

A mechanical energy analysis of gait initiation

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Abstract

The analysis of gait initiation (the transient state between standing and walking) is an important diagnostic tool to study pathologic gait and to evaluate prosthetic devices. While past studies have quantified mechanical energy of the body during steady-state gait, to date no one has computed the mechanical energy of the body during gait initiation. In this study, gait initiation in seven normal male subjects was studied using a mechanical energy analysis to compute total body energy. The data showed three separate states: quiet standing, gait initiation, and steady-state gait. During gait initiation, the trends in the energy data for the individual segments were similar to those seen during steady-state gait (and in Winter DA, Quanbury AO, Reimer GD. Analysis of instantaneous energy of normal gait. *J Biochem* 1976;9:253–257), but diminished in amplitude. However, these amplitudes increased to those seen in steady-state during the gait initiation event (GIE), with the greatest increase occurring in the second step due to the push-off of the foundation leg. The baseline level of mechanical energy was due to the potential energy of the individual segments, while the cyclic nature of the data was indicative of the kinetic energy of the particular leg in swing phase during that step. The data presented showed differences in energy trends during gait initiation from those of steady state, thereby demonstrating the importance of this event in the study of locomotion. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Gait initiation; Mechanical energy; Gait

1. Introduction

Nissan and Whittle [2] defined gait initiation as “When a subject is changing his/her mechanical condition from standing at rest to the cyclic movement of walking.” Gait initiation is an important part of locomotion; it is the transient state between two steady states: standing and walking. Gait initiation incorporates balance, coordination, central nervous system programming, and precise neuromotor control from the neuromuscular system, and momentum and mechanical energy generation from the musculoskeletal system. The analysis of gait initiation is an important diagnostic tool in the study of pathologic gait.

Persons with gait pathologies may learn to adapt to their impairment by recruiting different muscle groups or adopting a different motor program during steady state gait. However, during gait initiation, these deficiencies become readily apparent since more of the neuromuscular system is active [3,4]. The analysis of gait initiation may also be used in the evaluation of prosthetic devices. The data collected during this event leads to improved theoretical analysis, design, manufacturing, and fit of the device [3,5].

Mechanical energy is a single parameter that encompasses information relating mass, moment of inertia, linear velocity, angular velocity, and force. Mechanical energy in steady-state gait was first studied by Elftman [6]. He concluded that muscles not only cause movement of adjoining segments, but also regulate energy flows among the segments. Winter, et al. [1] computed instantaneous energy of the body segments during steady-state gait. Robertson and

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Winter [7] discussed energy absorption and generation in gait, and presented power data. They found that the joint power was as important as the muscle power in causing energy changes in adjacent segments. Others have examined mechanical energy or work during gait and discussed the body's ability to optimize energy expenditure [8–10]. Inman [10] commented, "... the body will integrate the motion of various segments of the body and control the activity of the muscles so that the energy required by each step is minimal."

During quiet standing, all body segments possess only potential energy. However, in steady state gait, the body segments contain not only potential energy, but also kinetic energy, thus a higher energy state. In other words, gait initiation raises the body from a lower energy state to a higher one. Since the mechanical energy patterns during quiet standing, gait initiation, and steady-state gait can be quantified, a mechanical energy analysis can be used to define each event.

To date, no study has been published that presents instantaneous mechanical energy data during gait initiation. Breniere, et al. [11] gave a brief, intuitive discussion of energy in gait initiation, but presented no data. Others have studied gait initiation using kinetic or kinematic analysis [12–15], or a combination of kinematics and EMG [16–19]. The objective of this study was to calculate the instantaneous mechanical energy of the body and its component segments during gait initiation using a three-dimensional (3-D) kinematic analysis.

2. Methods and materials

Seven male subjects (including one pilot subject [P]) were used for this study (age = 23.6 ± 2.3 years; height = 1.74 ± 0.07 m; weight = 726.3 ± 101.0 N). Volunteers were asked not to participate if they had any history of neural, muscular, or skeletal problems, or major surgery performed on the lower extremities. In compliance with the guidelines established by the University of Akron's Institutional Review Board for the Protection of Human Subjects, the entire procedure was reviewed with the subject, and all questions were answered. The subject then read and signed the informed consent form.

The subject's torso, and one leg and foot were targeted with 13 small, retroreflective markers (13 mm in diameter). The marker locations were: lateral aspect of the heel, head of the fifth metatarsal, superior aspect of the foot, lateral malleolus, two along the tibial crest, the fibular head, two on the anterior surface of the thigh along the long axis, greater trochanter, bilateral anterior superior iliac spines, and inferior point of the sternum. The positions of the markers were used to aid in defining the centers of mass, the joint centers, and

the inertial parameters of each body segment. Several measurements of the dimensions of the subject's legs, torso, and head were recorded with an anthropometer for the computation of mass moments of inertia, center of mass, and joint centers of each body segment.

