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Mechanical energy fluctuations during walking of healthy and ACL-reconstructed subjects

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In a clinical gait analysis, mechanical energy is the gait variable which can validate the energetic state of the disorder of patient's movement. The purpose of this study was to explore the possibilities of employing the total mechanical energy in estimating the mechanical cost of transport in normal and pathological human gait. One of the basic methods of determining mechanical energy (inverted pendulum model) was used to estimate the external mechanical work performed by the walking subjects based on externally observable measurements. Gait data was collected for healthy able-bodied men and patients after ACL reconstruction during physiotherapy process who demonstrate larger lateral center of gravity (CoG) excursions during gait. Based on predictions of the body's CoG trajectory during walking, algorithms were developed to determine the changes in components of total mechanical energy in normal and pathological gait. The utility of calculating mechanical energy in a patient population is questioned.

Key words: *gravitational potential and kinetic energy, human gait, ACL reconstruction*

1. Introduction

The third component of common gait analysis is energy consumption, which gives a measure of the amount of energy required to walk a given distance [1]. Level gait includes the generation and dispersion of various amounts of mechanical energy (performing negative or positive work) during the gait cycle [2]. It has previously been recognized that individuals tend to select a movement pattern in which their mechanical cost (mechanical energy rate) is minimized, known as the "optimal phenomenon" [3]–[6]. When surgical procedure on a ACL-deficient knee is applied, the changes to the normal energy fluctuation patterns are more likely to occur due to the loss of muscular control of the lower joints.

In literature, a number of different methods have been used to estimate the energy consumed and to determine internal and external mechanical work in the motion of humans [7], [8]. One uses mechanical energy changes (**absolute work**), the other integrates over time the product of angular acceleration and moment at each joint over the walking gait cycle (**absolute power**). Movements of an organism are assumed to be powered by muscles: positive muscle work is used to increase potential energy and kinetic energy, and negative muscle work to absorb potential energy and kinetic energy. **Internal work** is defined as the work required to move the segments relative to the body's centre of gravity (CoG). **External work** is done while moving the body's CoG. During walking, both the positive and the negative work actually done by the muscles to sustain the mechanical energy changes of the centre of gravity (positive and negative external work) are reduced by the pendular interchange of potential energy to kinetic energy and vice versa [9], [10]. Based on energy consumption, not only can measurements now distinguish between two different types of locomotion (i.e. normal or pathological) but the causes of inefficiencies can be identified and fully understood [11], [12]. A key example is WINTER's internal work equation [13] which attempted to quantify the internal work of locomotion.

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However, Winter's model has some basic defects (the cancellation of positive and negative work values). Attention has now turned to alternative methods for calculating the work involved in movement. ALESHINSKY ([12], part V) established the mathematical validity and recommended to use the integral of joint powers to find work. He overcame the traditional limitation of Winter's approach by integrating the absolute value of the joint powers.

One of the simplest methods of estimating the amount of work performed in human gait is to simply observe the motion of the centre of gravity of the body. This method measures the external work performed and no measure is made of the work performed to move the limbs relative to the trunk. CAVAGNA et al. [14], [15] measured the translational kinetic and potential energy of the body using the CoG motion over a range of walking speeds. At the same time the rotational kinetic motion was assumed to be negligible. This gave a simple expression of the total mechanical energy of the body:

$$E_{\text{tot}} = E_p + E_{kf} + E_{kv}, \tag{1}$$

where E_p is the potential energy and E_{kf}, E_{kv} are the kinetic energies in the forward and vertical directions, respectively. Cavagna notes that during walking gait, the sum of potential and kinetic energies oscillates with lower amplitude than either of the individual components.

As predicted by the model of KUO [16], [17] the mechanical cost of transport based on fluctuations in total mechanical energy done during step-to-step transitions increased with the square of step width, as did the metabolic cost, suggesting that the step transition of mechanical energy is a good estimate of a metabolic cost of transport.

2. Material and method

2.1. Material

Total of seventy-six barefoot adult volunteers participated in gait study while walking at their preferred speed. Of those fifty-three male (aged 31.5 ± 9.7) were patients of the Wrocław University College of Physiotherapy after the arthroscopic ACL reconstruction. Twenty-three healthy men (aged 22.1 ± 3.2) were classified into the control group.

All of the test patients underwent original physiotherapy process (Czamara, 2002) after the isolated ACL reconstruction, which involved harvesting the tendon graft (ST and GR) and rigid fixation.

