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Original Paper

Mechanical energy of the trunk during walking – does the model used influence the results?

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The paper presents two trunk models. In the first one, the trunk is modelled as a series of seven segments, whose dimensions and inertial properties are parametrically based on body stature and body mass. In the second one, the trunk is modelled as one rigid segment. These models are used to calculate kinetic energy of the trunk relative movement with respect to the body centre of mass. The results show that in the case of healthy subject both models give similar results, but in the case of stroke subjects the simplified model leads to the underestimation of the energy amount and does not reflect all phases of gait when energy is generated.

Key words: *gait, trunk, mechanical energy*

1. Introduction

The energy consumption of any living creature can be divided into two parts. The first part, the so-called *basic metabolic energy*, is responsible for keeping us alive, and in the case of mammals, for keeping a proper body temperature. The second part is connected with the tasks performed, both motor and intellectual.

During execution of movements the proper coordination of all body segments ensures the proper flow of potential and kinetic energy, which keeps the total energy on the constant level and minimizes the energy consumption. The direct measurement of the energy consumption is practically impossible, therefore the amount of energy could be assessed by measuring the oxygen consumption. Such a measurement revealed [1] that the energy consumption during gait increases in various groups of patients with gait pathology. This increase varies from 3% even up to 160% [1].

As the oxygen consumption measurements require special equipment, which not always is available, another method used to estimate energy cost of gait involves calculating mechanical energy. The simplest method calculates the potential and kinetic energy of the body centre of mass during gait. This method does not take into account the coordination of body segments during gait and leads to underestimated results [2]. Therefore CAVAGNA [3]–[7] proposed a new method in which, apart from potential and kinetic energy of the body centre of mass, the kinetic energy of linear and angular movements of body segments with respect to body centre of mass is calculated. He also identified two main mechanisms of energy conservation: the transfer of potential energy into kinetic one, and vice versa, and the storage of energy in elastic body structures in some phases of gait and its recovery in another phases.

The approach proposed by Cavagna requires division of the body into well defined segments, with well defined dimensions, mass, and inertial properties. It can be assumed that various body models could lead to different results of mechanical energy calculations, especially in pathological cases where the coordination of the movements of the body segments is deranged.

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Therefore the aim of this paper was to propose the parametric trunk model and to compare the mechanical energy calculated using this model with that calculated based on the model in which trunk is just one segment. The mechanical energy will be calculated for a healthy subject and for the subjects which suffer from stroke. Such a comparison will show whether the use of a simplified trunk model is justified both in healthy subjects and pathological cases or not.

In previous studies [8], [9], the segmental movements of spine were measured using eight markers placed over the spinal processes C7, Th4, Th8, Th10, Th12, L2, L4 and S2 in healthy subjects and in patients who suffered from stroke. These data will be used to calculate the mechanical energy in two conditions: using parametric trunk model and simplified trunk model. The comparison of the results obtained will show whether the use of a simplified trunk model is justified both in healthy and pathological subjects or not.

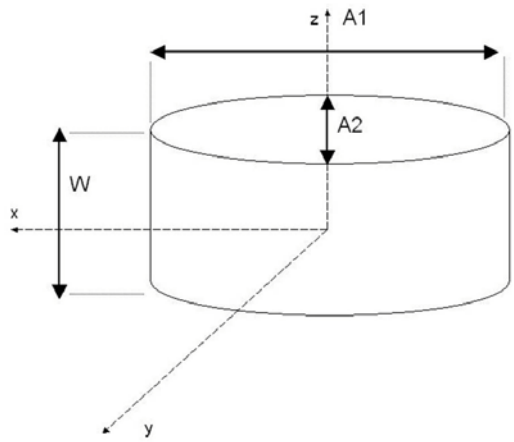

Fig. 1. The shape and dimensions of the trunk segment: plane *yz* – sagittal, plane *xz* – frontal, plane *xy* – transversal

Table 1. Dimensions of trunk segments as a function of body stature *H* for males

Trunk segment	A1	A2	W
1 (C7–Th3)	0.176 *H*	0.07 *H*	0.05 *H*
2 (Th3–Th8)	0.17 *H*	0.11 *H*	0.05 *H*
3 (Th8–Th10)	0.165 *H*	0.11 *H*	0.045 *H*
4 (Th10–Th12)	0.16 *H*	0.095 *H*	0.045 *H*
5 (Th12–L2)	0.16 *H*	0.08 *H*	0.05 *H*
6 (L2–L4)	0.18 *H*	0.07 *H*	0.025 *H*
7 (L4–S2)	0.2 *H*	0.07 *H*	0.035 *H*

2. Material and method

2.1. Parametric trunk model

The distribution of body mass among the segments was investigated by several researchers. The trunk mass was estimated as 44.2% of body mass by Harless, 45.2% by Fisher, 46.1% by Braune and Fisher, 48.6% by Dempster, and 50.7% by Clauser [10]–[12]. As the value of 46.1% given by Braune and Fisher is the mean value of the above given five percentages, thus this value was taken for further calculations.