Four footswitches (B & L Electronics, Sante Fe Springs, CA) were taped to the soles of the subject's feet with hypo-allergenic surgical tape. The four contact positions were the plantar surfaces of the great toe, the first and fifth metatarsal heads, and the heel. The footswitches were used for time synchronization of the data with defined events in the gait cycle. Two AMTI (Newton, MA) force plates, set level with the walking platform, recorded 3-D ground reaction forces and moments at a sampling rate of 250 Hz. Ground reaction forces were used to define the start of the gait initiation event (GIE). A Vicon motion analysis system (Oxford Metrics, Oxford, UK), implemented on a PDP-11 computer (Digital Corporation, MA), was used for the time synchronization and collection of footswitch, force plate, and target motion data. Three-dimensional marker position data were collected at 50 Hz.

The GIE was recorded in successive steps (Fig. 1) to ensure that each stride occurred within the calibration volume, which is centered about the force plates. Initially, data were recorded with the subject standing motionless on the force plate to obtain coordinate system rotation angles. For the first step, the subject stood astride the edge of the force plate, such that the marked leg was on the plate, and data were recorded. The next step was recorded with the subject starting one step behind the force plate, so the second step began with the marked leg on the force plate. Similarly, the third step of the marked leg was recorded with the subject starting two steps behind the force plate. Each subject performed three trials per gait initiation step recorded. The markers were then transferred to the contralateral leg, and the entire process was repeated.

Five subjects naturally began walking with their left leg; two subjects naturally began walking with their right leg. If a subject asked with which leg to start, the researcher replied, "Whatever feels natural for you". However subjects were asked to keep the starting leg consistent over all trials.

The 3-D position data were filtered using a two-pass, second order Butterworth filter with a cutoff frequency of 4 Hz to eliminate any 'noise' created by soft tissue motion [20]. Velocities of each marker for each frame were computed numerically via a 3-point central difference differentiation of the position data.

The anthropometric measurements, and the 3-D marker positions, and velocities were used in the energy analysis. The 3-D angular velocities (ω) of each segment were computed using the method of least squares described by Verstraete et al. [21]. The mass of each

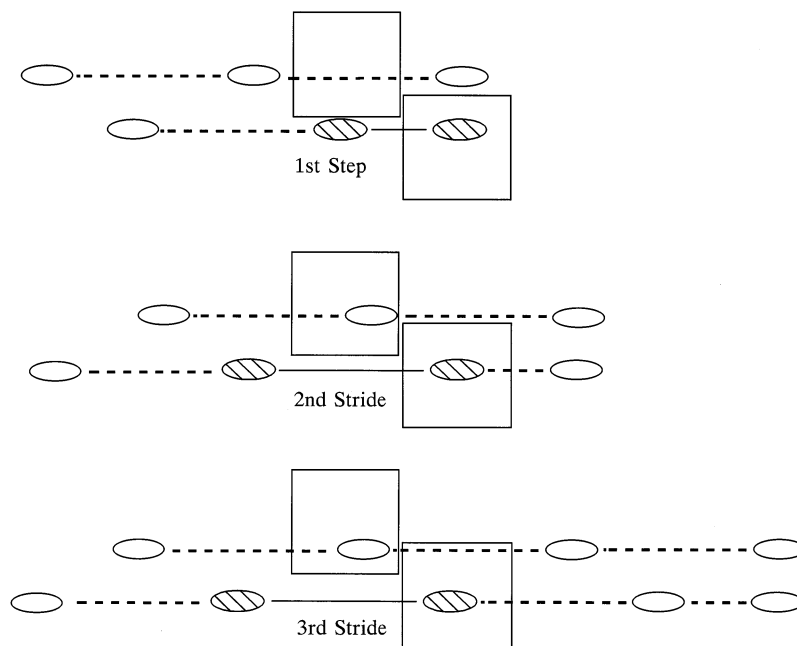


Fig. 1. The GIE recorded in successive strides. The hatched footfalls indicate the stride recorded. Progression is from right to left.

body segment was calculated using body weight ratios from Dempster [22]. The mass moments of inertia (I) for each body segment were computed based on geometric modeling of the body [23]. The shank and thigh were approximated by truncated right circular cones. The foot was approximated by a cube attached to a 3-D right triangle. The head, arms, and torso segment (HAT) was modeled as a box (to represent the arms and torso) and an offset ellipsoid (to represent the head). The HAT was treated as a single segment with one set of principal moments of inertia and one center of mass. The analysis utilized seven segments, consisting of two feet, two shanks, two thighs, and the HAT segment. The total mechanical energy of each segment was computed using the following equations:

$$PE = m\bar{g} \cdot \bar{h}$$

$$KE_t = \frac{1}{2} m\bar{v}_{cm} \cdot \bar{v}_{cm}$$

$$KE_r = \frac{1}{2} (\bar{\omega}^T \bar{I} \bar{\omega})$$

$$E_{tot} = PE + KE_t + KE_r$$

The range of data analyzed in each trial was one stride, which began with initial contact of the marked leg on the force plate, and ended one frame short of the next initial contact of that same leg. However, for the first step of each leg in gait initiation, there was no initial contact with which to start the data analysis. Hence, the start of the GIE was defined as the start of force plate activity as determined qualitatively by visual

inspection of the vertical reaction force data (based on data published by Nissan and Whittle [2]). The actual start of the energy analysis was just before the start of force plate activity so as to show quiet standing data in the final results.

