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Article

Does Accelerometry at the Centre of Mass Accurately Predict the Gait Energy Expenditure in Patients with Hemiparesis?

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Abstract: Background: The aim of this study was to compare energy expenditure (EE) predicted by accelerometery (EE_{ACC}) with indirect calorimetry (EE_{META}) in individuals with hemiparesis. Methods: Twenty-four participants (12 with stroke and 12 healthy controls) performed a six-minute walk test (6MWT) during which EE_{META} was measured using a portable indirect calorimetry system and EE_{ACC} was calculated using Bouten's equation (1993) with data from a 3-axis accelerometer positioned between L3 and L4. Results: Median EE_{META} was 9.85 [8.18;11.89] $W \cdot kg^{-1}$ in the stroke group, and 5.0 [4.56;5.46] $W \cdot kg^{-1}$ in the control group. Median EE_{ACC} was 8.57 [7.86;11.24] $W \cdot kg^{-1}$ in the control group and 8.2 [7.05;9.56] $W \cdot kg^{-1}$ in the stroke group. EE_{ACC} and EE_{META} were not significantly correlated in either the control (p=0.8) or the stroke groups (p=0.06). The Bland-Altman method showed a mean difference of 1.77±3.65 $W \cdot kg^{-1}$ between EE_{ACC} and EE_{META} in the stroke group and -2.08±1.59 $W \cdot kg^{-1}$ in the controls. Conclusions: The accuracy of the predicted EE, based on the accelerometer and the equations proposed by Bouten et al, is low in individuals with hemiparesis and impaired gait. This combination (sensor and Bouten's equation) is not yet suitable for use as a stand-alone measure in clinical practice for the evaluation of hemiparetic patients.

Keywords: accelerometery; energy expenditure; stroke; gait; six-minute walking test

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1. Introduction

Physical activity measurements have been used to indirectly quantify energy expenditure in individuals with various pathologies for several years [1–4]. Connected devices such as watches, bracelets or smartphone applications, which are designed to increase the activity levels of the general public, have become popular among clinicians due to their ease of use and their low cost. Such devices have thus been integrated into clinical practice and research to indirectly quantify energy expenditure [5]. Studies comparing results from off-the-shelf connected devices with specialised, equivalent medical devices or indirect calorimetry (which is the gold standard) have found that they accurately record data like the number of steps, distance covered and reliably estimate energy expenditure in healthy subject [6,7].

Increasing the level of physical activity for people with a chronic pathology, such as stroke, has been shown to reduce their co-morbidities [8,9]. The evaluation of the impact of stroke treatments would be improved if clinicians could reliably and easily measure the amount of activity performed by their patients [10]. Study have shown that patient with stroke are more inactive than healthy age-matched controls [11]. Research has also shown that energy expenditure is doubled in patients with stroke due the sequalae (mainly weakness and spasticity) of their hemiparesis [12].

Feedback on patients' activity levels would not only inform healthcare providers, it might also motivate individuals with stroke to perform regular physical activity, and is therefore recommended by the HAS (Haute Autorité de Santé) [13]. The accessibility of new technologies and connected devices that are easily integrated into peoples' daily lives and which allow activity to be tracked, such as smartphone applications and smart watches, have simplified the collection of detailed data relating to physical activity levels out with the hospital setting [14]. Nevertheless, several studies have indicated that inter-device reliability can be poor due to factors like the device's position on the body, the recording method used, and the equations used to process the data, all of which result in either an over- or under-estimation of energy expenditure [15]. As a result, the use of connected devices is currently a less reliable measurement technique than indirect calorimetry [16].

Therefore, despite the promise of such devices, the clinical interest in them and the work on their development, there is currently no consensus for their use in individuals with chronic diseases and significant gait asymmetry. Optimal sensor types and positions for the accurate evaluation of physical activity levels and energy expenditure have yet to be identified. One method frequently reported in the literature [17–20] is Bouten's method [21]. This method has been validated in healthy individuals although not in people with gait disorders [22]. Bouten's method uses a regression equation to calculate the integral of signal data recorded by an accelerometer, positioned between L3 and L4 (so as to be close to the person's centre of mass) in three planes of space (x, y, and z) in order to estimate energy expenditure during gait.

