INTRODUCTION

Inverse-dynamic models generally use cost functions to solve the load-sharing problem. Although it is often assumed that coordination is (at least partially) based on the minimum use of energy, most cost functions are mechanical cost functions based on muscle force (F), often weighted by physiological cross sectional area (PCSA) or maximal force (Tsirakos et al, 1997). Although some of these cost functions are supposed to be related to physiological costs like energy consumption or fatigue, clear relationships have never been proven.

The aim of this study was to analyse the relationships of two mechanical cost functions (the well known minimum stress cost function and a newly-proposed energy-related cost function) with experimentally determined muscle oxygen consumption. The energy-related cost function represents both the cross-bridges in parallel and in series, whereas the stress cost function only accounts for the cross-bridges in parallel. Since the metabolic cost of a muscle is the summed cost of the sarcomeres it was expected that the energy-related cost function would be a better representation of energy consumption than the stress cost function.

METHODS

The stress cost function is one of the most commonly used optimisation criteria and minimises squared muscle stress (Crowninshield and Brand, 1981):

$$\text{MIN} \sum_{i=1}^{n} \left( F_i / \text{PCSA} \right)^2$$  \hspace{1cm} (1)

of which Prilutsky (2000) stated that it is likely that this criterion leads to economy of metabolic energy expenditure. The energy-related cost function proposed here, is based on the two major energy consuming processes in the muscle: the detachment of cross-bridges and the re-uptake of calcium. Under isometric conditions the number of attached cross-bridges is linearly related to muscle force. When the same muscle force is maintained with longer muscle fibres, more sarcomeres are in series and more cross-bridges are attached. Therefore the energy consumption rate for detachment must be scaled by muscle length (l):

$$F \cdot l$$  \hspace{1cm} (2)

The re-uptake of calcium can be described by the product of muscle volume and active state:

$$V \cdot a = V \cdot (F/F_{\text{max}})$$  \hspace{1cm} (3)

A combination of Eq. 2 and 3 leads to the final cost function:

$$\text{MIN} \sum_{i=1}^{n} \left[ c_1 F_i / \text{PCSA} + c_2 \left( F_i / F_{\text{max}}(l,v) \right) \right]$$  \hspace{1cm} (4)

in which m is muscle mass and fibre length is represented by m/PCSA. c_1 and c_2 are constants.

Four subjects performed various isometric contractions generating combinations of elbow flexion/extension and pro/supination moments. Muscle oxygen consumption ($\dot{\text{VO}_2}$) of the m. biceps breve, the m. biceps longum, m. brachioradialis and m. triceps laterale was measured with Near Infrared Spectroscopy. An inverse-dynamic shoulder and elbow model (Van der Helm, 1997) was used for optimisation of both cost functions. For the four measured arm muscles the individual cost values were calculated, normalised and subsequently compared to normalised $\dot{\text{VO}_2}$ values.

RESULTS AND DISCUSSION

The stress cost function led to a good correspondence between $\dot{\text{VO}_2}$ and cost for the m. triceps laterale but for the flexor muscles cost was significantly lower. Several conditions were found in which the model predicted no muscle activity while $\dot{\text{VO}_2}$ did show activity or vice versa. It appeared that pro/supination moments have a disproportionately large effect on the optimisation, compared to flexion/extension moments. The energy-related cost function showed a far better correspondence between cost and $\dot{\text{VO}_2}$. T-tests did not show significant differences for any of the muscles. By including a linear term and muscle mass in the new criterion the load sharing changed in several ways. The contribution of the relatively small pronator and supinator muscles increased, leading to altered activation patterns of the flexor muscles that corresponded better to experimental results.

SUMMARY

In conclusion it can be said that the energy-related cost function appears to be a better measure for muscle energy consumption than the ‘standard’ stress cost function and leads to more realistic predictions of muscle activation. Further research on the effect of muscle length and the ideal ratio between the linear and quadratic term is expected to lead to further refinement of this energy-related cost function.

REFERENCES:


THE RELATIONSHIP BETWEEN MECHANICAL COST FUNCTIONS AND MUSCLE OXYGEN CONSUMPTION

Marit Praagman¹, Dirk Jan (H.E.J.) Veeger², Edward Chadwick² and Frans van der Helm²

¹ Faculty of Human Movement Sciences, Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands. m.praagman@fbw.vu.nl
² Man-machine Systems Group, Department of Mechanical Engineering, Delft University of Technology, Delft, The Netherlands