Journal of Medical Engineering & Technology, Vol. 29, No. 2, March/April 2005, 90–94

A quantitative gait assessment method based on energy exchange analysis during walking: a normal gait study

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In this paper a gait efficiency assessment method, Gait Energy Efficiency Index (GEEI), which can be used in evaluation of the progress of the rehabilitation process in disabled persons, is proposed and described. The method is based on calculation of cross correlation between normalized time courses of kinetic and potential energy of the body's centre of mass (COM). We hypothesized that GEEI in energetically optimal normal walking should be high and invariable of gait speed. The method was tested on twelve healthy subjects walking at three different speeds and contrasted to five established gait energy consumption assessment methods. The results showed that GEEI in normal walking is close to 1 regardless of walking speed.

Introduction

Energy consumption is a very important factor in the assessment of gait quality, and it has been used as a criterion in quantitative gait analysis for a long time. Energy consumption during walking can be calculated in different ways: (1) by measuring the consumption of oxygen [1]; (2) by measuring heart rate [2]; and (3) by measuring the coordinates of different points of human body (biomechanical measurements) [3, 4]. A human always tends to walk at minimum consumption of energy [5]. Several studies of energy efficiency during walking were undertaken. Most authors define gait efficiency as a quotient between the external mechanical work and the metabolic energy cost [5, 6].

Exchanges between potential and kinetic energies for all body segments are evident in walking of healthy subjects [7]. Effective exchanges of potential and kinetic energy are required for energy-efficient gait, and also in impaired subjects undergoing rehabilitation [8]. In our work we hypothesized that if gait is energy efficient then the fluctuations of potential and kinetic energy of the body's centre of mass (COM) should be close to ideal, and this should be reflected in a correlation between time courses of potential and kinetic energy being close to 1. Furthermore, the above statement should be valid for a range of different walking speeds.

The aim of this paper is to examine the above hypothesis and to propose a new simple method for quantitative gait assessment. The method comprises the calculation of correlation between time courses of potential and kinetic energies of the body's approximate centre of mass (COM) during walking. This correlation is obtained from the trajectory of a single marker attached to the back of a walking subject at the approximate middle level between the posterior superior iliac spine anatomical landmarks. The results of the proposed method are contrasted to the results of five established quantitative gait assessment methods.

Materials and methods

Subjects

Twelve healthy volunteers (eight males and four females) participated in the study. The subjects had an average age (mean ± SD) of 27.25 ± 4.37 years, height of 1.79 ± 0.09 m and mass of 72.83 ± 13.66 kg. Prior to the experiments the subjects signed a written consent.

Instrumentation

Biomechanical measurements. 3D coordinates of 17 hemispherical passive reflective markers attached to the subjects' bodies were measured by the Elite Motion Analysing System (BTS S.r.l., Milano, Italy) with four TV cameras. The cameras were positioned behind the subject. A pair was placed at each side of the subject in a vertical configuration

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Journal of Medical Engineering & Technology
ISSN 0309-1902 print/ISSN 1464-522X online
http://www.tandf.co.uk/journals
DOI: 10.1080/03091900412331271167

[9]. The markers were placed on the following anatomical landmarks: two markers on the fifth metatarsal heads, two markers on the lateral malleoli, two markers on the lateral femoral condyles, two markers on the posterior superior iliac spines (these markers were supported by small brackets in order to avoid the marker on one side being seen by the contralateral pair of TV cameras), one marker on the sacrum bone (this marker was supported by a pin), two markers on the acromion bones (supported by small brackets), two markers on the lateral humerus epicondyles, two markers on the styloideus process and two markers above the ear canals. The sampling frequency was 100 Hz, the acquired data were filtered by a LAMBDA (Linear-phase Autoregressive Model-Based Derivative Assessment algorithm) filter, which is incorporated in the Elite system. The LAMBDA algorithm is based on two principles: (1) cut-off frequency of the filter is set automatically thereby eliminating errors caused by operators; and (2) data are extrapolated for elimination of potential distortions. From the coordinates of markers on the lateral malleoli (ankles) the duration of a stride was determined. A 12-segment sagittal plane body model was developed. It was composed of three segments for each leg, two segments for each arm, one segment for the head and one segment for the trunk and the pelvis [9, 10].