Moreover, following a cardiovascular accident (stroke), we often observe motor impairment caused by either a hemorrhage (hemorrhagic stroke) or a blocked artery (ischemic stroke) in the motor cortex. Neuromuscular disorders result from that, causing locomotor impairments. In terms of spatiotemporal parameters of gait cycle, reduced the speed, cadence, and stride length are observed [23,24]. At the joint kinematic level, we can observe disturbance in flexion [25]. At the hip level, there can be limitations in knee elevation due to impaired flexion and/or hip extension [26]. This can lead to difficulties in overcoming obstacles. In terms of the knee joint, during the stance phase, hyperextension and a deficit in flexion during the swing phase can be observed [27]. These issues can be explained, on one hand, by the overactivity of the triceps surae, resulting in knee extension and plantar flexion disturbance, and on the other hand, possibly by the overactivation of the rectus femoris. Finally, at the ankle level, there is often hyperactivity of the plantar flexors and weakness of the dorsiflexors. These impairments can lead to foot drop [28]. The aforementioned impairments result in a significant increase in energy cost during walking [24]. This means that the patient will expend more energy per unit of distance compared to someone without pathology [29]. The need to evaluate the effects of therapies on these gait disorders is essential. Consequently, the evaluation of the energy cost of walking, or more simply of energy expenditure, is relevant to support clinicians in the overall evaluation of the effects of the therapies chosen. In fact, the connected objects allowing this indirect measurement have a preponderant place in the evaluation of the impact of therapeutics on the autonomy of walking. So, a question arises: are connected tools using the Bouten's method sufficiently accurate to estimate energy expenditure in patients who have had a stroke?

The aim of this study, therefore, was to compare the accuracy of energy expenditure values calculated using Bouten's regression equation method [21] with those obtained from the gold standard method of indirect calorimetry. This work would help to validate the use of Bouten's method as a simple way to assess people who have stroke-related hemiparesis and impaired gait. Data were compared for both methods from two groups of subjects, n=12 individuals with stroke and impaired gait, and n=12 healthy controls during a 6-minute walk test (6MWT).

2. Materials and Methods

2.1. Participants

Participants with stroke or impaired gait were recruited either during a routine follow-up medical consultation, or while they were hospitalised in rehabilitation. Inclusion criteria were: aged over 18 years, able to walk without assistance or assistive devices, able to carry out the 6MWT according to the recommendations and without any known cardiovascular contraindications [22]. Their main sequelae are locomotor disorders due to hemiparesis. The twelve participants with stroke included 10 males and 2 females; their median age was 50.5 years [interquartile range (IQR) 41.25;53.25]; median height: 175 [170.0;177.0]; median weight: 73kg [62.0;83.0]).

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A group of twelve control subjects (8 males and 4 females) were also recruited. Their results were important not only as they allowed a comparison between the two experimental groups, but also because their data ensured that any effects noted were not an artefact of the experimental set-up used in this study, since Bouten's method has been validated in healthy individuals [22]. Inclusion criteria for the control group were: aged over 18 years and with no known neuromuscular pathologies. Their median age was 29 years [IQR 24.0;33.7], median height =177cm [169.8;177.0] and median weight: 69kg [60.0;75.5].

The study was granted ethical approval, all participants provided informed consent for participation and the study was carried out according to the Helsinki declaration.

Study design

All participants performed the 6MWT, as recommended by American Thoracic Society [30], as quickly as possible along a 30m-long corridor that was marked every 2 metres. The distance covered was measured at the end of the test. Participants wore a portable gas exchanger (K4b^2, COSMED, Rome, Italy) and a three-axis accelerometer (EQO2, Equivital, Cambridge, UK). We choose the 6 Minute Walk Test (and its performance criteria including a walk that covers the greatest distance despite the difference in walking speed) by its common use for functional or cardio-respiratory evaluations.

2.2. Procedures

2.2.1. Indirect calorimetry

Analysis of the gas expired from each respiratory cycle provided the reference measurement of energy expenditure (EE$_{META}$). The system was calibrated in the corridor where the test was performed according to standard procedures.

EE$_{META}$ was calculated when $\dot{V}O_2$ kinetics reached a stable state. The $\dot{V}O_2$ values (Kcal·min^{-1}) were initially smoothed using a 3-point moving average, then the last 150 seconds of each 6MWT were averaged. The EE$_{META}$ was then converted to W·kg^{-1}.

2.2.2. Accelerometery

A lightweight (38g), compact (78x53x10mm), three-axis accelerometer (250 Hz) was used to capture the acceleration of the centre of mass in the three planes of space. It was positioned between the third and fourth lumbar vertebrae using a custom-made support. This has previously been recommended for the optimal estimation of energy expenditure [17,31,32]. A connected chest-strap monitor (EQO2, Equivital, Cambridge, UK) was used to measure heart rate during the 6MWT.