All energy data were time normalized such that a step was equal to 50% GIE and a full stride was equal to 100% GIE. The time from the beginning of one stride until the beginning of the next stride (first frame of the next data file) was subdivided into 100 evenly spaced increments, which were synchronized with the real time data. Normalized data points lying between the real time data were computed by linear interpola-

COMPONENT ENERGIES OF THE FOOT INITIATION LEG SUBJECT INI4

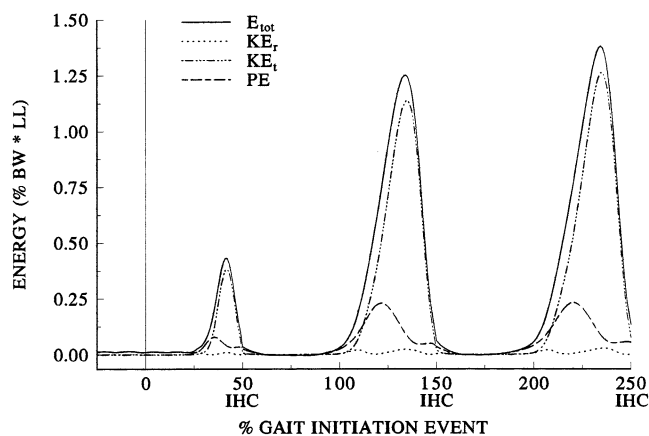


Fig. 2. Component mechanical energies of the foot of the initiation leg during gait initiation for subject INI4. Heel contacts of the initiator are denoted by IHC.

COMPONENT ENERGIES OF THE FOOT FOUNDATION LEG SUBJECT INI4

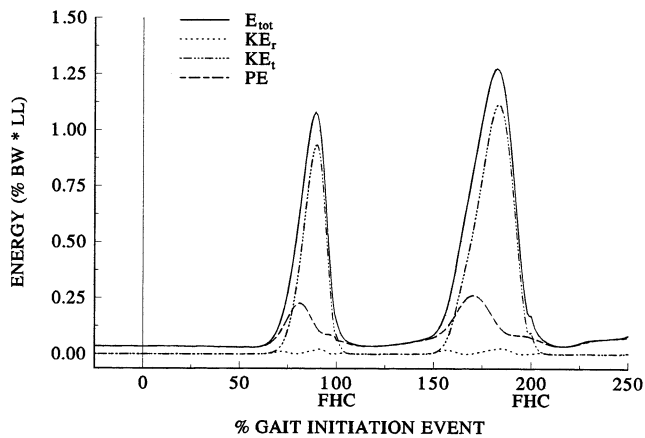


Fig. 3. Component mechanical energies of the foot of the foundation leg during gait initiation for subject INI4. Heel contacts of the foundation leg are denoted by FHC.

COMPONENT ENERGIES OF THE SHANK FOUNDATION LEG SUBJECT INI4

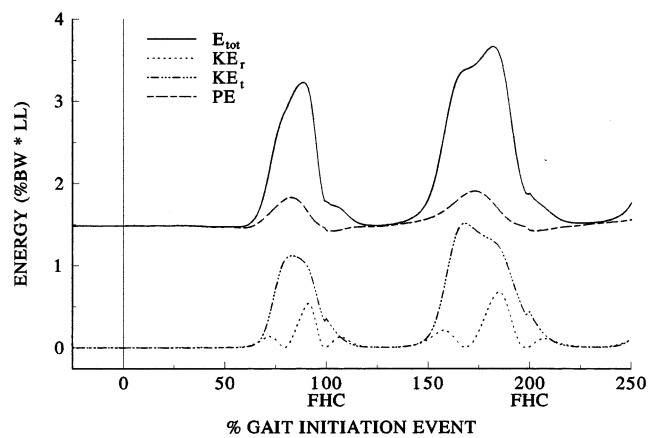


Fig. 5. Component mechanical energies of the shank of the foundation leg during gait initiation for subject INI4. Heel contacts of the foundation leg are denoted by FHC.

COMPONENT ENERGIES OF THE SHANK INITIATION LEG SUBJECT INI4

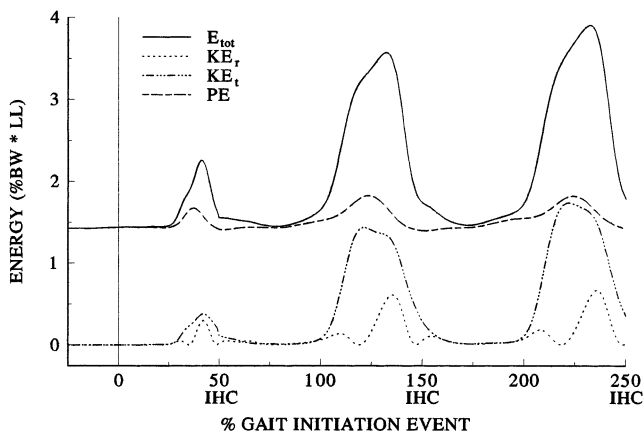
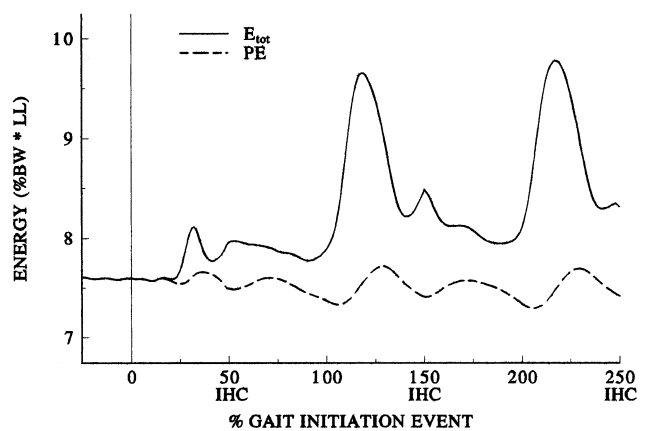


