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Estimation of muscle energy expenditure in a spinal-cord-injured subject during crutch-assisted gait

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ABSTRACT — *Determination of muscle energy expenditure by computer modeling and analysis is of great interest to estimate the whole body energy consumption, while avoiding the invasive character of in vivo experimental measurements. In previous papers, the authors presented optimization methods for estimating muscle forces in healthy gait and in spinal-cord-injured (SCI) subjects performing crutch-assisted gait. Starting from those results, this work addresses the estimation of the whole body energy consumption of a SCI subject during crutch-assisted gait using the models of human muscle energy expenditure proposed by Umberger and Bhargava. First, the two methods were applied to the gait of a healthy subject and experimentally validated by means of a portable gas analyzer on several 5-minute tests.*

1 Introduction

In the last decade, many mechanical and, more recently, electromechanical (or hybrid) devices have been developed to allow spinal cord injured (SCI) patients to stand and walk. At the moment, the additional use of crutches is required for gait stability. Despite these technological advances, most SCI subjects prefer the wheelchair to move for energetic efficiency reasons [1]. The gait efficiency can be defined as the percentage of energy input that is transformed into useful work. Use of a cane or a pair of crutches required about 33% more energy than normal walking [2]. In addition, some devices (like the conventional knee-ankle-foot orthosis) don't allow some joints to move, which implies another gait pattern even less efficient. But the main cause of the higher energy expenditure is that the structures of the upper extremities are designed primarily for prehensile activities, not to walk, unlike some animals, which produces shoulder and arm injuries in some patients.

Energy cost in subjects using crutches was mainly studied using experimental measurements [1-3], which is very invasive and is generally done during short distances, so that it can only give approximate results. Ijzerman and co-authors proposed a method to estimate the energy expenditure of paraplegic gait using measurements of heart rate and crutch forces [4]. In the present work, the authors use models of human muscle energy expenditure proposed to calculate the energy cost during gait of healthy people, and adapt them for the crutch gait of SCI subjects.

In the literature, various Hill-based models to calculate the human muscle energy expenditure can be found [5-8]. Miller proposed a comparison of these models for simulating human walking in [9]. According to his recommendations, the models of Umberger and Bhargava have been implemented in this work to calculate the energy cost of SCI subjects during crutch gait. Both muscle energy expenditure models considered are based on the Hill's muscle model and, hence, require the knowledge of some muscular parameters. Such parameters had been obtained by the authors in a previous work [10], where it was found that shoulder joint reaction forces during crutch-orthosis-assisted gait can reach up to 250% of the bodyweight, and may then explain the appearance of upper extremities injuries. The objective of this paper is to estimate the energy cost of SCI subjects during crutch gait from the motion capture of a full gait cycle in order to evaluate and compare the energy efficiency of assistive gait devices. First, the methods were applied to the gait of a healthy subject, and experimentally validated by means of a portable gas analyzer on several 5-minute tests.

2 Experiments and models

2.1 Subjects

The SCI subject was an adult male of mass 82 kg and height 1.85 m, with injury corresponding to Lower Extremity Muscle Score (LEMS) of 13/50. His injury allowed him a normal motion of the upper extremities and trunk, while partially limiting the actuation at the hips and right knee due to partial or no muscular innervation. Actuation and sensitivity at ankles and left knee was totally lost. Therefore, in order to walk he required the assistance of a passive knee ankle-foot orthosis at the left leg, a passive ankle-foot orthosis at the right leg and two crutches. In daily life he mainly used a wheelchair to move and resorted to the mentioned assisted gait only occasionally and during short periods of time. In order to assess muscle activity at hip and knee levels, surface EMG was used (equipment to measure deep muscles was not available).

The healthy subject was an adult male of mass 85 kg and height 1.87 m.