2.2.3. Estimation of energy expenditure (EE_{ACC})

Bouten's method was used to estimate energy expenditure [21]. The raw signals were initially filtered using a Butterworth filter (4th order with a 20 Hz cut-off frequency). The absolute values of the signal obtained in the three axes (IAAtot) were then calculated in 30-second periods then summed for the duration of the test [21]. The following equation was used to obtain predicted EE$_{ACC}$ (W·kg^{-1}):

$$EE_{ACC} = 0{,}104 + 0{,}23 \times IAAtot$$

2.3. Statistical analysis

The results for the descriptive and interferential statistics were described by the median, and the first and last quartiles (Q1 and Q3). The level of significance was set at $p \leq 0.05$. The normality of the distribution was verified using a Kolmogorov-Smirnov test.

The results from Bouten's method and indirect calorimetry we're not normally distributed therefore we chose to use a Mann-Whitney test to compared using a Mann-Whitney test (non-homogenous sample with independent samples). The relative agreement between the EE$_{META}$ and

EEACC values of the groups was compared using Spearman rank correlations. Absolute agreement was calculated using the Bland-Altman method (± limits of agreement set at 95%) [33].

3. Results

The variables measured during the 6MWT are presented in Table 1. There were significant differences between the groups for $\dot{V}O_2$ values and distance walked (highest in the control group), but no difference in heart rate.

Table 1. Variables measured during 6MWT.

	Control group			**Patient with stroke**			**Mann-Whitney**
	Médian	**Q1**	**Q3**	**Médian**	**Q1**	**Q3**	
HR (bpm)	140.0	98.1	143.7	116.0	90.1	126.5	p=0.08
$\dot{V}O_2$ (mL.min^{-1}.kg^{-1})	28.65	23.35	33.83	13.55	12.63	15.8	p=0.0001
Distance (m)	686.5	660.0	729.7	341.0	310.0	442.0	p=0.0001

We observe a significant difference in measurement between median EEMETA, for patient with stroke and control respectively. Median EEMETA was 9.85 [8.18;11.89] W·kg-1 in the stroke group, and 5.0 [4.56;5.46] W·kg-1 in the control group (p<0.0001). For the accelerometric method, median EEACC was not significantly different. EEACC was 8.2 [7.05;9.56] W·kg-1 in the stroke group and 8.57 [7.86;11.24] W·kg-1 in the control group (p=0.11) (Table 2).

Table 2. Comparison of EE measurements between methods (EEACC and EEMETA).

		Median	**Q1**	**Q3**	**Mann-Whitney**
EEMETA *(W·kg^{-1})*	Control group	9,85	8,18	11,89	**p<0,0001***
	Patient with stroke	5,0	4,56	5,46	
EEAcc *(W·kg^{-1})*	Control group	8,57	7,86	11,24	p=0,11
	Patient with stroke	8,2	7,05	9,56	

EEACC and EEMETA were not significantly correlated in either the control (Spearman's r=0.086: p=079) or the stroke groups (Spearman's r=0.56: p=0.06) (Table 3).

Table 3. Correlation between energy expenditure measured using K4b² and the accelerometric method.

		Median	**Q1**	**Q3**	**Correlation coefficient**
Control group	EEMETA *(W·kg^{-1})*	9.85	8.18	11.89	r=0.09 ; p=0.79
	EEAcc *(W·kg^{-1})*	8.57	7.86	11.24	
Patient with stroke	EEMETA *(W·kg^{-1})*	5.0	4.56	5.46	r=0.56 ; p=0.06
	EEAcc *(W·kg^{-1})*	8.2	7.05	9.56	

The Bland-Altman analysis showed large differences between EEMETA and EEACC measurements in the stroke group with a mean over-estimation of EEACC of 1.16 ± 3.70 W·kg^{-1} (p=0.3) relative to EEMETA (Figure 1A). In the healthy group, EEACC was under-estimated by a mean of -2.43 ± 1.45 W·kg^{-1} (Figure 1B).

