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Design and control in the maximization of human vertical jumping

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SUMMARY

We sought to explore an intriguing question: how can muscle mass be redistributed in leg muscles to allow for maximal jump performance? We performed forward simulations of human jumping movements using a four-segment inverted pendulum model of the skeleton and hill-type models of six leg muscles (soleus, gastrocnemius, vasti, hamstrings, rectus femoris and glutei). Preliminary results suggest that selectively changing relative muscle cross-sectional area and muscle lengths can result in jump height improvement by approximately 20%. The resulting muscle distributions are profoundly different than average human muscle distributions. In contrast, modest changes to the timing of muscle onsets are required for the new muscle distributions.

INTRODUCTION

Many human motor tasks are characterized by the goal of converting total mechanical muscular work into effective kinetic energy, whereby 'effective' energy is directed along some task constraint. For example, the maximization of jump height performance requires the selection of activation patterns of leg muscles, resulting in the conversion of muscle work into gravitational potential energy and linear vertical kinetic energy. Indeed, an active area in motor control research is concerned with how the central nervous system computes the set of motor commands that achieve an optimal movement. In this paper we turn this control question somewhat on its head, and ask a question about design: what changes can be made to the musculoskeletal system that lead to superior jumping performance?

Note that while it is clear that larger overall muscle mass will lead to greater jump height, it is not obvious how the redistribution of a constant total muscle mass could impact motor behavior. In this experiment we therefore explore the following questions about building a super-jumper that achieves maximal vertical squat jump height:

1) How can muscle mass be redistributed to result in maximal squat jump height (again, total muscle mass is kept constant and only relative muscle length and cross-sectional area may vary)? Does the resulting optimal distribution differ considerably from normal human muscle distributions?

2) How is the neural control of movement altered by the optimized muscle distributions?

METHODS

Forward simulations of vertical squat jumping were performed using a musculoskeletal model described previously (van Soest & Bobbert, 1993; Kistemaker et al. 2006). The human skeleton was modeled as four segments (foot, lower and upper leg, lumped head-arms-torso) connected with hinge joints representing ankle, knee and hip. The muscles were modeled as six lumped Hill-type units consisting of a contractile element, a parallel elastic element, and a series elastic element (for previous research demonstrating the muscle model's reproduction of characteristic features of muscle behavior, see Bogert et al. 1998; Zajac 1989). Activation dynamics were modeled with an implementation of Hatze (1981).

The following constraints were applied to muscle stimulations for jumping behavior. First, all jumps began from a stable equilibrium position that was selected as the muscle lengths and stimulations corresponding to lowest total relative muscle force. Second, stimulation for each muscle was binary: either this initial value, or maximal (i.e. 1). Third, muscle stimulation was only allowed to switch to its maximal value once. Thus, stimulation for each muscle during jumping is described by one parameter, and the optimization problem to achieve maximal jumping is six-dimensional.

We performed a constrained optimization to find muscle parameters allowing maximal jump height (as a first approach, we optimized for muscle length and cross-sectional area for each muscle). Total muscle mass of all leg muscles was held constant –i.e. the sum of the product of muscle length and muscle area was fixed - but individual muscle lengths and cross-sectional areas were allowed to vary for each of the six muscles, resulting in an 11-D free parameter space. We used a genetic algorithm to perform global optimization in this parameter space using a cluster at VU University Amsterdam.

RESULTS AND DISCUSSION

Figure 1 shows the preliminary results of the optimized model (MOD) in comparison to the baseline (BASE) model. Table 1 shows the relative muscle lengths and cross-sectional areas of the MOD system. Large increases to vasti, gastrocnemius and hamstrings and coincident decreases in soleus, rectus femoris and glutei (all to essentially zero) resulted in an increase in jump height (as defined by change in the height of the centre of mass from upright standing) of 18.8%, from 39.2 cm to 46.6cm.

	Sol	Gas	Vas	Rec	Glu	Ham
Muscle length	1.08	1.06	0.92	0.70	0.64	0.78
X-sectional area	0.05	2.53	2.30	0.05	0.05	2.28

Table 1: relative muscle lengths and cross-sectional areas of the MOD optimized model.

The ratio of effective energy (gravitational potential energy and vertical kinetic energy) to total mechanical muscle work has been termed *efficacy* ratio and has been used to describe optimal behavior (Bobbert & van Soest 2001). Efficacy ratio was increased slightly, accounting for a small portion of the increase in jump height.

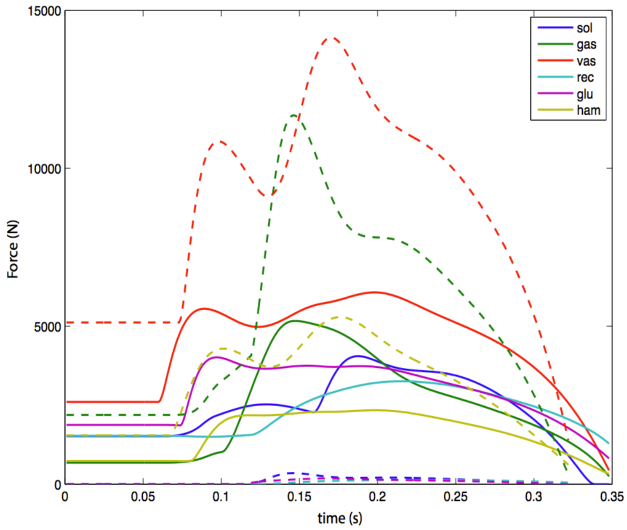

Figure 1: Force profiles over time during maximal squat jumping for the baseline model (solid lines) and optimal model (dashed lines). Muscles: sol=soleus; gas=gastrocnemius; vas=vasti; rec=rectus femoris; glu = glutei; ham = hamstrings.

CONCLUSIONS

Significant improvements to jump height can be made merely by redistributing muscle mass of leg muscles. It therefore is clear that human musculature is not optimized for this motor task. It might be interesting to investigate optimal muscle parameter values for other tasks such as locomotion.

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