Fig. 4. Component mechanical energies of the shank of the initiation leg during gait initiation for subject INI4. Heel contacts of the initiator are denoted by IHC.

tion of real time data on either side of the normalizing point. Therefore, every stride contained 100 equally spaced data points, each corresponding to 1% GIE. This facilitated summing the total segmental energies into an overall body energy, and eliminated time variations among subjects.

In the literature regarding gait initiation, the swing leg has been defined as the leg that took the first step, and the stance leg was the contralateral leg. For this study, a different nomenclature was used to avoid confusion in later steps (for instance, in the second step, the 'swing leg' would be in stance phase and the 'stance leg' would be in swing phase). The leg that took the first step was called the *initiation leg* or the *initiator*, and the contralateral leg was called the *foundation leg*.

COMPONENT ENERGIES OF THE THIGH INITIATION LEG SUBJECT INI4



COMPONENT ENERGIES OF THE THIGH INITIATION LEG SUBJECT INI4

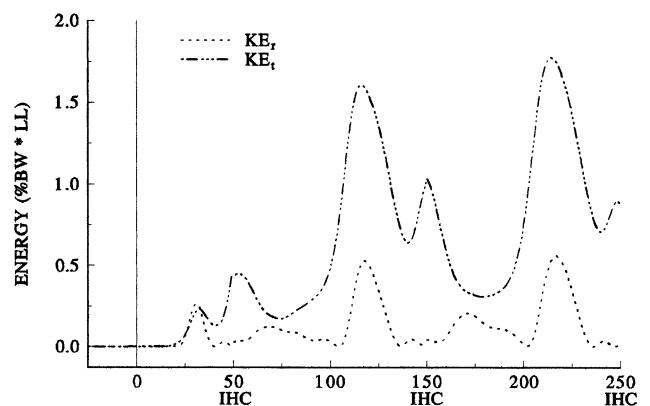
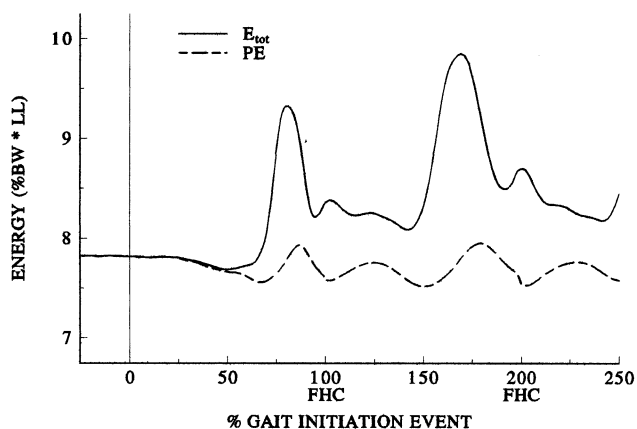
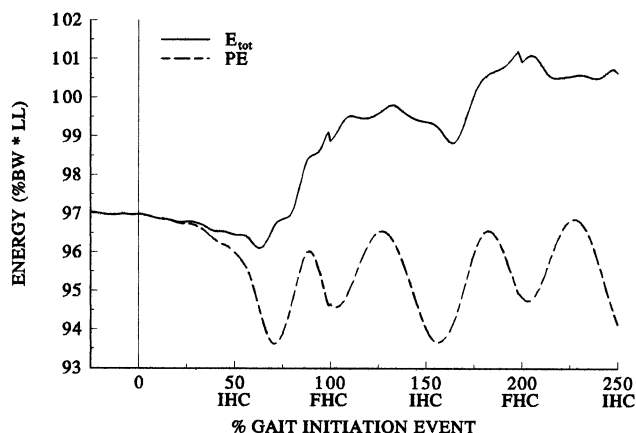


Fig. 6. Component mechanical energies of the thigh of the initiation leg during gait initiation for subject INI4. Heel contacts of the initiator are denoted by IHC.