2.2 Instrumentation and data collection

Subjects walked over two embedded force plates (AMTI, AccuGait, sampling at 100 Hz), with the help of two instrumented crutches for the SCI subject [11], while their motion was captured by 12 optical infrared cameras that computed the position of 37 optical markers (plus 3 for each crutch). Moreover, 16 EMG signals were recorded (5 at the right leg, 2 at the left leg, 2 at the trunk, 6 at the right arm and 1 at the left arm) in the SCI subject and 12 in the healthy subject at the lower extremities (Fig. 1a) and Fig. 3a)). A completed gait cycle was captured. The SCI patient showed a 4-point crutch-assisted gait cycle (Fig. 2).

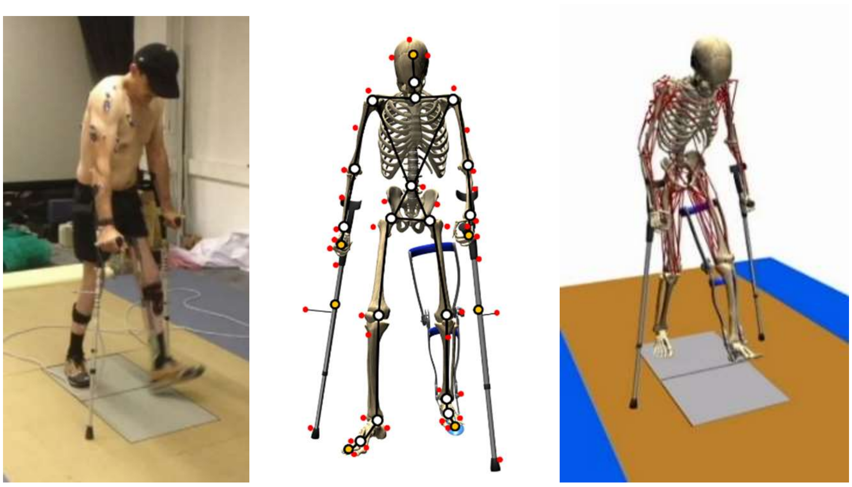

Fig. 1: Gait of SCI subject assisted by passive orthoses and crutches: a) motion-force-EMG capture; b) skeletal model; c) musculoskeletal model.

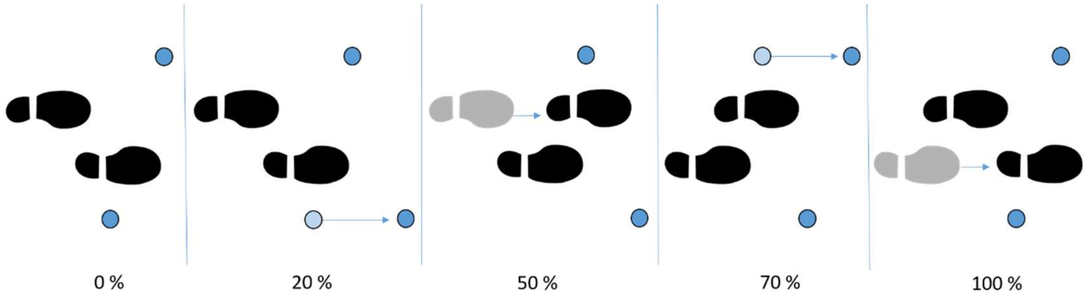

Fig. 2: 4-point crutch-assisted gait cycle.

For the healthy subject, 21 completed gait cycles were recorded at 7 different speeds (between free selected speed and fast speed) for energetic cost calculation. The energy expenditure was also measured experimentally by means of a portable gas analyzer (Cortex MetaMax 3B) on several 5-minute tests at free selected speed and fast speed (Fig. 3b). This experimental method requires that the subject maintains a constant activity during at least 5 min. Since this was thought to be too demanding for SCI subjects, it was decided to carry out the experimental validation with a healthy subject.

Fig. 3: Energy consumption in a healthy subject: a) motion-force-EMG capture; b) 5-minute test with portable gas analyzer.