The trunk was defined as the segment between C7 and S2 levels. In parametric model, the trunk was divided into seven segments, depending on the location of the markers along the spine (C7, Th4, Th8, Th10, Th12, L2, L4 and S2). The shape of the trunk segment is shown in figure 1.

The dimensions of the trunk segments were based on the measurements carried out by the team of Contini, Drillis, and Bluestein and by Erdman. In the seventies of the twentieth century the team of CONTINI et al. [13], [14] assessed the body proportions of healthy, adult males, i.e. they presented the dimensions of the segments as the function of body height. ERDMAN [15] investigated the trunk shape of healthy adult males using CT scans. Based on these papers the total trunk length (C7 to S2) was 0.3 *H* (*H* – body stature) for males. The dimensions calculated as a function of body stature are presented in table 1. In table 2, the moments of inertia of the trunk segments, as a function of body stature and body mass, are collected. It

Table 2. Parametric moments of inertia of trunk segments, presented as a function of body mass *M*, and body stature *H*

Trunk segment	I_{xx}	I_{yy}	I_{zz}
1 (C7–Th3)	$1.383\cdot10^{-4}\,H^2M$	$3.362\cdot10^{-4}\,H^2M$	$2.722\cdot10^{-4}\,H^2M$
2 (Th3–Th8)	$2.931\cdot10^{-4}\,H^2M$	$4.867\cdot10^{-4}\,H^2M$	$4.725\cdot10^{-4}\,H^2M$
3 (Th8–Th10)	$2.301\cdot10^{-4}\,H^2M$	$3.821\cdot10^{-4}\,H^2M$	$3.952\cdot10^{-4}\,H^2M$
4 (Th10–Th12)	$1.670\cdot10^{-4}\,H^2M$	$3.067\cdot10^{-4}\,H^2M$	$2.917\cdot10^{-4}\,H^2M$
5 (Th12–L2)	$1.993\cdot10^{-4}\,H^2M.$	$3.932\cdot10^{-4}\,H^2M$	$3.232\cdot10^{-4}\,H^2M$
6 (L2–L4)	$0.320\cdot10^{-4}\,H^2M.$	$1.260\cdot10^{-4}\,H^2M$	$1.450\cdot10^{-4}\,H^2M$
7 (L4–S2)	$0.692\cdot10^{-4}\,H^2M$	$2.519\cdot10^{-4}\,H^2M$	$2.716\cdot10^{-4}\,H^2M$

was assumed that all segments have the same density, thus the body mass was distributed among the segments proportionally to their volume.

2.2. Trunk modelled as a single segment

The model was created applying the following assumptions:

- the trunk height from C7 to S2 is equal to 0.3 H;
- the trunk mass is equal to 46.1% of total body mass;
- the width of the segment is equal to 0.173 H (mean of all trunk segments).

2.3. Mechanical energy

In the calculation of the mechanical energy, the approach of Cavagna was used:

$$E_{\text{total}} = mgh + \frac{1}{2}mV^2 + \sum_{i=1}^{n}\left(\frac{1}{2}I_i\omega_i^2 + \frac{1}{2}m_iV_i^2\right),$$

where:

E_{total} – total mechanical energy,
m – body mass,
h – height of body centre of mass,
V – velocity of body centre of mass,
I_i – moment of inertia of body segment i,
ω_i – angular velocity of segment i with respect to the body centre of mass,
V_i – linear velocity of segment i with respect to the body centre of mass.

In this paper, the calculations were limited to the potential and kinetic energy of the body centre of mass and mechanical energy of angular and linear movements of the trunk segments with respect to the body centre of mass.

For an easier comparison of the results of the both models (parametric and single segment) the calculations were done for a model male subject of the body stature H = 170 cm and the body mass M = 70 kg.

