MUSCLE FORCES IN THE LOWER LIMB PREDICTED BY STATIC AND DYNAMIC OPTIMIZATION

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INTRODUCTION

The estimation of individual muscle forces during movements has long been a topic of interest in biomechanics and motor control. To resolve the mechanical indeterminacy of the musculo-skeletal system, many researchers have resorted to mathematical optimization techniques [1,2].

Static optimization is a common approach for model-based estimation of muscle forces. One of the most popular objective functions is the minimization of the sum of cubed muscle stresses. Crowninshield and Brand [1] posed a physiological rational for this function for unimpaired walking, based on empirical and theoretical considerations of maximizing muscular endurance.

The Crowninshield and Brand [1] criterion has also been used to predict muscle forces during other movements, such as fast running [3] and jumping [4]. However, it is unlikely that the nervous system adopts an endurance-maximizing muscle activation strategy for these movements. Validating muscle force predictions by any method is difficult since no *in vivo* "gold standard" data are available. However, force predictions can be compared and evaluated against muscle forces from forward dynamics simulations, where the exact muscle forces actuating the model are known [2].

Therefore, the purpose of the study was to compare muscle forces obtained by minimizing cubed muscle stresses via static optimization for walking, sprinting, and jumping, to those predicted from forward dynamics simulations of these movements. It was hypothesized that muscle forces predicted by static optimization and by dynamic optimization of the forward dynamics simulations would be similar for walking, but not for sprinting or jumping.

METHODS

Forward Dynamics Simulations

Simulations of walking, sprinting, and jumping were generated using a 2D computer model comprised of a trunk and two legs (Fig. 1). Each leg was actuated by 12 Hill-based muscle models. A vertical sinusoidal force on the trunk represented the effect of arm swing during locomotion.

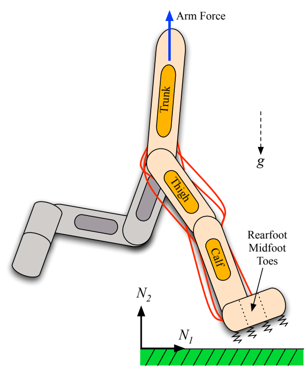

Figure 1: The computer model used in the forward dynamics simulations. The knee flexor and digitorum muscles are not shown.

The locomotion simulations began at initial foot contact and ended after one step. The jumping simulation began in a static squat and ended at the peak height. Dynamic optimization was used to find muscle model excitations that minimized the muscle energy expended per distance traveled (walking), maximized the average horizontal speed (sprinting), or maximized peak height (jumping).

Static Optimization

The same model (Fig. 1) was used to estimate the muscle forces using static optimization. At each time step, muscle forces that minimized the sum of cubed muscle stresses [1] were sought:

$$J = \sum_{m=1}^{12} \left(\frac{F_m}{PCSA_m} \right)^3$$

where F_m and $PCSA_m$ are the force and the physiological cross-sectional area of muscle *m*. Values for $PCSA_m$ were those used in the forward dynamics simulations, drawn from the literature.

The muscle forces were constrained to be tensile and beneath a maximum force, and were required to generate the net active muscle moments from the forward dynamics simulations within 0.001 Nm.

Muscle forces from static and dynamic optimization were deemed similar if: (1) the RMS difference was ≤ 15% of the maximum isometric muscle force (F_o), and (2) the cross-correlation coefficient was ≥ 0.85.

RESULTS AND DISCUSSION

The model's sprinting speed (7.33 m/s) and jumping height (43 cm) were both within 5% of recorded performance by the human subject from whom the model's parameters were derived. The model walked at the same speed as the subject (1.6 m/s) but spent 14% more energy (6.4 vs. 5.6 W/kg).

Seven muscle forces met both similarity criteria for walking, compared to four for sprinting and only one for jumping (Table 1). RMS differences averaged 12% F_o (125 N) for walking, 24% F_o (235 N) for sprinting, and 39% F_o (431 N) for jumping. Force timing, quantified by the cross-correlation coefficient, averaged 0.73 for walking, 0.78 for sprinting, and 0.39 for jumping.

Table 1. RMS differences (D, in % F_o) and cross-correlation coefficients (r) between the muscle forces predicted by static and dynamic optimization.

Muscle Model	Walking		Sprinting		Jumping	
	D	r	D	r	D	r
Iliopsoas	17	0.42	30	0.91*	74	0.40
Glutei	7*	0.97*	10*	0.95*	58	0.82
Rectus femoris	12*	0.76	19	0.77	81	0.11
Lateral hams.	19	0.12	21	0.96*	58	0.24
Medial hams.	11*	0.87*	25	0.62	65	0.48
Knee flexor	5*	0.16	51	0.15	42	0.35
Vasti	5*	0.89*	11*	0.88*	9*	0.98*
Gastrocnemius	9*	0.86*	5*	0.97*	24*	0.08
Soleus	5*	0.95*	8*	0.98*	14*	0.82
Tibialis anterior	11*	0.88*	21	0.63	13*	0.13
Extensor dig.	22	0.86	49	0.91*	20	0.14
Flexor dig.	15*	0.97*	41	0.65	10*	0.18

* = met similarity criterion

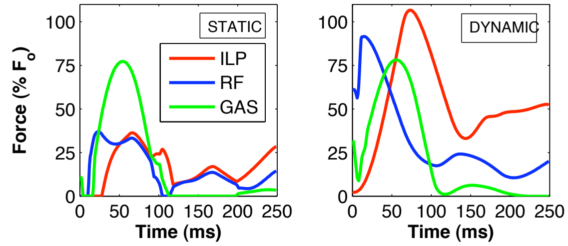

Figure 2. Muscle force predicted by static (left) and dynamic (right) optimization for sprinting.

Figure 2 shows muscles with high (iliopsoas), moderate (rectus femoris), and low (gastrocnemius) RMS differences for sprinting. Temporal patterns in force were qualitatively similar for most muscles, but peak forces differed by up to 70% of F_o.

CONCLUSIONS

Muscle forces predicted by static and dynamic optimization compared better for walking than for sprinting or jumping. If we assume that forward dynamics simulations are reasonable analogs of human movement actuated by reasonably realistic muscle forces, the Crowninshield and Brand [1] criterion appears to predict accurate muscle forces for low-intensity, cyclical motions like walking [2]. This finding was supported by the present results.

The present results suggest that the accuracy of muscle forces predicted using the Crowninshield and Brand [1] criterion may be compromised to varying degrees for high-intensity cyclical (e.g. sprinting) and discrete (e.g. jumping) motions. In these cases, where maximizing endurance likely does not dominate muscle coordination, static optimization and stress minimization may not be an appropriate framework, and researchers should consider other options for estimating muscle forces.

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