Measurement of consumption of oxygen. The expired air was collected in a meteorological balloon (Totex Corp., Tokyo, Japan) for two minutes. After each walking run, the volume and % of O_2 and CO_2 in the expired air were determined. Samples of the expired air were analysed according to standard procedures using the oxygen analyser MK 200 (Jožef Stefan Institute, Ljubljana, Slovenia), the carbon dioxide analyser ULTRAMAT 22P (Siemens AG, Munich, Germany) and the flow meter S430A (KL Engineering, Northridge, USA). The obtained values were corrected for STPD (standard temperature, pressure and dryness).

Measurement of heart rate. The heart rate (HR) was recorded for 1 minute by a system for physiological measurements [11]. Afterwards, the measured data were downloaded to a PC to calculate the average HR.

Protocol

In each measurement four trials were made. Each trial commenced with the measurement of oxygen consumption rate during rest. For this purpose the subjects sat on a chair in a relaxed position for 5 minutes. During the final three minutes, expired air was collected in the balloon. Afterwards, the subjects walked on a 15-m long walkway at three different speeds (0.4 m s^{-1}, 1.4 m s^{-1} and 1.8 m s^{-1}). The speed was controlled by a self-constructed mechanism consisting of two wheels (0.1 m in diameter, placed 15 m apart) and a wire stretched around the wheels. One wheel was powered by a small electromotor with adjustable angular velocity. The subjects were instructed to follow a mark attached to the wire. They walked in a plane parallel to the coordinate system of the optical measurement system. On each side of the leading wire the subjects turned and started walking in the opposite direction. Subjects walked at a constant speed for 7 minutes. In the fifth minute five strides were captured by the optical measurement system. During the sixth and seventh minutes expired air was collected in the meteorological balloon. HR was monitored during seventh minute of walking. After the trial the content of the balloon was analysed and the HR data downloaded to a PC.

Data analysis

The positions of the COM for each segment and the whole body were calculated from the 3D kinematics by using tables in the literature [7]. Height and speed of the body's COM were calculated, yielding its potential and kinetic energy, PE_k and KE_k, respectively:

$$PE_k = Mgh_k, \tag{1}$$

$$KE_k = \frac{Mv_k^2}{2}, \tag{2}$$

where M represents the mass of the body, h_k the height of body's COM in the k-th time interval and v_k the horizontal speed of body's COM in the k-th time interval.

The time courses of the body's COM potential and kinetic energy were first normalized:

$$PE_k^{(\mathrm{NORM})} = \frac{PE_k}{\sqrt{\sum_{k=1}^{N} PE_k^2}}, \tag{3}$$

$$KE_k^{(\mathrm{NORM})} = \frac{KE_k}{\sqrt{\sum_{k=1}^{N} KE_k^2}}, \tag{4}$$

where $PE_k^{(\mathrm{NORM})}$ and $KE_k^{(\mathrm{NORM})}$ are normalized potential and kinetic energies of the body's COM in the k-th time interval, respectively. The index k represents samples ($k = 1, 2, \ldots, N$) and N is the number of samples in one stride. The cross-correlation (ρ_p) between the normalized functions was calculated as follows:

$$\rho_p = \sum_{q=0}^{N-|p|-1} PE_p^{(\mathrm{NORM})} KE_{p+q}^{(\mathrm{NORM})}, \tag{5}$$

where p represents the number of the corresponding sample, $p = -(N-1), \ldots, 0, \ldots, N-1$. The first half of the cross-correlation function (i.e. for p ranging from $(N-1)$ to 0) was compared with the discrete function F_k, which was defined as:

$$F_k = k, \tag{6}$$

where $k = 1, 2, 3, \ldots, N$. Pearson's correlation coefficients (r) were calculated between the samples of ρ_p and F_k:

$$r = \frac{N \cdot \sum(\rho F) - (\sum \rho)(\sum F)}{\sqrt{N\sum \rho^2 - (\sum \rho)^2}\sqrt{N\sum F^2 - (\sum F)^2}}, \quad (7)$$

where $\Sigma(\rho F)$ is the cumulative sum of products of each pair of samples, $\Sigma\rho$ is the sum of samples of ρ_p, ΣF is the sum of samples of F_k, $\Sigma\rho^2$ is the sum of squared samples of ρ_p, and ΣF^2 is the sum of squared samples of F_k. Gait Energy Efficiency Index (*GEEI*) was defined as

$$GEEI = r. \quad (8)$$

GEEI is a measure of the similarity between the time courses of PE_k and KE_k. The higher the value of GEEI the closer is similarity between time courses of compared energies. Ideally, this value should be 1.