2.4. Kinematic data

In two previous papers [8], [9], the movements of spinal segments were measured in sagittal and frontal planes during walking of healthy and post-stroke subjects. Additionally the relative shoulder/pelvis movements were measured. The analysis of these data revealed that the stroke patients did not form a homogeneous group. On the contrary, three subgroups could be distinguished. Each subgroup had its characteristic movement pattern of the spinal segments. These data were used to calculate the mechanical energy of the trunk segments and the kinetic and potential energy of the body centre of mass. As the body centre of mass is located within the pelvis, below the umbilicus, it was assumed that the trajectory of the S2 marker represented the body centre of mass trajectory.

All calculations were done in MATLAB based on user's own procedures.

3. Results

Figures 2–5 present the potential and kinetic energy of the centre of mass during gait for four model subjects: one healthy and three after a stroke, whose spinal movement pattern represented the three stroke subgroups.

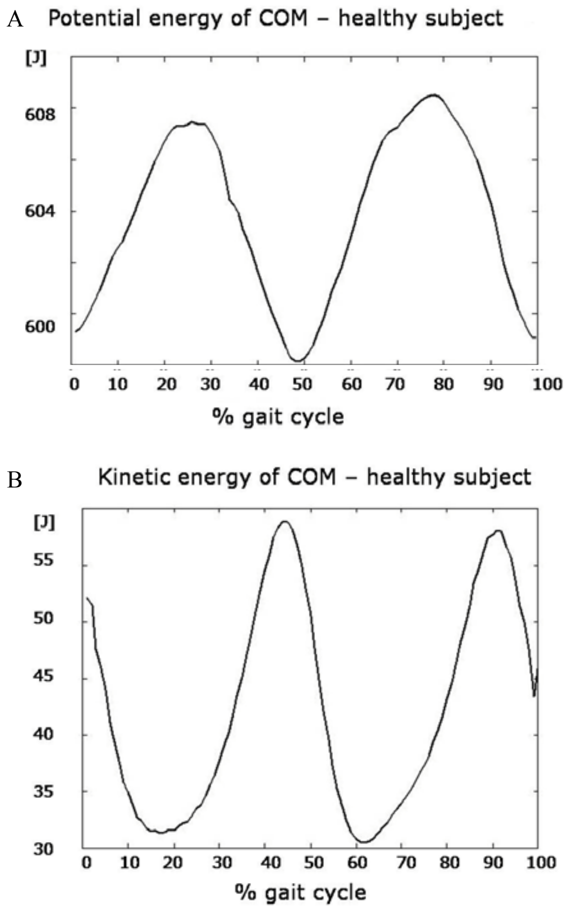

Fig. 2. Energy of body centre of mass of healthy model subject. A. Potential energy. B. Kinetic energy

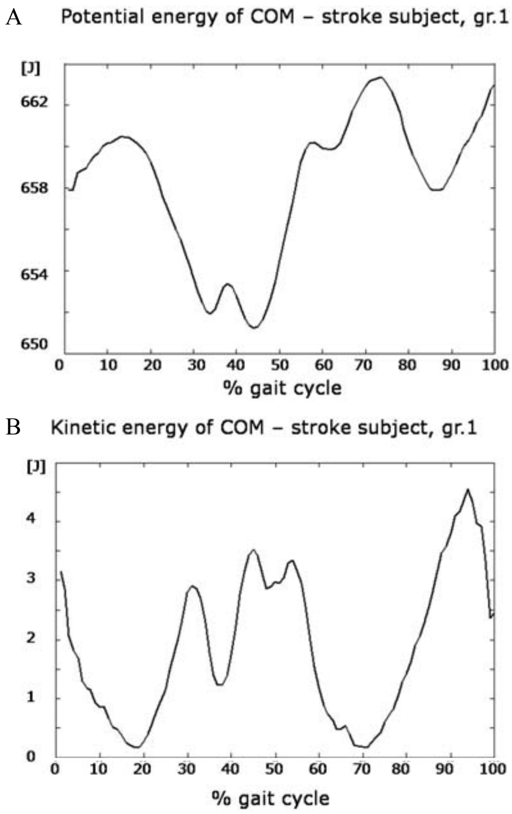

Fig. 3. Energy of body centre of mass of stroke model subject from first subgroup. A. Potential energy. B. Kinetic energy