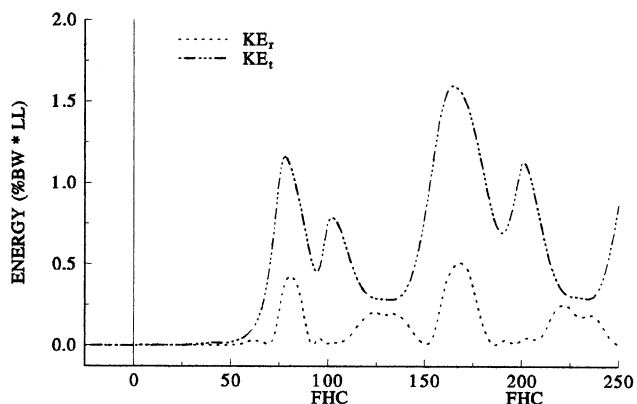
COMPONENT ENERGIES OF THE THIGH
FOUNDATION LEG SUBJECT INI4



COMPONENT ENERGIES OF THE HAT
SUBJECT INI4



COMPONENT ENERGIES OF THE THIGH
FOUNDATION LEG SUBJECT INI4



COMPONENT ENERGIES OF THE HAT
SUBJECT INI4

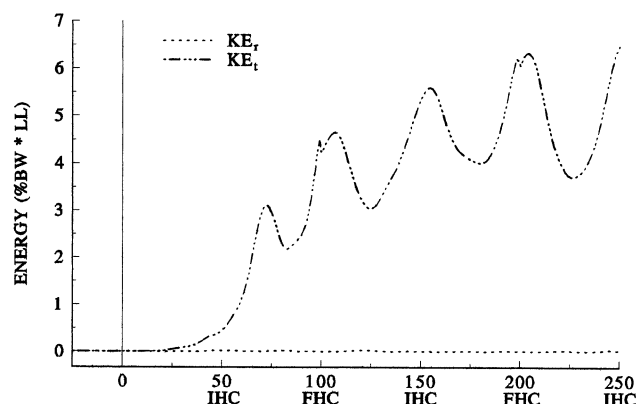


Fig. 7. Component mechanical energies of the thigh of the foundation leg during gait initiation for subject INI4. Heel contacts of the foundation leg are denoted by FHC.

Fig. 8. Component mechanical energies of the HAT during gait initiation for subject INI4.

For the first step of each leg, the normalization began at the start of force plate activity (0% GIE). The first stride of the foundation leg was normalized to 100% GIE. However, the first step of the initiator was normalized only to 50% GIE (50 increments) because it was not representative of a full stride. Therefore, the successive initial contacts of the initiator occurred at 50, 150, and 250% GIE. The successive initial contacts of the foundation leg occurred at 100%, and 200% GIE. Assuming that the GIE was repeatable, the data for successive strides of each leg were spliced together after time normalization to form a single file of data for each segment covering the entire GIE.

The total energy of the body (E_b) was defined as the sum of the seven individual segment total energies at each normalized time point.

$$E_b = \sum_{j=1}^7 E_{tot,j}$$

TOTAL MECHANICAL ENERGY OF THE BODY
ALL SUBJECTS ONE TRIAL

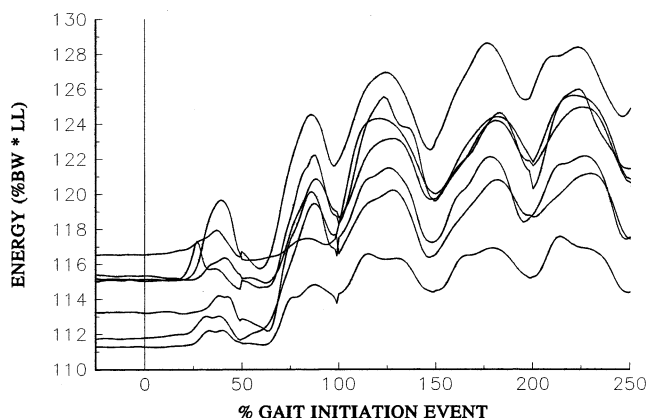


Fig. 9. Total mechanical energy of the body (E_b) for one representative trial of all seven subjects.

Table 1
Peak value of total energy in each step (%BW*LL)