Following each stage of physiotherapy process, ACL-reconstructed patients were monitored by the motion analysis system. Stage 1 was held between 2–4 weeks postoperatively, stage 2: 5–8 weeks and stage 3: 9–12 weeks postoperatively.

Prior to participation, each subject signed a consent form approved by the ethical committee of the University School of Physical Education in Wrocław.

2.2. Method

A set of 18 reflective passive markers was used to denote the subjects' main upper and lower body parts as described by the Clauser model. Additional four reflective markers were placed on the force plate and served as the points of reference for transformation of local system of coordinates to global kinematic coordinates.

Kinematic data were recorded via a data acquisition system (SIMI Motion System). Two 100 Hz digital JVC cameras were positioned ca. 4 m from the sagittal plane along the progression plane of the subject's gait path and were separated by an angle of approx. 80 deg (figure 1A). The two digital JVC camcorders were connected to the computer mainframe and synchronized with an optical starting signal. A cubic (1 m × 1 m × 1 m), metal box was used for the calibration procedure and made up the laboratory frame of reference. Right-handed inertial reference system of coordinates was employed for both left and right body segments as well as the Global Coordinates System (GCS). The GCS is consistent with the Standardization and Terminology Committee of the ISB recommendations for standardization in the reporting of kinematic data [18], [19].

Each subject began walking at a sufficient distance from the measurement volume so that the self-selected pace was attained prior to the foot of the test limb making contact with the ground. The length of the walkway (6 m) limited the number of movement strides to around 3–5, depending on the subject's velocity. With the help of the SIMI Motion software, from the recorded motion it was possible to compute the time related changes in location of each marker and to divide each gait cycle into its characteristic phases: initial double stance, single stance, terminal double stance and swing phase for each limb.

The data analysis consisted in registering the positions of CoG for each of the 14 segments and calculating the position of the resultant body CoG for every

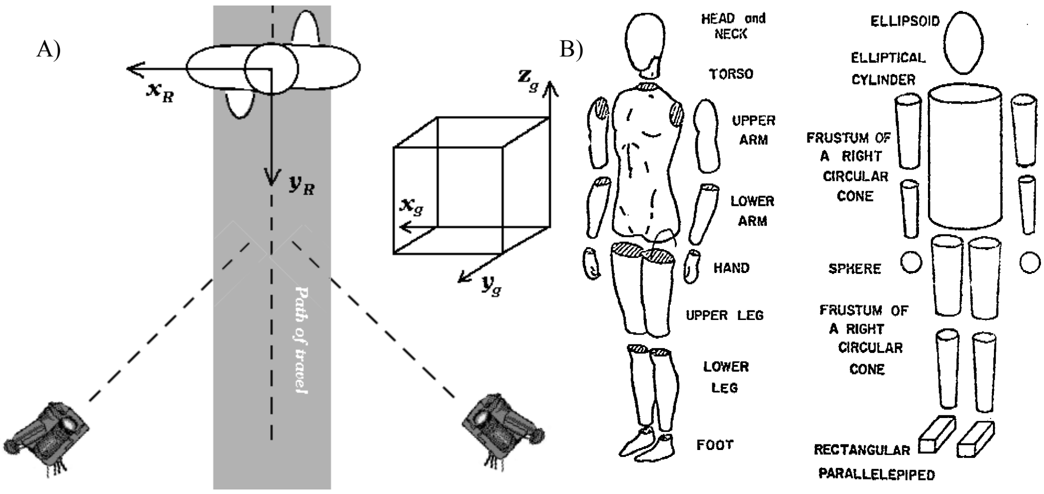

Fig. 1. The measurement setup for the movement analysis (A) and the anthropomorphic 14-segment Clauser model for derivation of the body CoG (B). Two JVC digital cameras are connected to a computer mainframe for the synchronized data acquisition. The calibration box, the right-handed subject's and general system of coordinates are also shown

frame of the registered gate cycle. Clauser's anthropometric data (figure 1B) were used to evaluate the path of body CoG with the help of regression equations [20], [21]. Then the height and absolute velocity of body CoG were calculated as a function of time together with the potential and absolute kinetic energy. The forward and vertical velocity and acceleration of CoG were computed by differentiation operation while digitally processed (Butterworth 2nd-order filter with the cut-off frequency of 6 Hz) [22]. Finally, the body CoG height and velocity were normalized according to the following expressions:

$$h_{\mathrm{BCoG}}^{\mathrm{norm}}(t) = \frac{h_{\mathrm{BCoG}}(t)}{L}, \tag{2}$$

