Original article

Predicting the oxygen cost of walking in hemiparetic stroke patients

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ABSTRACT

Objective: To verify the relation between spontaneous walking speed (Sfree) and oxygen cost of walking at Sfree (Cwfree) in post-stroke hemiparetic patients and to test the validity of a prediction model to estimate Cwfree based on Sfree.

Design: We included 26 participants (mean age 65.1 years [SD 15.7]) with mild to moderate disability after stroke who walked at Sfree using mobility aids if necessary for 6 min. The Cwfree was measured at a stabilized metabolic rate by indirect calorimetry with the Metamax 3B spiroergometry device. The relation between Sfree and Cwfree was analyzed by the correlation coefficient (r) and coefficient of determination (R2). The Cwfree prediction model was developed from a regression equation, then tested on a second population of 29 patients (mean age 62.1 years [SD 13.4]) with the same inclusion and exclusion criteria.

Results: For the 26 participants, the Sfree and Cwfree were highly correlated (r = −0.94 and R2 = 0.97), which allowed for formulating a regression equation and developing the Cwfree prediction model based on Sfree. The prediction model tests yielded accurate results (mean bias −0.02 mL.kg −1.m −1; 95% limits of agreement −0.31 to 0.26 mL.kg −1.m −1). The relation between Cwfree estimated by the model and measured by Metamax was high (R2 = 0.98).

Conclusion: Cwfree was strongly correlated with Sfree, which allowed for the development of a valid Cwfree prediction model. A practitioner could estimate the energy expenditure of walking for a patient without using an indirect calorimeter.

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1. Introduction

Strokes are the worldwide main cause of acquired disability in adults [1]. Consequently, stroke patients are deconditioned and predisposed to a sedentary lifestyle [2], which adversely affects performance in activities of daily living and may contribute to heightened risk for recurrent stroke and supplementary cardiovascular diseases [3]. Physical exercise improves cardiorespiratory fitness, functional independence, walking ability and the ability to perform activities of daily living after a stroke [3,4]. However, the optimal amount and intensity of post-stroke fitness training remains unclear [4]. Monitoring the amount and intensity of physical activity a stroke patient performs is fundamental to ensure safety and generate benefits [3].

The oxygen cost of walking (Cw) is a marker of metabolic solicitation that quantifies the energy cost of walking after conversion of the oxygen volume into kilocalories [5]. However, the Cw at spontaneous walking speed (Sfree) − Cwfree − is extremely variable among individuals [5]. Measuring Cwfree in stroke patients requires the use of advanced instrumentation such as a respiratory gas exchange analyzer and is not commonly performed because of the cost of this device and the practical constraints in terms of the measuring protocol [6].

However, several authors have shown that the Cwfree is highly correlated with the Sfree. Zamparo et al. found a high correlation coefficient (0.92, P < 0.001) between Sfree measured over a 40-m loop and Cwfree measured by indirect calorimetry in 20 post-stroke hemiparetic patients [7]. Thus, Cwfree was closely associated with Sfree in hemiparetic stroke patients, and the authors could develop a regression equation for estimating Cwfree from Sfree [8]. Polese et al. reported that Sfree accounted for 81% of the Cwfree variance. Reisman et al. found a high correlation (r = 0.86, P < 0.001) between Sfree measured over 10 m and Cwfree measured by indirect calorimetry in 16 hemiparetic stroke patients [9]. This close relation between Sfree and Cwfree in hemiparetic stroke patients could allow practitioners to predict the Cwfree from the Sfree value, a reliable and easily measurable parameter in...
clinical practice [10]. Therefore, estimating the $C_w$ would be simple without the need for a gas exchange measuring device.

The objectives of the study were to verify the relation between $S_{free}$ and $C_{w_{free}}$ in hemiparetic stroke patients and to test the validity of a prediction model designed to estimate $C_{w_{free}}$ based on $S_{free}$.

2. Methods

2.1. Study design

We recruited 2 samples of participants, the first population used to explore the relation between $S_{free}$ and $C_{w_{free}}$ in case of a close relation between the 2 variables, we performed the development of a regression equation to develop a prediction model of $C_{w_{free}}$ based on $S_{free}$. A second population was recruited to evaluate the validity of the model. We also compared $C_{w_{free}}$ estimated by the prediction model and $C_{w_{free}}$ measured by the Metamax 3B spirometry device. We ensured that the criteria for inclusion and exclusion were the same for both populations.

2.2. Participant selection

Participants were recruited in the Physical and Rehabilitation Medicine Department of our hospital. The inclusion criteria were:

- a single stroke in any area of the brain, except the cerebellum and brain stem, confirmed by brain imaging;
- ability to walk continuously for 6 min with or without mobility aids.