2.3 Model description

For the healthy subject, the human 3D model consisted of 18 anatomical segments: pelvis, torso, neck, head, and two hind feet, forefeet, shanks, thighs, arms, forearms and hands. For the SCI subject (Fig. 1b), the same model was used, but the hands were rigidly connected to the crutches and the orthoses were embedded in the corresponding body links (thighs, calves and feet). The segments were linked by ideal spherical joints, thus defining a model with 57 degrees of freedom (6 of the base body plus 17x3 of the joints). The geometric and inertial parameters of the model were obtained, for the lower limbs, by applying correlation equations from a reduced set of measurements taken on the subject, following the procedures described in [12]. For the upper part of the body, data from standard tables [13] was scaled according to the mass and height of the subject. In order to adjust the total mass of the subject, a second scaling was applied to the inertial parameters of the upper part of the body. Assistive devices were taken into account by altering the inertia properties of hands (crutches) and thighs, calves and feet (orthoses).

As explained before, the musculoskeletal model was adapted to the subject according to his muscle activity (previously measured through EMG). The musculoskeletal model (Fig. 1c) was composed of 112 muscles for the whole body: 28 at the right hip, 5 at the right knee, 21 at the left hip, 6 at the trunk, 15 at each shoulder and 11 at each elbow. Muscle properties were taken from

[14]. The Hill's muscle model was used, being considered both the tendon and the muscle (with its contractile (CE) and passive (PE) element) (Fig. 4).

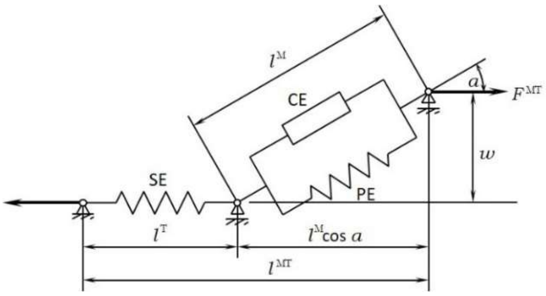

Fig. 4: Hill's muscle model.

3 Energy expenditure

For the healthy subject, after obtaining the muscular activity by the physiological static optimization method, results were validated with the experimental EMG measurements. From this calculation, the activation, the length, the velocity and the force muscles were used as input of the two applied models of energy expenditure. Both of them are based on the first law of thermodynamics. According to this law, the total rate of energy consumption $\dot{E}$, is equal to the rate at which heat is liberated, $\dot{H}$, plus the rate at which work is done, $\dot{W}$:

$$\dot{E} = \dot{H} + \dot{W} \tag{1}$$

3.1 Umberger's model

The muscle energy expenditure model of Umberger [8] considers the activation heat rate ($\dot{h}_A$), the maintenance heat rate ($\dot{h}_M$), the shortening/lengthening heat rate ($\dot{h}_{SL}$), and the mechanical work rate of the contractile element of the muscle ($\dot{w}_{CE}$), to determine the total rate of muscle energy expenditure ($\dot{E}$). The relation is given by the sum of this four terms expressed in (2), where $\dot{E}$ is calculated for each muscle in $W.kg^{-1}$.

$$\dot{E} = \dot{h}_A + \dot{h}_M + \dot{h}_{SL} + \dot{w}_{CE} \tag{2}$$

Activation and Maintenance heat rate:
A combined expression of the activation and maintenance heat rate is used for this first term,

$$\dot{h}_A + \dot{h}_M = \dot{h}_{AM} = \boldsymbol{m}(1.28 \times \%\boldsymbol{FT} + 25) \tag{3}$$

where $\%FT$ represents the percentage of fast twitch and m is the mass of the muscle; both can be found in [15].

Shortening and Lengthening heat rate:

During CE shortening, the rate of heat production is modelled as the product of a coefficient α_S and V_M , the velocity of the muscular contractile element:

$$\dot{h}_{SL} = \begin{cases} m(\alpha_{S(ST)}\tilde{V}_M(1-\%FT/100) - \alpha_{S(FT)}\tilde{V}_M(1-\%FT/100)) & \text{if} \quad V_M \leq 0 \\ m\alpha_L\tilde{V}_M & \text{if} \quad V_M > 0 \end{cases} \tag{4}$$

with the constant terms $\alpha_{S(ST)} = \dfrac{4\times25}{\tilde{V}_{M(MAX-ST)}}$, $\alpha_{S(FT)} = \dfrac{153}{\tilde{V}_{M(MAX-FT)}}$, $\alpha_L = 4\alpha_{S(ST)}$, $\tilde{V}_{M(MAX-FT)} = \dfrac{V^M_{MAX}}{l^M_0}$, $\tilde{V}_{M(MAX-ST)} = \tilde{V}_{M(MAX-FT)} / 2.5$ and $V^M_{MAX} = l^M_0 / 0.1$.