$$v_{\mathrm{BCoG}}^{\mathrm{norm}}(t) = \frac{v_{\mathrm{BCoG}}(t)}{\sqrt{gL}}, \tag{3}$$

where $h_{\mathrm{BCoG}}^{\mathrm{norm}}(t)$, $v_{\mathrm{BCoG}}^{\mathrm{norm}}(t)$ are the body CoG height and absolute velocity function of time normalized to body length (L) and gravitational constant (g). The two components of the normalized total mechanical energy, gravitational potential and absolute kinetic energies as a function of gait cycle time, give:

$$E_{\mathrm{pot.}}^{\mathrm{norm}}(t) = \frac{E_{\mathrm{pot.}}(t)}{m \cdot g \cdot L} = h_{\mathrm{BCoG}}^{\mathrm{norm}}(t), \tag{4}$$

$$E_{\mathrm{kinet.}}^{\mathrm{norm}}(t) = \frac{E_{\mathrm{kin.}}(t)}{m \cdot g \cdot L} = \frac{1}{2}(v_{\mathrm{BCoG}}^{\mathrm{norm}}(t))^2. \tag{5}$$

Finally, the total mechanical energy defined by equation (1) yields:

$$E_{\mathrm{total}}^{\mathrm{norm}}(t) = \frac{E_{\mathrm{pot.}}(t) + E_{\mathrm{kinet.}}(t)}{m \cdot g \cdot L} = h_{\mathrm{BCoG}}^{\mathrm{norm}}(t) + \frac{1}{2}(v_{\mathrm{BCoG}}^{\mathrm{norm}}(t))^2. \tag{6}$$

The normalization procedure employed above was in accordance with the commonly used procedures of scaling gait parameters to body size data [23]–[25]. All measured parameters in isolated cycles were averaged over 4 trials, and standard deviation was calculated.

The analysis and data processing and evaluation were supported by the SIMI Motion analysis system (SIMI Reality Motion Systems GmbH, Unterschleissheim, Germany). All measurements were made in the Biomechanical Analysis Laboratory of the University of Physical Education in Wrocław (ISO quality standards: ISO 9001:2001).

3. Results

The normalized potential energy as a function of gait cycle time for normal (control) and ACL-reconstructed (stage 1 of physiotherapy) subjects is presented in figure 2. The (normalized) potential energy curve oscillates between the values slightly higher and slightly lower than 0.55 (or 0.55·m·g·L in Joules; see equation (4)) for both of the analyzed groups, but the amplitude of oscillation is significantly smaller for the test group (ca. 0.035 for the control and ca. 0.004 for the test group). As one can expect, the maximum of potential energy coincides with the rise of the body

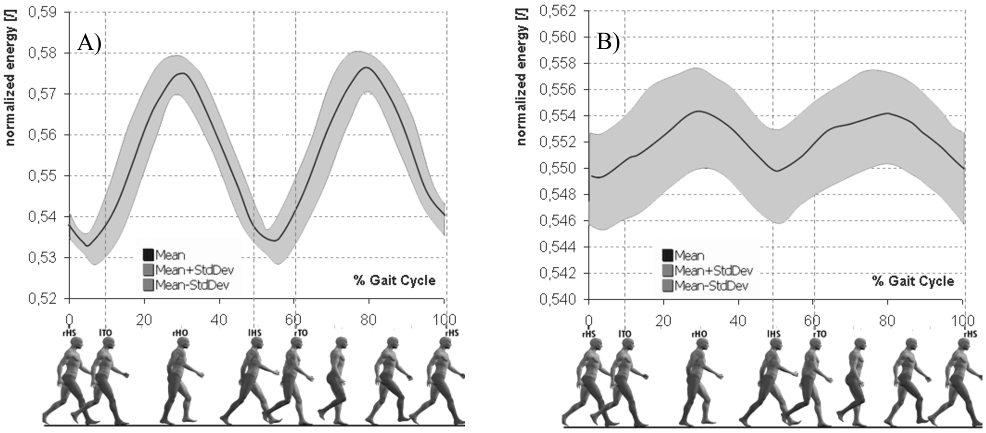

Fig. 2. Normalized potential energy for normal–control (A) and ACL-reconstructed–test (B) groups