The exclusion criteria were acute cardiac or respiratory pathologies or decompensated chronic pathologies. Cardiac disorders were identified by complementary examinations usually performed at post-stroke assessment (i.e., electrocardiography and cardiac ultrasonography). We did not perform a stress test before the study.

The health professional responsible for the protocol informed the patients of the details of the protocol before registering their verbal consent. This consent was transcribed in the database. The research protocol was approved by the French ethics committee (No. CERNI 2015-01-13-57).

2.3. Hemiplegia evaluation

Motor impairment was evaluated by the Demeurisse motricity index [11]. This test quickly assesses a patient’s motor impairment at 3 different points per deficient limb and is validated in stroke patients. A score is calculated from 5 levels of voluntary motor control on a scale to 0–100, a score of 100 considered healthy [11,12]. Spasticity was evaluated by the modified Ashworth scale [13]. Walking autonomy was assessed by the Functional Ambulation Classification modified [14]. Autonomy related to activities of daily living was evaluated by the Barthel index [15]. All these evaluations were performed by the same experimenter for all participants.

2.4. Equipment

$O_2$ consumption when walking was measured by indirect calorimetry with the breathing gas-exchange portable analyzer, Metamax 3B (Cortex Medical, Leipzig, Germany). The Metamax is a portable metabolic measurement system composed of a measurement module and a battery module. It measures gas volume by a bidirectional digital turbine. The $O_2$ and $CO_2$ concentrations are measured by using an electrochemical cell and an infrared analyzer. Oxygen flow ($VO_2$) and carbon dioxide flow ($VCO_2$) were calculated by standard metabolic algorithms based on the Haldane transformation [16]. Respiratory volume data and respiratory gas concentrations were transmitted live by telemetry to a computer. The system was paired to the Metasoft 3 software, v3.7.0 SR2.

The system was turned on for at least 20 min before each use and was calibrated before every test according to the manufacturer’s recommendations. The gas analyzers were first calibrated by using a reference gas (14.97% $O_2$, 4.96% $CO_2$, balance N2: ± 0.02% absolute, Hong Kong Specialty Gases), then the calibration exposed to ambient air was checked. Additionally, volume calibration involved using a standardized 3-L syringe (5530 series, Hans Rudolph, Inc., Shawnee, KS, USA).

2.5. Experimental design

All participants performed the whole test under the same conditions. The Metamax was first placed on the patient. With the patient resting on a chair, gas exchanges were recorded for 6 min. Then, the patient was asked to walk for 6 min in a 40-m loop, with no obstacle or U-turn. This 6-min duration was chosen because about 4 min are required to achieve metabolic stability in individuals with chronic pathologies [17,18]. Several studies of $C_w$ in post-stroke hemiparetic individuals have used a similar duration to obtain a stable metabolic state [7,9,19]. The main instruction for each patient was to maintain their $S_{free}$ for the duration of the test. $S_{free}$ was then calculated by dividing the distance walked by the time of the test (6 min).

2.6. Calculating $C_{w_{free}}$

$C_{w_{free}}$ was calculated from the patient’s $O_2$ consumption measured at a stabilized metabolic rate, defined by a variation in $VO_2$ lower than 2 mL$kg^{-1}$min$^{-1}$, as described in previous studies related to the oxygen cost of walking for post-stroke individuals [9]. To estimate $C_{w_{free}}$, we divided the $VO_2$ value at a stabilized metabolic rate per unit of time by $S_{free}$. Therefore, $C_{w_{free}}$ was expressed in milliliters of $O_2$ per kg$^{-1}$m$^{-1}$.

2.7. Statistical analysis

Our first objective was to evaluate the correlation between $C_w$ and $S_{free}$. Several authors have shown a high correlation between the two ($r = 0.8–0.9$, $P < 0.05$) in populations of fewer than 20 individuals [7,9,19]. Therefore, we considered we needed about 20 participants to demonstrate a statistically significant correlation. To validate the model, we considered that the average bias should be lower than 15%, with limits of confidence (± 2 SD) of about 30%. The mean oxygen cost values were about 0.63 mL$kg^{-1}$m$^{-1}$ (95% confidence interval [Cl], 0.53–0.72) [5]. Thus, the estimated mean bias was 0.1 mL$kg^{-1}$m$^{-1}$ (SD about 0.1 mL$kg^{-1}$m$^{-1}$). We used an alpha risk of 0.05 and a power of 80%. Using the formula provided by Bland–Altman, we estimated that we needed a sample of 32 participants to test the validity of the model [20].