| | Standing | 1 | 2 | 3 | 4 | 5 |
|-------------------|----------|--------|--------|--------|--------|--------|
| Foot | | | | | | |
| INIP | 0.05 | 0.50 | 1.23 | 1.18 | 1.30 | 1.30 |
| INI1 | 0.07 | 0.40 | 1.32 | 1.44 | 1.23 | 1.38 |
| INI2 | 0.07 | 0.43 | 1.17 | 1.19 | 1.52 | 1.19 |
| INI3 | 0.05 | 0.43 | 1.19 | 1.29 | 1.29 | 1.26 |
| INI4 | 0.01 | 0.45 | 1.07 | 1.27 | 1.28 | 1.40 |
| INI5 | 0.06 | 0.41 | 1.15 | 1.11 | 1.30 | 1.25 |
| INI6 | 0.04 | 0.26 | 0.55 | 0.69 | 0.74 | 0.74 |
| Shank | | | | | | |
| INIP | 1.47 | 2.28 | 3.62 | 3.45 | 3.70 | 3.75 |
| INI1 | 1.53 | 2.60 | 3.56 | 3.86 | 3.88 | 3.67 |
| INI2 | 1.47 | 2.16 | 3.54 | 3.57 | 4.16 | 3.63 |
| INI3 | 1.46 | 2.17 | 3.44 | 3.70 | 3.58 | 3.54 |
| INI4 | 1.44 | 2.20 | 3.26 | 3.60 | 3.65 | 3.81 |
| INI5 | 1.50 | 2.17 | 3.38 | 3.50 | 3.64 | 3.75 |
| INI6 | 1.54 | 1.93 | 2.41 | 2.70 | 2.69 | 2.78 |
| Thigh | | | | | | |
| INIP | 7.76 | 8.41 | 9.23 | 9.64 | 9.57 | 9.85 |
| INI1 | 7.81 | 9.66 | 9.86 | 10.74 | 10.29 | 10.35 |
| INI2 | 7.82 | 8.18 | 9.38 | 9.85 | 10.19 | 10.07 |
| INI3 | 7.72 | 8.36 | 9.52 | 9.99 | 10.06 | 10.15 |
| INI4 | 7.60 | 8.08 | 9.30 | 9.73 | 9.94 | 9.91 |
| INI5 | 7.85 | 8.39 | 9.64 | 9.82 | 10.06 | 10.16 |
| INI6 | 7.90 | 8.32 | 8.77 | 9.15 | 9.30 | 9.33 |
| HAT | | | | | | |
| INIP | 93.42 | 93.58 | 96.92 | 97.10 | 97.51 | 97.42 |
| INI1 | 96.05 | 96.10 | 99.17 | 99.83 | 100.09 | 100.61 |
| INI2 | 98.01 | 98.31 | 101.17 | 103.12 | 103.68 | 104.51 |
| INI3 | 96.75 | 96.75 | 97.78 | 100.23 | 101.17 | 101.36 |
| INI4 | 96.89 | 96.91 | 98.90 | 99.78 | 100.88 | 100.90 |
| INI5 | 94.55 | 94.58 | 97.14 | 98.65 | 98.62 | 98.38 |
| INI6 | 92.72 | 92.86 | 94.66 | 95.21 | 95.46 | 95.69 |
| Total body | | | | | | |
| INIP | 114.85 | 113.05 | 119.60 | 120.05 | 120.65 | 120.85 |
| INI1 | 115.05 | 117.40 | 122.35 | 124.90 | 123.80 | 125.45 |
| INI2 | 116.57 | 117.97 | 124.07 | 126.77 | 128.27 | 128.47 |
| INI3 | 115.17 | 119.53 | 117.50 | 124.00 | 124.43 | 125.20 |
| INI4 | 115.20 | 116.30 | 120.73 | 123.27 | 123.77 | 124.53 |
| INI5 | 113.23 | 114.13 | 120.03 | 121.60 | 122.27 | 122.00 |
| INI6 | 111.30 | 112.10 | 115.07 | 116.47 | 117.00 | 117.33 |

The body energy, in joules, was normalized to the subject's body weight (N) and average leg length (m) to eliminate size variations. Leg length was defined as the vertical distance from the floor to the greater trochanter of the femur.

3. Results and discussion

Energy data from the second trial of the fourth subject (INI4) is presented for discussion, and it is representative of all subject trials. As mentioned previously, the energy data were normalized, and the steps were time normalized. The data covered 250% GIE, or five steps. A separate analysis by Miller and Verstraete

[24] showed that the step duration of gait initiation is three full steps. Hence, the data show the entire GIE and two steady state steps afterward for comparison.

Mechanical energy data for the foot segment of the initiation and foundation legs are shown in Figs. 2 and 3, respectively. From 0 to 60%, the foundation foot was in stance phase providing support for the start of gait initiation. There was no translational kinetic energy (KE_t) or rotational kinetic energy (KE_r), so potential energy (PE) accounted for all of the total energy. For both feet, there were noticeable peaks in the total energy, indicative of the swing phase of the given foot. The primary component of the total-energy peaks was KE_t , due to the velocity of the center of mass of the foot during swing phase. The PE was at a maximum

early in swing, when the foot lifted off the ground after toe off. The dorsiflexion of the foot preparing for the next initial contact was represented by both a minor peak in KE_r and a small plateau in the downward trend of the PE late in swing phase. The component energy data followed the above trends in all steps, whether they occur during gait initiation or steady state gait. The amplitudes of the peaks increased greatly from the first step to the second, and to a lesser extent from the second to the third. This was most marked in the KE_t and total energy data. The PE , on the other hand, attained its steady-state amplitude in the second step.

Figs. 4 and 5 show the component energies of the shank segments. It was noticeable in these graphs that the minimum level of the total energy was dependent

Table 2
Change in total energy from previous step (%BW*LL)