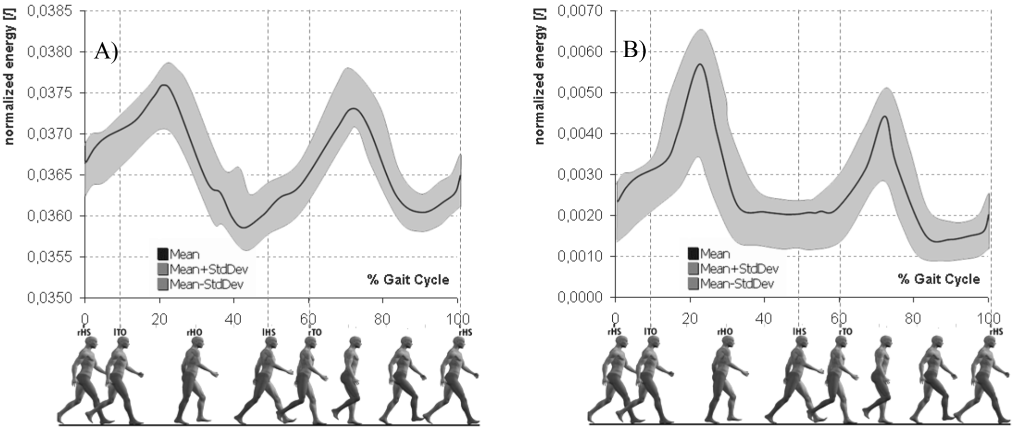

Fig. 3. Normalized kinetic energy for control (A) and test (B) groups

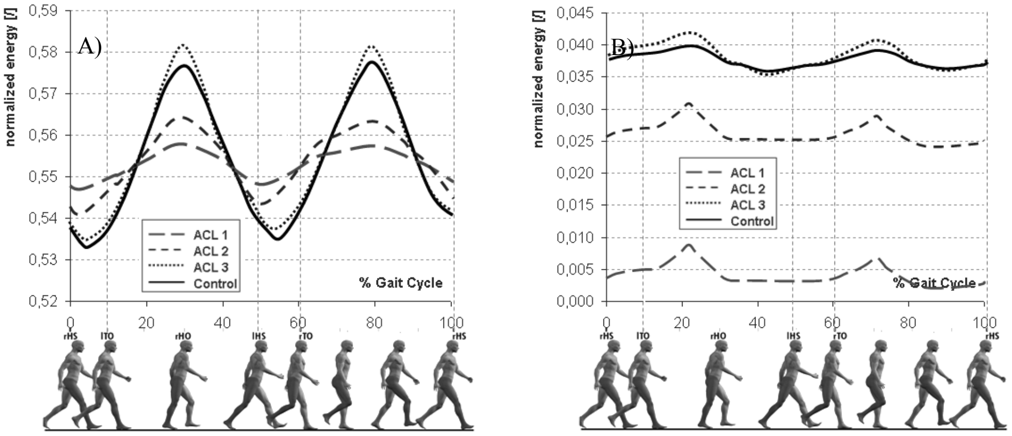

Fig. 4. Comparison of relative change in gravitational potential (A) and kinetic (B)
energies for the test group in three stages of physiotherapy and for the control group

CoG in midstance and the minimum with the drop of CoG in double-stance.

Figure 3 represents the resultant kinetic energy for control and test (stage 1) groups as a function of normalized time of gait cycle. Normal kinetic energy pattern fluctuates around 0.037 with an amplitude of 0.018 and is ahead of the maximum event for the potential energy (out of phase) by around 10% of gait cycle time. The maximum value of kinetic energy corresponds to the beginning of single-stance and is consistent with the maximum of absolute speed. The lowest value of kinetic energy (and speed of body CoG) appears at the end of single-stance.

Figure 4 represents the curves of potential end kinetic energy versus gait cycle time for the three physiotherapy stages plotted against the appropriate energy curve for the control group. The normalized potential energy (figure 4A) fluctuates around the 0.55 for all the measurements with the changing amplitude. The smallest amplitude is for the test group at the third stage of physiotherapy and rises subsequently with the physiotherapy time. The absolute normalized kinetic energy (figure 4B) represents completely different characteristics during the period of recovery. The kinetic energy changes for both the mean value and the range of oscillations. The smallest values were obtained in the first stage and the largest in the third stage of physiotherapy process.

Both potential and kinetic energies for the third measurement of the test group demonstrated no significant differences compared to the control group.

4. Discussion and conclusions

Comparative studies of locomotion in humans in recent years have revealed patterns of movement that positively diversify normal and pathological function of locomotor apparatus [11], [12]. Cyclical changes in the position and speed of the body's center of gravity (CoG) are one such pattern and these are hypothesized to increase overall energetic efficiency through the interchange of kinetic and gravitational potential energies [26], [27].