Normally distributed data were analyzed by Anova and non-normally distributed data by a Mann–Whitney type of nonparametric test. Categorical data were analyzed by Chi$^2$ test. Correlation analysis of $S_{free}$ and $C_{w_{free}}$ involved the Spearman coefficient ($r$) and the coefficient of determination (R2). The rule of thumb for interpreting the size of a correlation coefficient was 0.90 to 1.00, very high; 0.70 to 0.90, high; 0.50 to 0.70, moderate; 0.30 to 0.50, low; and 0.00 to 0.30, negligible [21]. The accuracy was analyzed by the mean bias and difference percentages. The association between the estimated and measured $C_{w_{free}}$ was examined by
**Table 1**
Characteristics of the population.

<table>
<thead>
<tr>
<th></th>
<th>First population n = 26</th>
<th>Second population n = 29</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex (M/W)</strong></td>
<td>16/10</td>
<td>23/6</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Age (years)</strong></td>
<td>65.1 (15.7)</td>
<td>62.1 (13.4)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>BMI (kg.m⁻²)</strong></td>
<td>27.0 (5.7)</td>
<td>25.8 (4.3)</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Time since stroke (day)</strong></td>
<td>52.5 (9–5110)</td>
<td>80 (9–2920)</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>Stroke side (left/right)</strong></td>
<td>13/13</td>
<td>13/16</td>
<td>NS</td>
</tr>
<tr>
<td><strong>Index of Motricity of Demeurisse</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower limb (/100)</td>
<td>76 (43–100)</td>
<td>75 (47–100)</td>
<td>NS</td>
</tr>
<tr>
<td>Upper limb (/100)</td>
<td>77 (1–100)</td>
<td>75 (1–100)</td>
<td>NS</td>
</tr>
<tr>
<td>Spasticity (Ashworth scale modified) (/4)</td>
<td>1 (0–3)</td>
<td>1 (0–3)</td>
<td>NS</td>
</tr>
<tr>
<td>Barthel Index (/100)</td>
<td>72 (40–100)</td>
<td>80 (45–100)</td>
<td>NS</td>
</tr>
<tr>
<td>FACm (/8)</td>
<td>6 (3–8)</td>
<td>6 (3–8)</td>
<td>NS</td>
</tr>
<tr>
<td>Sfree (m.s⁻¹)</td>
<td>0.54 (0.30)</td>
<td>0.49 (0.30)</td>
<td>NS</td>
</tr>
<tr>
<td>Ambulation categories</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without AD = 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cane = 10</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Walker = 6</td>
<td></td>
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Data are mean (SD) or median (min–max).
BMI: body mass index; FACm: Functional Ambulation Classification modified; AD: assistive device; Sfree: spontaneous walking speed; NS: not significant.

Bland–Altman analysis. The significance level was evaluated by Fisher tests. For all tests, the statistical significance threshold was \( P < 0.05 \). All statistical analyses involved using RealStat2011.

### 3. Results

#### 3.1. Population

The first population included 26 participants and the second population 29 participants. Participants were included between January 2015 and April 2015. The 2 groups differed only in sex \( (P = 0.02) \) and time since stroke \( (P = 0.04) \) (Table 1). The populations were heterogeneous on several parameters: time elapsed since stroke, motricity impairment score, modes of ambulation, walking autonomy and activities of daily living scores.

#### 3.2. Relation between Cwfree and Sfree in the first population

The Cwfree values ranged from 0.18 to 2.74 mL.kg⁻¹.m⁻¹ (mean 0.54 [SD 0.51] mL.kg⁻¹.m⁻¹). Sfree was highly correlated with Cwfree \( (r = -0.94; \ R^2 = 0.97, \ P < 0.001) \) (Fig. 1). The relation between Sfree and Cwfree was modeled with the following regression equation: Cwfree = 0.2109.Sfree⁻⁰.⁸⁷⁷.

#### 3.3. Test of the validity of the Cwfree prediction model

We calculated the Cwfree of the second population \( (n = 29) \) by using the regression equation to test the validity of this model. The values of Cwfree for the 29 included participants were measured on the Metamax per the initial protocol and ranged from 0.18 to 4.80 mL.kg⁻¹.m⁻¹ (mean 0.82 [SD 1.10] mL.kg⁻¹.m⁻¹). The Cwfree values estimated with the prediction model ranged from 0.19 to 4.88 mL.kg⁻¹.m⁻¹ (mean 0.83 [SD 1.12] mL.kg⁻¹.m⁻¹). The correlation between Cwfree estimated by the model and measured with Metamax was high \( (r = 0.99 [95\% \ CI: 0.97–0.99] \) and \( R^2 = 0.98) \) (Fig. 2). Bland-Altman analysis showed a mean bias of −0.02 mL.kg⁻¹.m⁻¹ — mean difference percentage of 4%. The 95% limits of agreement were −0.31 to 0.26 mL.kg⁻¹.m⁻¹ — 30.9% of the mean measured Cwfree (Fig. 3).