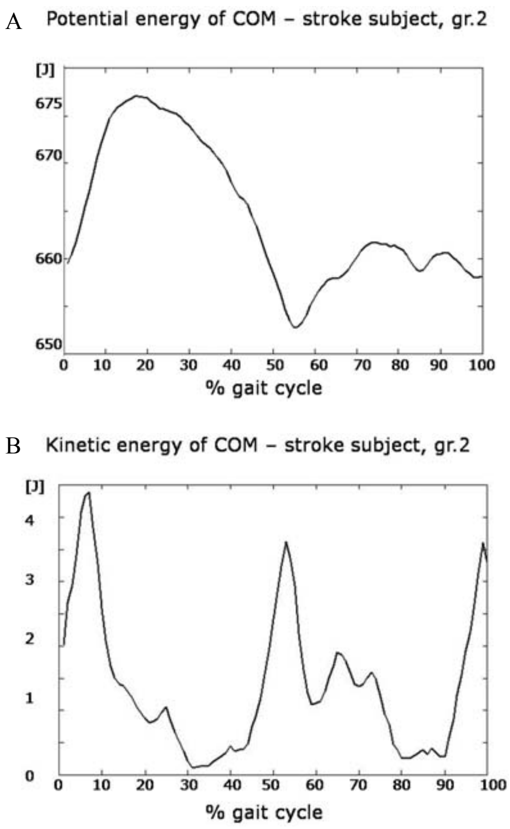

Fig. 4. Energy of body centre of mass of stroke model subject from second subgroup. A. Potential energy. B. Kinetic energy

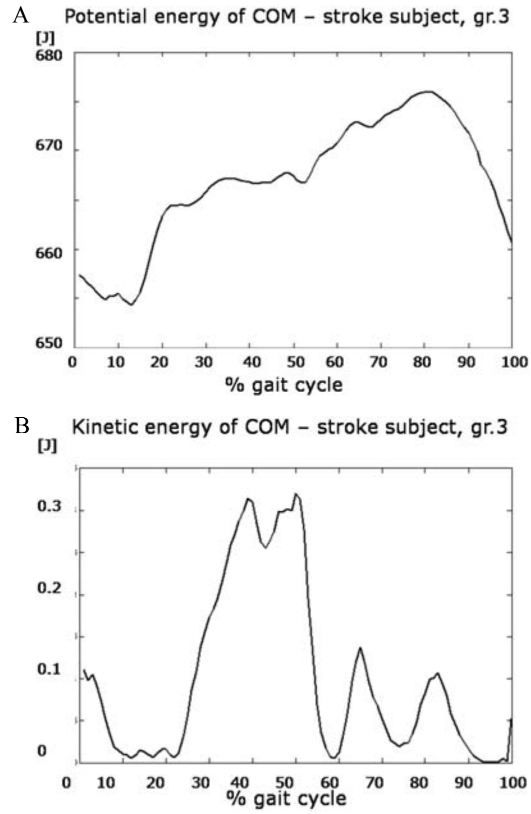

Fig. 5. Energy of body centre of mass of stroke model subject from third subgroup. A. Potential energy. B. Kinetic energy

Figures 6–9 present the kinetic energy of seven trunk segments with respect to the centre of body mass (kinetic energy of linear and angular movements) for four model subjects: one healthy and three after a stroke.

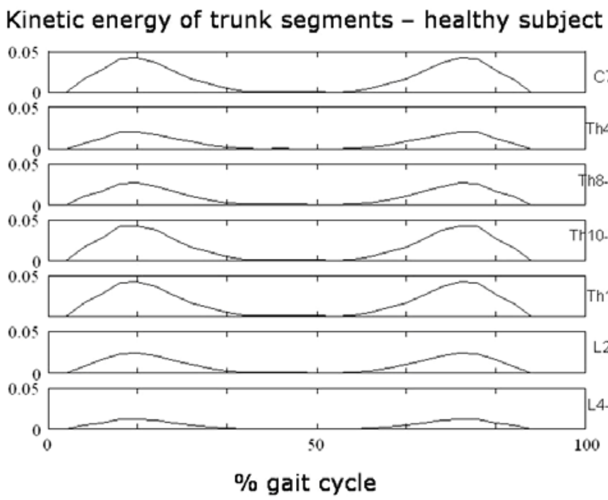

Fig. 6. Kinetic energy of the trunk segments (from linear and angular movements in respect of the body centre of mass) in healthy subject