As well as from defining and calculating GEEI we repeated the whole calculation of equations (1–8) for an approximate value of COM, derived from the trajectory of the midline position of both markers attached to posterior superior iliac spine anatomical landmarks. The resulting measure was defined as AGEEI. This was done to investigate the potential similarity between the two similar gait energy efficiency measures.

ETASEG is a measure of mechanical work performed during one stride. Mechanical work is a sum of changes in mechanical energy of all body segments during one stride, calculated according to Pierrynowski [13]:

$$W_{wb} = \sum_{k=1}^{N}\left|\sum_{i=1}^{S}(\Delta E_{i,k})\right|, \quad (9)$$

where W_{wb} denotes the mechanical work performed during one stride, and $\Delta E_{i,k}$ the change in mechanical energy of the i-th body segment during the k-th time sample. N is number of time samples during one stride and S is number of body segments.

ETASEG was calculated from the data of body segment energies during single stride according to the definition of Winter [3]:

$$ETASEG = \frac{W_{wb}}{Ml}, \quad (10)$$

where l is the change in the horizontal coordinate of the body's COM.

GEEI, AGEEI and *ETASEG* for each subject were obtained by averaging values of five captured strides.

The metabolic energy expenditures during rest and walking (E_r and E_w, respectively) were calculated using the energy equivalent of the oxygen. The metabolic energy consumption rate (*NE*) and the Energy Physiological Cost Index (*EPCI*) were calculated [10] as follows:

$$NE = E_w - E_r, \quad (11)$$

$$EPCI = \frac{E_w - E_r}{v}, \quad (12)$$

where v is the walking speed.

From the averaged HR of each trial the Heart Rate Increase (*HRI*) and the Physiological Cost Index (*PCI*) were calculated [2, 12]:

$$HRI = HR_w - HR_r, \quad (13)$$

$$PCI = \frac{HR_w - HR_r}{v}, \quad (14)$$

where HR_w and HR_r are average heart rates during walking and rest, respectively.

Results and discussion

Figure 1 shows representative time trajectories for the potential and kinetic energy of COM in one of the tested subjects at a gait velocity of 1.8 m s^{-1}. We can observe almost perfect out-of-phase fluctuations, suggesting efficient energy exchange. Figure 2 shows the averaged values and standard deviations of GEEI and AGEEI across the twelve tested subjects. We can observe the values of both measures being very close to 1 at all tested gait velocities. We can see higher variability of both measures at the lowest test gait velocity as compared to the other two tested gait velocities. However, these differences have practically no meaning as we can conclude from the results that in normal walking almost perfect energy exchange between potential and kinetic energy takes place. Furthermore, we can also

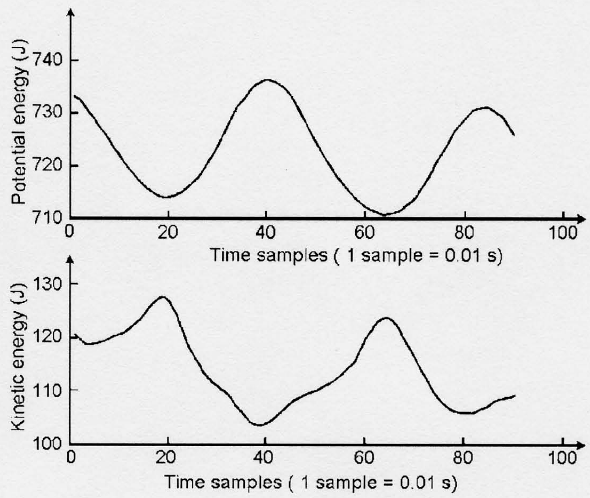

Figure 1. Representative example of potential and kinetic energy trajectories during walking at gait velocity 1.8 m s^{-1}.

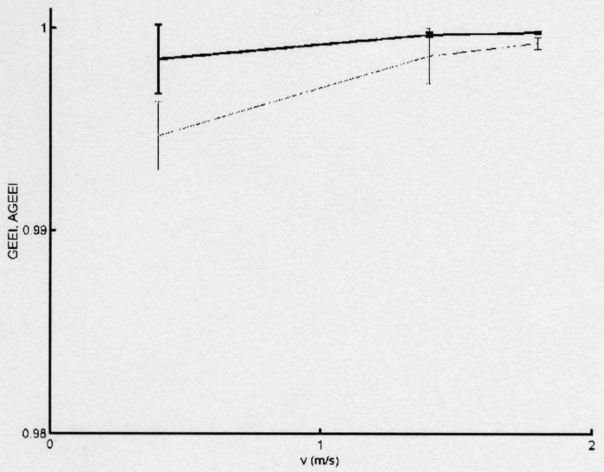

Figure 2. Graphic representation of the results of GEEI (bold) and AGEEI (thin) in twelve subjects walking at three different walking speeds.