Fluctuations in gravitational potential energy (*Ep*) and absolute kinetic energy (*Ek*) of the body's CoG are generally out of phase. In this work, normal energy pattern (for the two components of the total mechanical energy) agreeably corresponds to the one presented by other authors. The current investigation revealed mean value of *Ep* around 700 J with an amplitude of oscillation of 45 J and mean value of *Ek* of around 50 J with amplitude of 25 J*. Testing 8 subjects walking at different speeds, WINTER [28] obtained *Ep* mean value equal to 440 J with the 10 J range of oscillations and *Ek* equal to 35 J with the 15 J range of change. GRIFFIN et al. [29] presented results for a typical subject walking at 1.0 m/s. He found that potential and kinetic energies fluctuate around 20 J and kinetic around 15 J and the oscillations are out of phase so that the total mechanical energy exhibited even smaller fluctuations. GIDER et al. [30] found *Ep* equal to 725 J changing within the range of 20 J and *Ek* equal to 115 J changing with an amplitude of 25 J. NEPTUNE et al. [31] found that *Ep* fluctuates around 700 J within the range of 25 J and *Ek* fluctuates around 90 J with the amplitude of 20 J. The discrepancies between the above experiments and the current one, especially in the amplitude of the potential and kinetic energies, may be mainly due to a more abundant material tested and a moderate speed of gait in the current experiment.

In the initial part of the step cycle, some kinetic energy used for moving the body forward raises the CoG and increases gravitational potential energy. As the CoG falls, potential energy is converted into kinetic energy, some of which can be used for initiating the next step cycle. The inverted pendulum model [15], [32] predicts that changes in potential and forward kinetic energies should occur 180° out of phase. In the spring-loaded inverted-pendulum (SLIP) model [10], [12], [33], [34], elastic elements in the legs provide transient energy storage. Specifically, as the CoG descends under the force of gravity, elastic elements in the legs (muscles, tendons and bones) are deformed, and forces produced by subsequent elastic recoil of these elements are used to propel the CoG upward and forward to initiate a new cycle. In contrast to the IP model, the SLIP model predicts that forward kinetic and gravitational potential energies fluctuate almost in phase, which is consisted with the results.

Normalized potential energy increased during physiotherapy process due to an increase in amplitude of body CoG trajectory. In stage 3 of physiotherapy process, it was significantly smaller than in the control group. The total mechanical cost (the sum of potential and kinetic energies) was still lower than that the in control group as a result of the significantly lower amplitude of body CoG trajectory. The last conclusion may be related to the fact that during the physiotherapy process both potential and kinetic energies have significantly increased as would be expected to be otherwise. In the case of measuring the energy expenditure, more appropriate would be to use the average power (average energy per unit time) or the economy of gait (average energy per unit mass and distance travelled) instead of the pure energy measure.

To accurately estimate the work performed by the muscles and to obtain any insight into the flow of energy through the biomechanical system, another method of analysis is required. To be of value in predicting physiological effort, the results of a mechani-

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* All conversions for the mean subject's mass of 77.9 kg and mean body length of 179.9 cm.

cal energy analysis should have some correlation with the metabolic energy requirements of performing the same motion. BURDETT et al. [35] measured the metabolic energy consumption of quiet standing and walking at 5 different speeds. Metabolic energy cost was determined using the oxygen consumption rate. The mechanical energy for each walk was calculated using 3 methods: total energy of the center of the mass, segmental energy and joint moments. Comparing the metabolic rate with mechanical energy rate at each velocity, the strongest correlation was found using the centre of mass energy calculation followed by the joint moment calculation and the segmental work method. While the center of gravity calculation neglects the movement of the limbs in the calculation, it requires only kinematic data to be measured, and is less susceptible to errors in measurement and calculation. The simple model used in this work cannot give any insight into the work involved in moving the limb segments relative to the centre of gravity. The conclusion reached by WILLIAMS [36] is that an agreement on a best energy-based model does not exist.

Based on the current results, the future estimation of timing and magnitude of the external mechanical work or the mechanical energetic cost would be useful to test how much mechanical work is performed by muscles to redirect the body CoG during double support, and how much is used during single-limb support (e.g., for extending the knee and raising the CoG). The muscle mechanical energy expenditure as the CoG rises and descends during single-limb support is not predicted by inverted pendulum models.

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