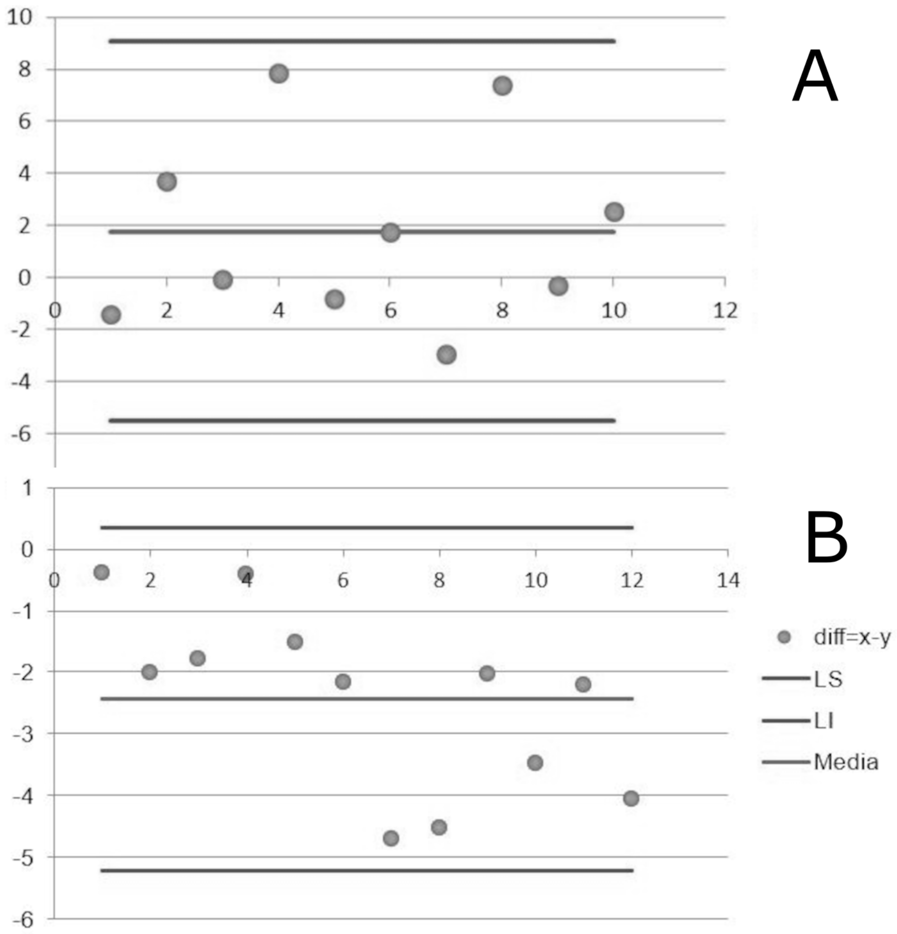

Figure 1. Bland-Altman stroke (A) and with healthy participant. UL (B) between EE_{META} and EE_{ACC}.

4. Discussion

The purpose of this study was to compare the accuracy of energy expenditure values calculated using accelerometry signal, via Bouten’s regression equation method, with those obtained from the oxygen uptake of in-direct calorimetry. The results of this study showed differences between energy expenditure (EE) during a 6MWT calculated by indirect calorimetry (EE_{META}) and estimated using Bouten’s method (EE_{ACC}) in both healthy volunteers (control) and individuals with stroke. The use of Bouten’s regression equation led to a 17% under-estimation in the control group and a 49% over-estimation in the calculated energy expenditure in comparison to the gold standard indirect calorimetry results in the stroke group (i.e., $EE_{ACC}>EE_{META}$).

The first interesting result (Table 2) shows that when EE is calculated using indirect calorimetry, there is a significant difference between the control group and patients with stroke. This difference is consistent with the study by Slawinski, which shows that strokes have a lower EE because their walking speed is significantly lower than that of healthy subjects. In this study, these authors also found that the addition of obstacles during a gait test did not affect $\dot{V}O_2$ in patients with stroke [24] as they were already at their $\dot{V}O_2$ peak and could not increase their O_2 consumption further because of their limited gait. Our EE_{META} results agree with those from that study, namely that the EE_{META} value of the stroke group participants was half that of the control EE_{META}. This difference was mainly due to the difference in the distances covered during performance of the 6MWT: the stroke group covered an average of 339 m, whereas the controls covered, on average, 696 m. Collectively these results suggest that the reduction in distance covered by patients with stroke is related to an increase in extraneous movements required for movement control and balance in these patients.

The second interesting result concerns the comparison between strokes and controls in terms of EE estimated using accelerometery and the Bouten’s method. In fact, there is no longer difference in

EE_{ACC}. In other words, EE_{ACC} is the same for both, strokes and controls. These results confirm the previous hypothesis regarding extraneous movements associated with the locomotion of patients with stroke. In the stroke group, the over-estimation of EE_{ACC} by Bouten's method (compared to gold standard method) was likely due to the individuals' abnormal segmental kinematics. An increase in vertical oscillations of the pelvis is a common gait anomaly following stroke [27]; it is related to various kinematic anomalies such as knee hyperextension (genu recurvatum) or a stiff gait (lack of knee flexion during swing) [34,35]. The position of the accelerometer just above the pelvis (between L3 and L4) meant that all compensatory movements performed by the subjects as a result of motor and sensory impairments were also recorded. The use of the integral of the unit vector of the accelerometer (IAA_{tot}) to calculate EE in Bouten's method then amplified the EE_{ACC} value. More the accelerometer moves due of the compensating movements, higher is the amplitude of the accelerometer signals and bigger is the IAA_{tot}.