| | 1 | 2 | 3 | 4 | 5 |
|-------------------|-------|-------|-------|-------|-------|
| Foot | | | | | |
| INIP | 0.44 | 0.74 | -0.06 | 0.13 | 0.00 |
| INI1 | 0.33 | 0.92 | 0.12 | -0.21 | 0.15 |
| INI2 | 0.36 | 0.74 | 0.02 | 0.32 | -0.32 |
| INI3 | 0.37 | 0.76 | 0.10 | 0.00 | -0.03 |
| INI4 | 0.43 | 0.62 | 0.20 | 0.01 | 0.12 |
| INI5 | 0.35 | 0.74 | -0.04 | 0.19 | -0.06 |
| INI6 | 0.22 | 0.29 | 0.13 | 0.05 | 0.00 |
| Shank | | | | | |
| INIP | 0.81 | 1.35 | -0.18 | 0.25 | 0.05 |
| INI1 | 1.07 | 0.96 | 0.31 | 0.02 | -0.21 |
| INI2 | 0.69 | 1.38 | 0.03 | 0.58 | -0.53 |
| INI3 | 0.71 | 1.27 | 0.26 | -0.11 | -0.04 |
| INI4 | 0.76 | 1.06 | 0.34 | 0.05 | 0.16 |
| INI5 | 0.67 | 1.21 | 0.12 | 0.14 | 0.11 |
| INI6 | 0.39 | 0.48 | 0.29 | -0.01 | 0.10 |
| Thigh | | | | | |
| INIP | 0.65 | 0.82 | 0.41 | -0.07 | 0.28 |
| INI1 | 1.85 | 0.20 | 0.88 | -0.45 | 0.06 |
| INI2 | 0.36 | 1.20 | 0.47 | 0.34 | -0.12 |
| INI3 | 0.64 | 1.16 | 0.47 | 0.06 | 0.09 |
| INI4 | 0.48 | 1.22 | 0.43 | 0.21 | -0.03 |
| INI5 | 0.54 | 1.25 | 0.18 | 0.24 | 0.09 |
| INI6 | 0.43 | 0.45 | 0.38 | 0.15 | 0.04 |
| HAT | | | | | |
| INIP | 0.15 | 3.35 | 0.17 | 0.41 | -0.08 |
| INI1 | 0.04 | 3.07 | 0.66 | 0.27 | 0.52 |
| INI2 | 0.30 | 2.86 | 1.95 | 0.56 | 0.83 |
| INI3 | 0.00 | 1.03 | 2.45 | 0.94 | 0.19 |
| INI4 | 0.02 | 1.99 | 0.88 | 1.10 | 0.03 |
| INI5 | 0.02 | 2.56 | 1.51 | -0.02 | -0.24 |
| INI6 | 0.14 | 1.80 | 0.55 | 0.25 | 0.23 |
| Total body | | | | | |
| INIP | -1.80 | 6.55 | 0.45 | 0.60 | 0.20 |
| INI1 | 2.35 | 4.95 | 2.55 | -1.10 | 1.65 |
| INI2 | 1.40 | 6.10 | 2.70 | 1.50 | 0.20 |
| INI3 | 4.37 | -2.03 | 6.50 | 0.43 | 0.77 |
| INI4 | 1.10 | 4.43 | 2.53 | 0.50 | 0.77 |
| INI5 | 0.90 | 5.90 | 1.57 | 0.67 | -0.27 |
| INI6 | 0.80 | 2.97 | 1.40 | 0.53 | 0.33 |

on the minimal level of the PE , due to the height of the center of mass of the shank (as will be seen in all subsequent segments). During each leg's respective swing phase, the KE_t increased from the push off of the given leg, followed by a downward sloping plateau showing the swinging of the leg forward. During swing phase, KE_r was most pronounced in the shank and thigh. The largest peak of KE_r occurred in late swing from the extension of the shank before initial contact of the heel with a lower peak earlier in swing phase just after push off. When the shank was in stance phase, the kinetic energies exhibited a concave upward pattern indicative of the shank losing then gaining velocity as it 'rolled' over the ankle joint. Just as in the feet, the peak in the shank PE reached its steady-state level in the second step. In each step, the KE_r maintained its aforementioned pattern; only the magnitudes of the peaks increased markedly until the third step. On the other hand, the KE_t data took three steps to develop its steady-state pattern and magnitudes. In the first step, the shank energy data bore little resemblance to that of later steps, except for the KE_r . This was due to the short extension of the shank in the first step of the initiator.

Figs. 6 and 7 show the component energies of the thighs. The PE level of the thigh during quiet standing was higher than the average PE level during motion. The thigh was the first segment to show this characteristic. This was consistent with literature [25], where it was shown that in steady state gait, there is a constant knee flex during stance phase, so the body never attains its standing height. Hence the approximate mean PE levels of the thigh and HAT during motion were expected to be less than that of quiet standing. The PE data for the thigh peaked in the middle of swing phase signifying the maximum lifting of the leg. During stance phase, the gradual increase then decrease of the PE data, as well as the peaks seen in the KE_r , showed the leg 'rolling' over the ankle. Both kinetic energies peaked in phase with each other in the early part of swing phase, which represented the lifting of the thigh. The KE_t peaked again at initial contact which was caused by the push off created by the opposing leg. It should be noticed that the pattern of KE_t data was the same from the second step onward—a large peak at the beginning of swing phase with a subsequent peak at the push-off of the contralateral leg. However in the first step, the first peak of KE_t (at 35% GIE) was very modest, while the second peak (at 50% GIE) was much greater. This seemed to signify that the foundation leg, which was in stance phase during the first step, created a large push-off to accelerate the body towards walking at a steady state.

An examination of the HAT data (Fig. 8) showed the 'fall forward' of the torso that begins gait initiation. The PE and total energy decreased simultaneously until

25% GIE. Then, the PE continued decreasing but with a corresponding increase in KE_t until 50% (the end of the first step). After 50%, the conservative nature of the segment became apparent as shown by the anti-phasic patterns of KE_t and PE . Once again the PE level of quiet standing was greater than the average level during the motion (as noted in the thigh). The KE_t peaks and troughs increased to steady state levels with each successive step. It was also noted that during the entire event of gait initiation, the KE_r of the HAT was at or very near zero. This supported the assumption made by Winter, et al. [1] that KE_r of the HAT was negligible and could be ignored in future analyses.