### 4. Discussion

Our first objective was to assess the relation between Sfree and Cwfree. We found Sfree and Cwfree highly correlated, with \( r \) and \( R^2 \) values greater than 0.90. These results suggest that Cwfree could be predicted from Sfree with the model Cwfree = 0.2109.Sfree⁻⁰.⁸⁷⁷. Our second objective was to evaluate the accuracy of the Cwfree prediction model based on Sfree. We found a high correlation between Cwfree estimated by the model and measured by Metamax, with \( r \) and \( R^2 \) values greater than 0.90. The mean bias was less than 5% and the limits of agreement were close to 30% of the measured Cwfree. These results suggest that the Cwfree prediction model is valid.

Our results show a high correlation between Sfree and Cwfree, which is consistent with the results of previous studies in this domain. Zamparo et al. found a correlation coefficient of 0.92 \( (P < 0.001) \) between Sfree measured in a 40-m loop and Cwfree measured by indirect calorimetry in 20 post-stroke hemiparetic individuals [8]. Teissi et al. also reported a high correlation \( (r = 0.66, \ P < 0.001) \) between Sfree and Cwfree measured by indirect calorimetry in a literature review that included 54 hemiparetic stroke individuals [22]. Polase et al. reported a strong curvilinear relationship between Sfree and Cwfree in 55 stroke patients; the Sfree explained more than 80% of the variance in Cw [23].

However, the relation between Sfree and Cwfree is interpreted differently by each author. We decided to report a regression equation between Sfree and Cwfree like Zamparo et al., who had evaluated this relation in a population of 20 hemiparetic stroke individuals [8] (time elapsed since the stroke ranged from 3 to 264 months) walking in a 40-m loop. The authors reported the following regression equation between Sfree and Cwfree: ln(Cwfree) = 1.27–0.718 ln(Sfree). Once converted from logarithmic
to exponential, this equation is similar to our equation: $C_{\text{wfree}} = 3.56S_{\text{free}}^{-0.718}$. However, our results differ from Reisman et al. [9] and Detrembleur et al. [19], showing a rather heterogeneous linear relation between Cwfree and Sfree. Our combined populations represented 55 stroke patients with spread-out values for Sfree (mean 0.54 [SD 0.30] m.s$^{-1}$), whereas the population studied by Detrembleur et al. included 9 individuals with a mean Sfree of 0.73 (SD 0.21) m.s$^{-1}$ and the one studied by Reisman et al. comprised 16 individuals with a mean Sfree of 0.62 (SD 0.22) m.s$^{-1}$ [19]. Moreover, in the studies conducted by Detrembleur et al. and Reisman et al., the participants walked on a treadmill, which, according to other studies, can influence the Cw in older people and post-stroke individuals [24,25]. The close relation we found between Cwfree and Sfree is easier to demonstrate in a large sample of people with various levels of Sfree, which provides enough power to produce a robust analysis. However, Detrembleur et al. and Reisman et al. did not report the formulas of the regression equations shown in their figures, which prevents us from exploring these hypotheses further.

Deducing the Cwfree from the Sfree facilitates its measurement in clinical practice. Indeed, Cwfree requires the use of a costly and inconvenient breath gas analyzer, whereas Sfree measurement is simple, valid and reliable, with high (> 0.90) test–retest and inter-rater reliabilities [10]. Many Sfree measurement methods have been described and the results they provide are generally close or equivalent among various methods [10]. Some studies report that measurements of Sfree with a short distance (6–15 m) overestimate the resulting value of Sfree in a 6-min walk [26]. However, Dobkin et al. found that this hypothesis was not confirmed in stroke patients, with equivalent values of Sfree between a 10-m and 6-min measurement [27]. In our study, we chose to measure Sfree over 6 min to simplify the test because we could measure Cwfree concurrently. We believe that a measurement over 10 m would have had no significant impact on the relation with Cwfree. Indeed, our results are close to those of Polese et al., who showed that Sfree measured over 10 m explained 81% of the variance of Cwfree in a population of 55 stroke patients [23].