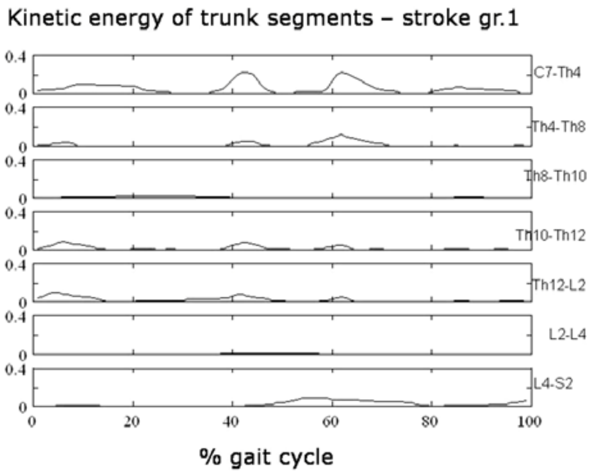

Fig. 7. Kinetic energy of the trunk segments (from linear and angular movements in respect of the body centre of mass) in stroke subject from first subgroup

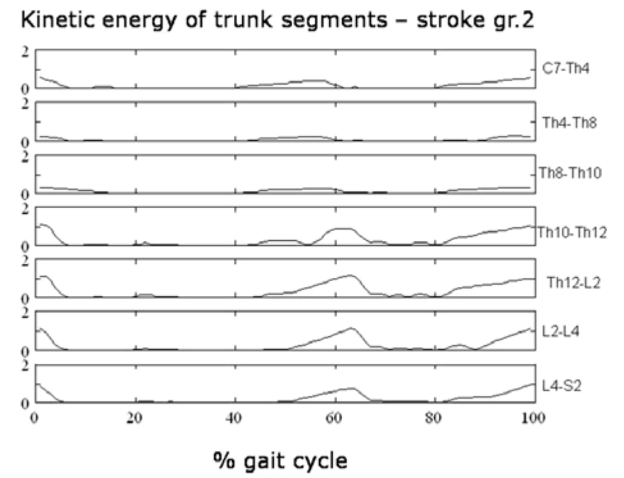

Fig. 8. Kinetic energy of the trunk segments (from linear and angular movements in respect of the body centre of mass) in stroke subject from second subgroup

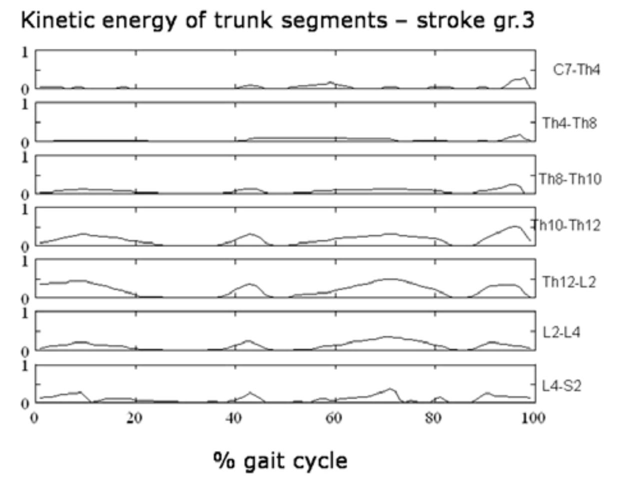

Fig. 9. Kinetic energy of the trunk segments (from linear and angular movements in respect of the body centre of mass) in stroke subject from third subgroup