Mechanical work rate:

The specific mechanical work rate is given by:

$$\dot{w}_{CE} = -F^M_{CE} V_M \tag{5}$$

Total energy expenditure scaled:

Equation (2) provides the energy expenditure of the muscle for the case of full activation and optimal muscular length l^M_0 of the contractile element. Scaling factors are needed to account for the length and activation dependence of $\dot{h}_{AM}$ (A_{AM}) and $\dot{h}_{SL}$ (A_{SL}), and the dependence of the total heat rate on the metabolic working conditions ($S = 1$ for primarily anaerobic conditions and $S = 1.5$ for primarily aerobic conditions),

$$\dot{E} = \begin{cases} \dot{h}_{AM} A_{AM} S + \dot{h}_{SL} A_{SL} S + \dot{w}_{CE} & \text{if} \quad l^M \le l^M_0 \\ (0.4\times\dot{h}_{AM} + 0.6\times\dot{h}_{AM}\times F^M_0) A_{AM} S + \dot{h}_{SL} A_{SL} S + \dot{w}_{CE} & \text{if} \quad l^M > l^M_0 \end{cases} \tag{6}$$

with $A_{AM} = A^{0.6}$, $A_{SL} = A^2$, and

$$A = \begin{cases} u(t) & \text{if} \quad u(t) \le a(t) \\ (u(t) + a(t))/2 & \text{if} \quad u(t) > a(t) \end{cases} \tag{7}$$

where u and a represent the excitation and activation of the muscle respectively.

3.2 Bhargava's model

Bhargava's model presents some similarities with the previous one, since both start from equation (2), but the details in the other equations are different.

Activation heat rate:

$$\dot{h}_A = \phi m f_{FT} \dot{A}_{FT} u_{FT}(t) + \phi m f_{ST} \dot{A}_{ST} u_{ST}(t) \tag{7}$$

with $$\phi = 0.06 + \exp(-t_{stim} u(t) / \tau_\phi), \tag{8}$$

$$u_{FT}(t) = 1 - \cos(\frac{\pi}{2} u(t)) \text{ and } u_{ST}(t) = \sin(\frac{\pi}{2} u(t)), \tag{9-10}$$

and the constant terms: $f_{FT} = \%FT / 100$, $f_{ST} = (1 - \%FT)/100$, $\dot{A}_{FT}$ =133 and $\dot{A}_{ST}$=40.

Maintenance heat rate:

$$\dot{h}_M = L(\tilde{l}^M) m f_{FT} \dot{M}_{FT} u_{FT}(t) + L(\tilde{l}^M) m f_{ST} \dot{M}_{ST} u_{ST}(t) \tag{11}$$

where $L(\tilde{l}^M)$ is a function that models the dependence on muscle length:

$$L(\tilde{l}^M) = \begin{cases} 0.5 & \text{if} \quad \tilde{l}^M \le 0.5 \\ \tilde{l}^M & \text{if} \quad 0.5 < \tilde{l}^M \le 1 \\ -2(\tilde{l}^M) + 3 & \text{if} \quad 1 < \tilde{l}^M \le 1.5 \\ 0 & \text{if} \quad \tilde{l}^M > 1.5 \end{cases} \tag{12}$$

and the maintenance heat rate constants: $\dot{M}_{FT} = 111$ and $\dot{M}_{FT} = 74$.