Several authors have hypotheses to explain the relation between Sfree and Cwfree. Speed of movement is associated with level of energy expenditure [28,29]. According to Schrack et al., the reduction in Sfree corresponds to an adaptation mechanism to restrict the increase in energy cost caused by deficiencies. However, this adaptation occurs at the expense of Cwfree because the human body is designed to have an optimal Cwfree for a Sfree between 1.1 and 1.3 m.s$^{-1}$ [30]. With a lower Sfree, the Cwfree is increased, so walking is more expensive in energy for the same distance travelled. If Cwfree is higher, the person’s energetic capacities are exhausted more quickly, leading to increased fatigue, lack of stamina or even discontinuation of activity [5,31]. Sfree would be the clinical representation of concepts of both biomechanical and energetic solicitation of walking, so it is clinically relevant and prognostic.

A number of studies has shown that gait speed is primordial for the effectiveness of walking-centered rehabilitation interventions [32] and is highly associated with the different levels of community ambulation [33,34,35]. Perry et al. classified gait speed of > 0.4 m.s$^{-1}$ as equivalent to room ambulation, 0.4 to 0.8 m.s$^{-1}$ as equivalent to limited community ambulation, and > 0.8 m.s$^{-1}$ as equivalent to community ambulation [35]. In comparison, Franceschini et al. established that a Cwfree threshold of 0.40 mL.kg$^{-1}$.m$^{-1}$ discriminates an individual with ability for community ambulation (Walking Handicap Scale > 3) [35]. According to our work, a value of 0.40 mL.kg$^{-1}$.m$^{-1}$ corresponds to a walking speed of 0.5 m.s$^{-1}$, which is consistent with the results of Perry et al. Therefore, our results would allow for matching the Cwfree values to Sfree prognostic values, which has not often been reported. This would then be one of the elements to explain why these Sfree values are so discriminating.

Thus, from measuring Sfree, the practitioner would have access to oxygen consumption per meter and then to energy expenditure

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**Fig. 2.** Correlation between estimated and measured Cwfree.

**Fig. 3.** Bland–Altman analysis of estimated and measured Cwfree.
after conversion of oxygen volumes by an energy equivalent. Although rigorously converting an oxygen volume to kcal requires an estimated energetic equivalents (kcal) per 1 L of O₂ consumed for a selected respiratory quotient values [36], many authors admit that 1 L of O₂ consumed during activities of moderate intensity equals a value close to 5 kcal [7,37,38]. With this approximation, it would then be possible to quantify the energy expenditure for each individual based on their Sfree. To our knowledge, no study has evaluated this type of prediction model to estimate energy expenditure in stroke individuals.

Several practical applications are worth considering. For example, we could construct a table of the subjects’ energy expenditure according to their weight and Sfree, for easily and quickly assessing their energy expenditure (additional Fig. S1). Thus, the practitioner could quantify the energy expenditure summarily by evaluating the walking distance travelled by the patient over a day. This approach would allow practitioners to judge whether the patient reaches the energy expenditure levels recommended by the US Department of Health and Human Services of 142 kcal/day [39]. In addition, it would be possible to prescribe a customized daily walking distance based on the patient’s Cwfree to achieve their recommended energy expenditure objective (additional Fig. S2). To guarantee the objectivity of the distance measurement, an accelerometer could be included among the models validated in a post-stroke population [40]. In our opinion, this is an interesting approach for quantifying and prescribing physical activity in this type of population. Complementary studies are required to evaluate the feasibility and effectiveness of this type of intervention.

Limitations: our study may have been limited by the number of included subjects. However, our results are bolstered by our results confirming the study performed by Zamparo et al. and by testing our model on a second population. Patients with extreme values of Cwfree and Sfree also allowed for strengthening the correlation between these two values. Without the inclusion of these patients, the relation found between Sfree and Cwfree might have been different. One of the strengths of this model is its accuracy regardless of the participant’s walking speed (very slow to subnormal). In addition, our results are consistent with those of Zamparo et al., who included participants with similar characteristics to ours. This association will have to be confirmed by other works including participants with homogeneous walking speeds. Moreover, our work did not explore the sensitivity to change (smallest worthwhile change) and reliability of the model (intraclass correlation coefficient). Further work is needed to assess these parameters.

5. Conclusions
This study demonstrates a very high correlation between Cwfree and Sfree, which led to the development of an accurate prediction model of Cwfree based on Sfree. The availability of Cwfree in clinical practice may help the practitioner estimate the level of energy expenditure of walking in each stroke patient and establish walking distance recommendations adapted to their metabolic demands.

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Disclosure of interest
The authors declare that they have no competing interest.

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Appendix A. Supplementary data
Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rehab.2018.03.001.

References