The third surprising (table 3 and figure 1) results was to find that the control group results contrasted with those described by Bouten et al.[22] The original paper had reported a mean over-estimation of EE_{ACC} of 15% in a group of 11 young healthy adults walking at different speeds. However, for a gait speed of 7 $km.h^{-1}$, EE_{ACC} was overestimated by 8%. By contrast, in the present study, at almost the same gait speed (6.97 ± 0.79 $Km.h^{-1}$), Bouten's method actually under-estimated energy expenditure in the control group by 17%. This contradiction has been observed elsewhere: other studies have also reported both over- and under-estimations of EE when using accelerometery and comparing the results to indirect calorimetry in healthy subjects [36]. Indeed, two studies that used accelerometer device reported opposing results: Bai et al. (2016) found an over-estimation [37] while Imboden et al. (2018) found an under-estimation [38]. These variations were likely due to differences in the tasks (gait speed, cadence etc.). There is currently no consensus regarding the level of acceptable errors or whether they relate to under or over-estimations of EE. For strokes, EE_{ACC} over-estimate EE of 1.16 ± 3.70 $W \cdot kg^{-1}$. These results confirm the variability of accelerometric measurements when used to estimate energy expenditure. This measurement variability likely explains the lack of correlation observed between the two measurement methods.

The present results associated with those of previous studies shows that there is currently no consensus regarding the level of acceptable errors or whether they relate to under or over-estimations of EE. The variety of EE_{ACC} results obtained by different research groups suggests that it is important to be aware of the limitations in the use of accelerometers. We recommend that in order to take advantage of the convenience of accelerometer measurements, healthcare practitioners should produce their own reference data within their own setting and in patients with different pathologies using both indirect calorimetry and accelerometery in order to make informed interpretations of the accelerometery data.

The present study was different to other studies of EE_{ACC} with regards to two methodological aspects: (1) the choice of accelerometer signal processing method and (2) the positioning of the sensor. In terms of the first point, signal processing by the root mean square has been largely replaced by count per minute [39]. Nevertheless, there is currently no accepted consensus in the literature regarding threshold values for activity detection. This may, at least in part, be due to inter-individual variations caused by variables such as age or existing medical conditions. For example, it has been reported that it was difficult to calculate EE_{ACC} in older patients when using gait thresholds taken from younger adults: older people had a naturally wider range of inappropriate movements compared to younger adults which led to unreliable detection of EE in the older population [16].

With regards to sensor position, Compagnat et al. (2018)[40] found a mean difference in predicted energy expenditure between 3 and 58% in patients with hemiparesis when the sensor was positioned on the wrist rather than the pelvis. However, Bouten et al. (1997) recommends positioning the sensor between L3 and L4 [17] in order to quantify movement of the centre of mass, and this position is used in many studies [18,20,24,35,36]. We think that it seems more logical to place the sensor around the pelvis if the aim is to record compensatory gait movements, and to objectify the patient's progress during rehabilitation. Finally, recent works[41] demonstrated that the choice of the oxygen cost prediction equation ;can greatly improve the estimation of stokes daily energy expenditure.

The main limitation of this study was the inclusion of patients with diverse gait patterns. Unfortunately, there were too few patients with each type of gait pattern to determine the effects of different compensatory movements and to refine the prediction equation accordingly. On the other hand, our sample was small and did not walk at the same speed. We can also observe a mismatch between gender and age.

5. Conclusions

In conclusion, therefore, results from this study suggest that the 1993 Bouten method [21] does have potential to be of considerable practical value for quantifying rehabilitation-induced changes in gait (better gait is and less compensatory movement acting on the IAA_{tot}). In addition to being it being cheaper and more accessible than indirect calorimetry, Bouten's method to assess energy expenditure using an accelerometer also accounts for compensatory lower limb movements that occur as part of pathological gait. However, we should also stress that this method is, at present, unvalidated in the wider research community and not always predictable in terms of how EE_{ACC} results vary in comparison to EE_{META}, even from the same populations. Therefore, this tool is not yet suitable for use as a stand-alone measurement in routine practice for the assessment for any patient with stroke-related hemiparesis and impaired gait. Further investigations are required to ensure that necessary corrective coefficients are known for different patient groups, and pathologies, in order to ensure the accuracy and reliability and reproducibility of EE_{ACC} values for the different combinations of patient demographics and pathologies.

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