THE EFFECTS OF ADDED LEG MASS ON THE BIOMECHANICS AND ENERGETICS OF WALKING

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INTRODUCTION

During normal locomotion, humans select a movement pattern that minimizes the rate of metabolic energy consumption (Margaria, 1976). Do stance or swing phase mechanics predominately drive this energetic optimization? Adding leg mass does not change the inverted pendulum mechanics of the stance phase of walking. Thus, if the energetically optimal gait pattern is driven by stance phase mechanics, adding leg mass should have no effect. If the pendular swing phase mechanics drive the optimization, adding leg mass should alter the gait pattern. Adding mass to the feet has been shown to increase the energy cost (Ralston, et al., 1969) and alter the kinematics of walking (Inman, et al., 1981), but there are little data on the effects of thigh and shank loading.

Understanding the effects of added leg mass has practical importance in the design of powered exoskeletons (Yang, 2004), i.e. the effects of location and mass of motors/actuators on the energy cost and muscle control strategies of walking.

We hypothesized that with leg and trunk loading:

1. Kinematics would be conserved.
2. Net muscle moment magnitudes during swing would increase.
3. EMG of leg muscles would increase.
4. Metabolic cost would increase and the increase would be greater with more distal load location.

METHODS

Five healthy male volunteers, (74.16 kg ± 5.18 kg, mean ± s.d.) walked on a motorized treadmill at 1.25 m/sec. Subjects completed a series of 7-minute trials with at least 5 minute rest between trials. Trials included unloaded, foot, shank, thigh and waist load trials in random order. Foot and shank loads were 2 kg and 4 kg per foot/shank. Thigh loads were 4 kg and 8 kg per leg. Waist loads were 4, 8, and 16 kg. Loads did not change segment center of mass location. Footswitches and 200Hz video recorded kinematics. We calculated net muscle moments about the ankle, knee and hip during the swing phase using an inverse dynamics solution. Surface electrodes recorded the electrical activity of: medial gastrocnemius (MG), soleus (SOL), tibialis anterior (TA), vastus medialis (VM), rectus femoris (RF), and semitendinosus (ST). We determined the rate of metabolic energy consumption from expired gas analysis and subtracted the standing metabolic rate to yield net metabolic rate.

RESULTS AND DISCUSSION

Stride kinematics and net muscle moments were similar to the normal unloaded condition except for the foot loads. For the 2 kg and 4 kg/foot trials, stride frequency decreased by 6 and 10% respectively. Greater magnitude muscle moments were needed for swinging the 2 and 4 kg/foot loads (Figure 1).

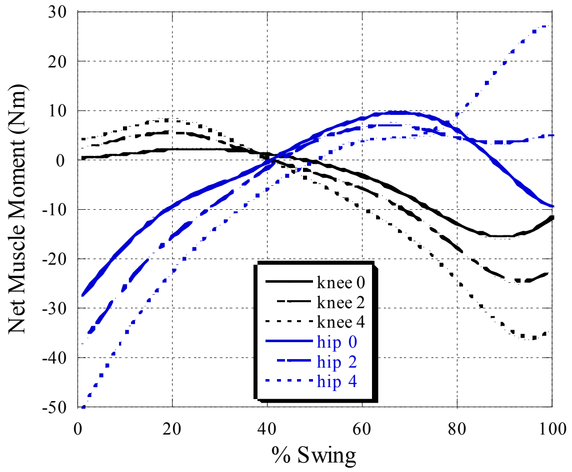

Figure 1. Net muscle moments during swing vs. foot load (0, 2, 4 kg).

EMG increased during swing initiation. During the second half of the stance phase MG mEMG increased by 23 and 32% for the 2 and 4 kg/foot loads and 9% for the 4 kg/shank load. MG mEMG increased by 22% with the 8 kg/thigh load and 16% with the 16 kg waist load. The RF mEMG during the second half of stance increased by 33 and 60% for the 2 and 4 kg/foot loads. During the first half of the swing phase, the mean RF EMG increased by 25 and 54% with the 2 and 4 kg/foot loads. These EMG results suggest that the ankle plantarflexors are important swing initiators and provide forward propulsion, while the RF acts to initiate and propagate leg swing as load increases.

As expected, leg loading increased the metabolic cost of walking, and more distal loads were more expensive (Figure 2). Carrying 4 and 16 kg at the waist increased metabolic rate by 6 and 27% respectively. Foot loads increased metabolic rate 36 and 68% for 2 and 4 kg per foot. Carrying 8 kg on the waist increased metabolic rate by 11%, whereas carrying 4 kg on each thigh, shank and foot increased metabolic rate by 29, 25 and 68%.

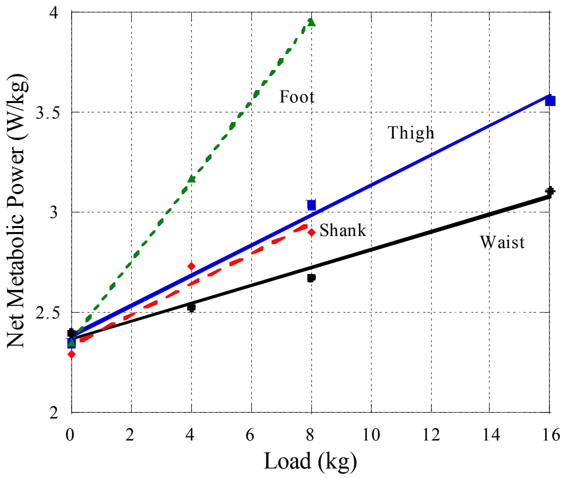

Figure 2. Net metabolic power vs. load

Foot loads elicit a disproportionately higher metabolic cost because of the increase in muscle activity required to swing the leg. The disproportionate increase in the cost of thigh loads was likely due to the wide steps required, which has been shown to increase metabolic cost (Donelan, et al., 2001).

Gait patterns were largely conserved despite dramatic leg loads suggesting that stance-phase mechanics dominate the gait optimization process. Powered exoskeleton mass should be concentrated proximally to minimize energy cost and alterations to gait patterns.

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