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

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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 model of the human muscle energy expenditure proposed by Umberger [2]. First, the method was applied to the gait of a healthy subject and experimentally validated by means of a portable gas analyzer on several 5-minute tests.

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. In the experiment (Fig. 1a), he was wearing a passive knee ankle-foot orthosis at the left leg and a passive ankle-foot orthosis at the right leg, while walking over two embedded force plates with the help of two instrumented crutches [3]. His motion was captured by 12 optical infrared cameras that computed the position of 43 optical markers. 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).

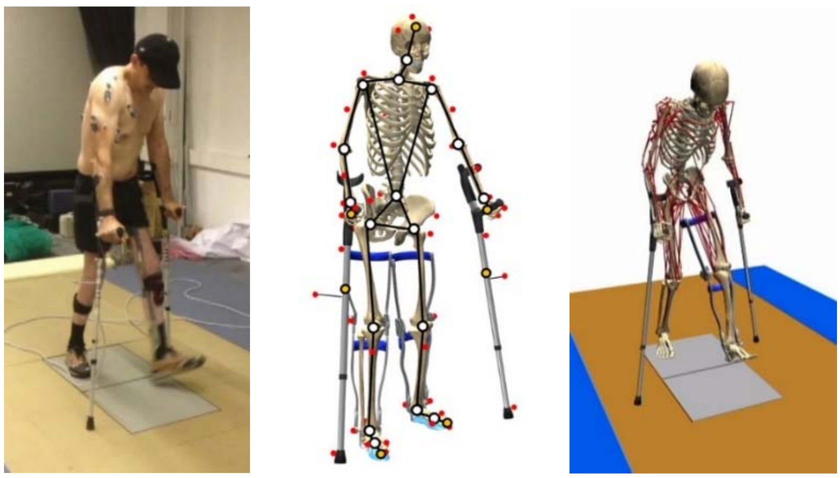

Fig. 1: Gait of SCI subject assisted by passive orthoses and crutches: a) motion-force-EMG capture; b) skeletal model; c) musculoskeletal model.

The human 3D model (Fig. 1b) consisted of 18 anatomical segments, with the hands rigidly connected to the crutches. The segments were linked by ideal spherical joints, thus defining a model with 57 degrees of freedom. As explained in [1], 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 trunk, 15 at the right and left shoulder and 11 at the right and left elbow. Muscle properties were taken from [4].

Muscular activity was estimated through a physiological static optimization method. Results were validated against the experimental EMG measurements.

The muscle energy expenditure model 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 ($\dot{E}$) [2]. The relation is given by the sum of this four terms expressed in (1), where $\dot{E}$ is calculated for each muscle in W.kg^{-1}.

$$\dot{E} = \dot{h}_A + \dot{h}_M + \dot{h}_{SL} + \dot{w}_{CE} \tag{1}$$

The whole body energy consumption is obtained by integrating the sum of muscle energy expenditure of all the muscles of the model plus a basal metabolic rate during a full stride. Experimental measurements of the energy consumption require that the subject maintains a constant activity during at least 5 min. To avoid disturbing the SCI subject, model results were validated in a healthy subject (Fig. 2) at several gait velocities. A linear relation was obtained between gait velocity and energy consumption, with a good correlation with experimental measurements and literature [5] at the self-selected speed of the subject. However, slope discrepancy in the linear relation was observed when testing at different speeds.

Fig. 2: Energy consumption in a healthy subject: a) motion-force-EMG capture; b) 5-minute test.

While, according to [5], 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 (3 W.kg^{-1}) was lower than that provided in the mentioned reference (5.13W.kg^{-1}).

Acknowledgments

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