and prescription, ninth edition, *Curr. Sports Med. Rep.* 12 (4) (2013) 215–217, <https://doi.org/10.1249/JSR.0b013e31829a68cf>.

- [26] G. Demeurisse, O. Demol, E. Robaye, Motor evaluation in vascular hemiplegia, *Eur. Neurol.* 19 (1980) 382–389, <https://doi.org/10.1159/000115178>.
- [27] M.K. Holden, K.M. Gill, M.R. Magliozzi, J. Nathan, L. Piehl-Baker, Clinical gait assessment in the neurologically impaired. Reliability and meaningfulness, *Phys. Ther.* 64 (1) (1984) 35–40.
- [28] K.O. Berg, S.L. Wood-Dauphinee, J.I. Williams, B. Maki, Measuring balance in the elderly: validation of an instrument, *Can. J. Public Health* 83 (Suppl. 2) (1992) S7–11. Accessed October 19, 2017, <http://www.ncbi.nlm.nih.gov/pubmed/1468055>.
- [29] K. Berg, S. Wood-Dauphinee, J.I. Williams, D. Gayton, Measuring balance in the elderly: preliminary development of an instrument, *Physiother. Can.* 41 (6) (1989) 304–311, <https://doi.org/10.3138/ptc.41.6.304>.
- [30] G. Borg, Perceived exertion as an indicator of somatic stress, *Scand. J. Rehabil. Med.* 2 (2) (1970) 92–98.
- [31] T. Ijmker, H. Houdijk, C.J. Lamoth, et al., Effect of balance support on the energy cost of walking after stroke, *Arch. Phys. Med. Rehabil.* 94 (11) (2013) 2255–2261, <https://doi.org/10.1016/j.apmr.2013.04.022>.
- [32] J. Gäverth, R. Parker, M. MacKay-Lyons, Exercise stress testing after stroke or transient ischemic attack: a scoping review, *Arch. Phys. Med. Rehabil.* 96 (7) (2015) 1349–1359, <https://doi.org/10.1016/j.apmr.2015.03.005>.
- [33] C. Olivier, J. Doré, S. Blanchet, et al., Maximal cardiorespiratory fitness testing in individuals with chronic stroke with cognitive impairment: practice test effects and test-retest reliability, *Arch. Phys. Med. Rehabil.* 94 (11) (2013) 2277–2282, <https://doi.org/10.1016/j.apmr.2013.03.016>.
- [34] I.G.L. van de Port, G. Kwakkel, H. Wittink, Systematic review of cardiopulmonary exercise testing post stroke: are we adhering to practice recommendations? *J. Rehabil. Med.* 47 (10) (2015) 881–900, <https://doi.org/10.2340/16501977-2031>.
- [35] E. Edvardsen, E. Hem, S.A. Anderssen, End criteria for reaching maximal oxygen uptake must be strict and adjusted to sex and age: a cross-sectional study, *PLoS One* 9 (1) (2014) 18–20, <https://doi.org/10.1371/journal.pone.0085276>.
- [36] W. Beaver, K. Wasserman, B. Whipp, A new method for detecting anaerobic threshold by gas exchange, *J. Appl. Physiol.* 60 (7) (1986) 2020–2027. Accessed October 30, 2013, <http://jap.physiology.org/content/60/6/2020.short>.
- [37] M.M. Di Ng, K.D. Hill, F. Batchelor, E. Burton, Factors predicting falls and mobility outcomes in patients with stroke returning home after rehabilitation who are at risk of falling, *Arch. Phys. Med. Rehabil.* 98 (12) (2017) 2433–2441, <https://doi.org/10.1016/j.apmr.2017.05.018>.
- [38] D. Wezenberg, L.H. Van Der Woude, W.X. Faber, A. De Haan, H. Houdijk, Relation between aerobic capacity and walking ability in older adults with a lower-limb amputation, *Arch. Phys. Med. Rehabil.* 94 (9) (2013) 1714–1720, <https://doi.org/10.1016/j.apmr.2013.02.016>.
- [39] T. Ijmker, C.J. Lamoth, H. Houdijk, et al., Effects of handrail hold and light touch on energetics, step parameters, and neuromuscular activity during walking after stroke, *J. Neuroeng. Rehabil.* 12 (1) (2015) 70, <https://doi.org/10.1186/s12984-015-0051-3>.
- [40] A.P.C. Loureiro, B. Langhammer, T. Gjøvaag, H. Ihle-Hansen, L.C. Guarita-Souza, Skeletal muscle metabolism after stroke: a comparative study using treadmill and overground walking tests, *J. Rehabil. Med.* 49 (7) (2017) 558–564, <https://doi.org/10.2340/16501977-2255>.