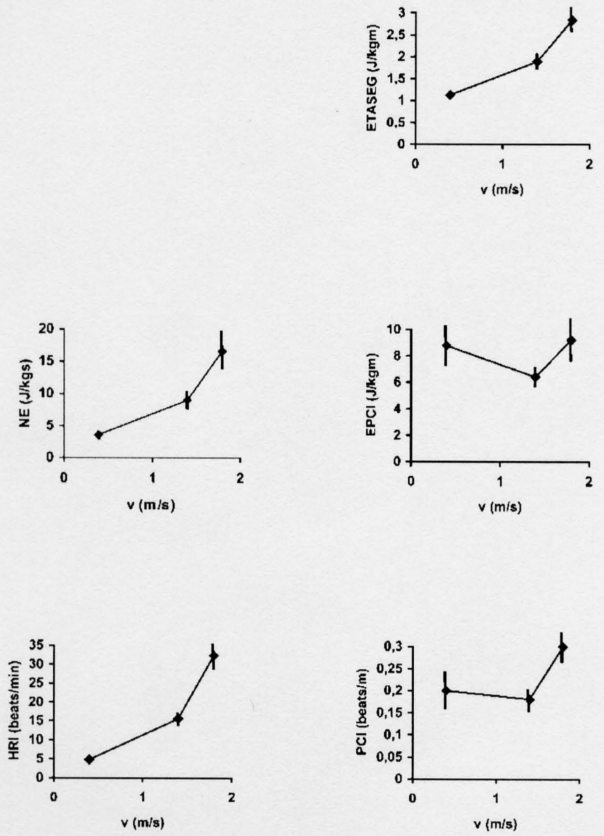

Figure 3. Graphic representation of the results of gait energy consumption related assessment methods in 12 subjects walking at three different walking speeds.

conclude that a recording of a single marker trajectory attached to a proper body anatomical landmark brings about results that are very close to those obtained from measuring movement of all major body segments. GEEI and AGEEI are practically equal. This has important implications for potential use of the proposed gait energy efficiency measure in rehabilitation.

Figure 3 displays the results of the described methods for quantitative gait assessment. The obtained results of *ETASEG* are comparable to the findings of Winter [3]. The metabolic energy expenditure increases with the speed of walking. The function (*NE vs. v*) is similar to the results of Waters and Yakura [1]. The results of *EPCI* are comparable to the results of other authors [10]. The results of the heart rate analysis of gait are in agreement with the findings of MacGregor [12]. *HRI* shows the increase in the heart rate during walking in comparison with the resting position. The results of *PCI* follow the curvilinear distribution with the lowest value at the subject's preferred walking speed, i.e. between 1.3 m s^{-1} and 1.4 m s^{-1} for normal subjects [1].

As we hypothesized, the proposed GEEI and AGEEI gait energy efficiency indexes did not vary with walking speed and were close to 1, which confirms the accepted notion that humans tend to maximize gait efficiency regardless of selected walking speed [5]. This characteristic of the proposed GEEI and AGEEI is unique as compared to the results of all other gait assessment methods. This is because GEEI and AGEEI indicate only the degree of energy exchange efficiency, while not providing the absolute values of energy demands. Therefore, they cannot replace the existing well-established methods for measuring absolute values of energy cost in walking of a particular subject. However, they could be a very useful measure to indicate progress of the rehabilitation process. Since the excessive out-of-phase vertical and horizontal movement of the trunk constitutes major contribution to abnormal energy consumption it is fair to assume that by improving the energy exchanges between the potential and kinetic energy of the body's COM, also energy expenditure of gait is reduced. As in pathological cases, where the time courses of potential and kinetic energies are very different as compared to normal walking, also the values of GEEI and AGEEI should be significantly lower.

Conclusions

A simple method for quantitative gait assessment based on energy exchange analysis during walking has been proposed following the testing of the proposed hypothesis on 12 healthy subjects. Implications of the presented work are important for rehabilitation practice. A simple marker-tracking device based on either radio, ultrasound or infrared technology could be used for measuring the movement of the approximated body COM and a simple algorithm could be implemented to provide a single-number datum indicating current gait efficiency of a particular subject undergoing rehabilitation treatment, and this should be observed throughout the rehabilitation process.

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