Shortening and Lengthening heat rate:

During CE shortening, in this model, the rate of heat production is modelled as the product of a coefficient α_S and V_M too,

$$\dot{h}_{SL} = -\alpha_S \tilde{V}_M \tag{13}$$

but expression of α_S is different:

$$\alpha_S = \begin{cases} 0.16 F_0^M + 0.18 F_{CE}^M & \text{if} \quad V_M \le 0 \\ 0.157 F_{CE}^M & \text{if} \quad V_M > 0 \end{cases} \tag{14}$$

Basal heat rate:

In addition, Bhargava's model proposes a basal metabolic rate calculated from a frog skeletal model at 0ºC and given by:

$$\dot{h}_B = 0.0225 m \tag{15}$$

Mechanical work rate:

Both authors consider the same expression for the mechanical work rate:

$$\dot{w}_{CE} = -F_{CE}^M V_M \tag{16}$$

4 Results

The whole body energy consumption was obtained through both methods by integrating the sum of muscle energy expenditure of all the muscles of the model during a full stride, and adding a basal metabolic rate of 1.2 $W.kg^{-1}$ which corresponds to the basal metabolic rate for upright quiet standing [3]. As some variability was observed in the obtained values of energy cost for different tests at the same speed, a mean value is represented in Fig 5.

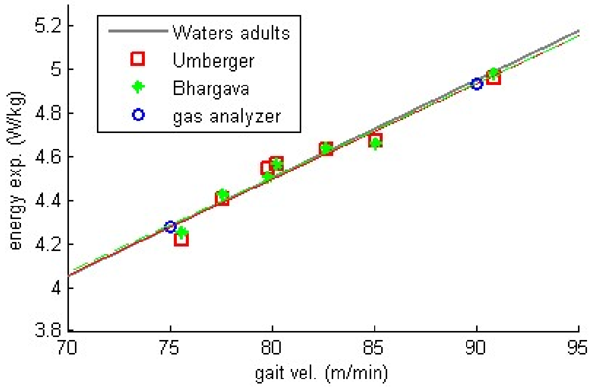

Fig. 5: Energy expenditure in healthy subject

As it can be seen in Fig. 5, a linear relation was obtained between gait speed and energy consumption, showing a good correlation with both experimental measurements and literature [3]. Since a constant discrepancy of the results was observed with respect to the measured energy values,the model was calibrated with such a constant (0.12 $W.kg^{-1}$ for Umberger's model and 1.9 $W.kg^{-1}$ for Bhargava's model). This calibration can be considered as an adjustment of the whole-body basal metabolic rate.

On the other hand, the energy consumption of the SCI subject was calculated for his self-selected speed with the two models. The obtained energy cost was of 3.07 $W.kg^{-1}$ with Umberger and of 2.13 $W.kg^{-1}$ with Bhargava. While, according to [3], the speed of the SCI subject ([0.35,0.4] m/s) approximated the speed corresponding to his LEMS (0.34 m/s), his energy consumption was lower than that provided in the mentioned reference (5.13 $W.kg^{-1}$). Again, it can be assumed that the difference comes from the whole-body basal metabolic rate, but it is expected that the relation between gait velocity and energy expenditure will be preserved. The pursued objective is to compare the current energy consumption of the SCI subject with that obtained when he wears an active orthosis (still in construction) on his left leg instead of the passive one, so as to assess the energetic improvement provided by the smart device.

5 Conclusion

The energy expenditure of a healthy male during gait was calculated, based on the muscular magnitudes obtained from a motion-force-EMG capture and a musculoskeltal model of the subject, through the application of two methods found in the literature, (Umberger's and Bhargava's) and was validated by experimental measurements and references from literature for several gait velocities. Results showed that calibration of the methods is necessary to evaluate the whole-body basal metabolic rate. However, the slopes (energy cost vs. gait speed) obtained with both methods were coincident and agreed with those from literature, which is the essential point to compare two activities performed by the same subject and using the same model.

Afterwards, the energy expenditure of a spinal cord injured adult male assisted by a passive knee-ankle-foot orthosis and two crutches was calculated in the same way with the two methods. Again, calibration was required to adjust the whole-body basal metabolic rate. In a next step, the energy cost will also be calculated for the same subject wearing an active knee-ankle-foot orthosis, so as to assess the energetic improvement provided by the smart device.

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