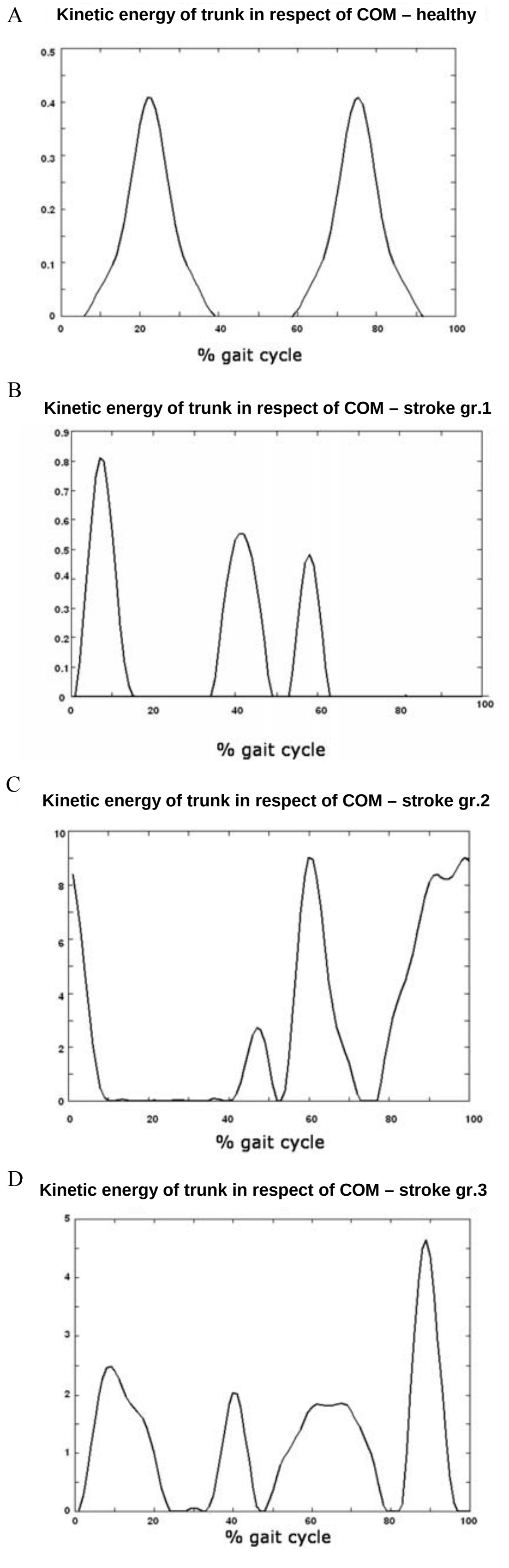

Fig. 10. Kinetic energy of the trunk (from linear and angular movements in respect of the body centre of mass) in model subjects. A. Healthy subject. B. Stroke subject from first subgroup. C. Stroke subject from second subgroup. D. Stroke subject from third subgroup

Figure 10 shows the kinetic energy of the trunk in respect of the body centre of mass, when the trunk was modelled as one rigid segment, for one healthy model subject and three after a stroke.

4. Discussion

The results of the potential and kinetic energy of the centre of mass for the healthy model subject are in good agreement with the data from the literature [16]. The kinetic energy is relatively low (approximately 10%) in comparison with the potential energy, and the change of one type of energy is mirrored by the second one.

The kinetic energy of the trunk segments in respect of the body centre of mass is small, despite the high mass of the trunk. This is caused by the relatively low velocity (both linear and angular) of the trunk segments with respect to the centre of mass.

In three model subjects representing three subgroups of the stroke patients, the results are different.

The potential energy of the body centre of mass is higher in the stroke subjects than in the healthy subjects. As all the calculations were done for the same model subject (constant mass and body height) this difference indicates that the vertical excursion of the trajectory of centre of the body was higher in stroke subjects, probably because of variations of the hip, knee and ankle movements. The difference between the highest and lowest levels of the potential energy was approximately 8 J (see figure 2A), while in the stroke subjects it varied from 12 J to 25 J. This finding indicated much bigger vertical excursion of the body centre of mass in the stroke subjects.

The kinetic energy is smaller in the stroke patients than in the healthy ones, which was caused by the limited gait velocity. In all three model stroke subjects, there was no mirroring of the potential and kinetic energy of the body centre of mass. This means that there was no transfer of one form of the energy into anther one, i.e. no conservation of the energy.

The comparison of the kinetic energy of the trunk segments with respect to the body centre of mass revealed that this energy is much higher in the case of stroke subjects than in the healthy one. Moreover, in the healthy subject, the energy was generated in the same phases of the gait cycle in all seven segments, the first phase was between 5 and 30% of the gait cycle, and the second one between 60 and 95% of the gait cycle.

In the stroke subjects, there was no similarity in the generation of the energy between the segments. The energy was also generated in different ways between the three stroke subgroups.

When the kinetic energy was calculated using the trunk modelled as one rigid segment (figure 10), in the healthy subject the energy was generated in the same phases of gait as that in the trunk modelled by seven segments. The amount of energy was approximately equal to the sum of energy generated in each of the seven segments. Thus there was no difference between the results obtained from the two models.

The results obtained for the stroke subjects were different. The one-segment model suggested the generation of the energy in a way similar to that typical of the middle segment of the seven-segment model (Th10–Th12). The sum of the energy from the seven-segment model was not equal to the amount of the energy calculated from the one-segment model: it was much higher.

These results indicate that while in the healthy subjects there is no need to use more complicated trunk models, in the case of pathological gait the use of simplified models leads to underestimation of the amount of mechanical energy generated during gait. Moreover, the simplified model does not show all the phases of the gait cycle when the kinetic energy is generated.

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