The total energy of the body (E_b) was computed by taking the sum of the total energies of each segment at each normalized time point. Fig. 9 shows the total energy data for one representative trial of all seven subjects. The data showed three separate energy states. The first state (< 0% GIE) was that of quiet standing, where the total energy level was constant. The second state (0–150% GIE) was the transient state between quiet standing and steady state, i.e., gait initiation. The final state (> 150% GIE) showed the cyclic energy pattern indicative of steady state walking. The trough of energy at 60% was less than the energy level of quiet standing; this indicated that the body had not yet generated enough kinetic energy to overcome the decrease in potential energy of the HAT and thighs during the ‘fall forward’. The general trend of the total body energy was much like that of the total energy of the HAT. The oscillatory nature of the body energy within each step was primarily due to the total energy changes of the leg in swing phase during that step. The first step (0–50% GIE) showed a small peak of total body energy, mainly from the initiator taking a modest step forward in preparation for the second step. The body underwent a major increase in energy during the second step (50–100% GIE), when the foundation leg created a large push off. The basic trends in the component energy data are very similar to those during steady state reported by Winter, et al. [1], especially in the second and third steps of gait initiation (50–100% GIE and 100–150% GIE, respectively). However during gait initiation, the amplitudes of the component energy data are not as great as during steady state, showing the distinct event of gait initiation.

This increase in peak energy during gait initiation can also be seen in the individual segments as well. Table 1 shows peak total energy values of the foot, shank, thigh, HAT and total body during quiet standing and the five analyzed steps for each of the seven subjects. (It should be noted that for the foot, shank, and thigh, the reported values are for the leg that was in swing phase during that step; i.e., for steps 1, 3, and 5, the peak values for the initiation leg are reported, while the peak values for the foundation leg are re-

ported for steps 2 and 4). In all leg segments (and therefore the total body), the peak total energy value in the first step was greater than that of quiet standing but less than the steady state levels. The HAT peak total energy in the first step was similar to its level in quiet standing, because the segment was still ‘falling forward’. In the second step, all segments exhibited peak energy values near the steady state levels due to the push-off of the foundation leg. Peak energy levels were nearly constant in the body in the three remaining steps.

Table 2 shows the difference in peak total energy of a segment from the previous step. In general, the greatest peak energy increase occurred in the second step, due to the push-off of the foundation leg. The second greatest increase in all of the segments came in the first step as the body started the gait initiation process. In general, the increase in total energy in step three was less than those of the previous two steps and greater than those of the following two steps (steady state), although some increases calculated in step three were very similar to those seen in the steady state steps that followed. This may represent a ‘fine-tuning’ of the total body energy to reach the required walking velocity.

Therefore, the three steps of gait initiation may be categorized as follows [24]. The first step is used to propel the body into a dynamic state. The initiator steps forward to act as a base for the push off in the next step. In the next step, the foundation leg creates a large energy input (push off) to raise the body to a higher energy state. Finally in the third step, the body readjusts its energy level to attain the desired walking speed.

Errors may have been produced in the splicing of data and the small population size, and these are recognized as limitations of this method. If the subjects varied their walking speed greatly from trial to trial, then large discontinuities in the component energy data of each body segment would have resulted at ‘splice points.’ Inspection of this data revealed no large discontinuities that may have invalidated the results.

4. Conclusions

In this study, we calculated the component mechanical energies of the body during gait initiation on seven healthy male subjects (average age = 23.6 years). The general level of mechanical energy was due to the potential energy of the individual segments, while the cyclic nature of the data was indicative of the kinetic energy of the particular leg in swing phase during that step. Patterns observed in the energy data began to resemble those of steady state in the second step, while the magnitudes of the peaks in the data approached steady-state levels in the third step. The greatest in

crease in magnitude came in the second step, due to a great push-off by the foundation leg. The data clearly showed the three phases of the transition from standing to walking: (1) quiet standing, where the total body energy was constant and was completely made up of the PE of the individual segments; (2) gait initiation, where steady-state energy patterns emerged as magnitudes increased; and (3) steady-state walking, where the energy data exhibited its cyclic nature.

The normal data presented here may be useful in the study of pathologic gait initiation or in the evaluation of prosthetic devices. Future studies should include collecting data on female subjects and elderly subjects to see if there are any gender or age-specific differences. Finally, data should be collected on clinical subjects to observe variations in their energy patterns from 'non-pathologic' subjects.

Appendix A. Nomenclature

| | |
|-----------|---|
| E_b | total energy of the body (J) |
| E_{tot} | segment total energy (J) |
| g | acceleration due to gravity (m/s^2) |
| h | height of segment center of mass above walking platform (m) |
| I | segment moment of inertia (kg/m^2) |
| KE_r | rotational kinetic energy (J) |
| KE_t | translational kinetic energy (J) |
| m | body segment mass (kg) |
| PE | potential energy (J) |
| v_{cm} | velocity of segment center of mass (m/s) |
| ω | segment angular velocity (rad/s) |

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