

MECHANICS AND ENERGETICS OF HUMAN HOPPING WITH A PASSIVE-ELASTIC ANKLE EXOSKELETON

Gregory S. Sawicki¹, Dominic J. Farris¹

¹Joint Dept. of Biomedical Engineering, North Carolina State University and University of North Carolina-Chapel Hill, Raleigh, NC, USA

e-mail: greg_sawicki@ncsu.edu

INTRODUCTION

A major goal of powered lower-limb exoskeletons is to act in parallel with the user's leg muscles and reduce metabolic energy consumption during locomotion. One approach is to deliver power to the limbs using attached motors/actuators to perform net mechanical work and help drive the lower-limb joints. An alternative is to use passive elastic elements (i.e. springs) to recycle center of mass energy, storing it at one phase of the gait and returning it later.

The passive, 'energy-neutral' approach is appealing because it requires no outside power source and can still reduce the mechanical demands placed on biological muscle-tendon units. In fact, Ferris et al. showed significant reductions in triceps surae EMG when humans hopped on one-leg with an elastic ankle exoskeleton over a range of hopping frequencies [1]. That study did not measure metabolic energy consumption.

A recent study by Grabowski et al. was the first to our knowledge to document a reduction in metabolic cost during human locomotion with a passive exoskeleton. They showed that when humans hop on two-legs with assistance from bilateral leaf springs attached from hip to heel user's reduced net metabolic power by up to 27% [2].

Our goal in this study was to determine whether providing mechanical assistance with parallel springs acting at the ankle joint

only could reduce the metabolic cost of two-legged hopping. Based on the results of Grabowski et al. [2] we hypothesized that (1) net metabolic power would be lower in the springs versus no springs condition, independent of hopping frequency (2) reductions would be larger for more compliant springs and (3) peak reductions would be less than 27% because our device only provides assistance at the ankle rather than over the whole leg.

METHODS

We constructed a pair of custom-made carbon fiber elastic ankle exoskeletons for a single subject (mass=63 kg, height= 170 cm) following [1]. To spring-load the ankle we attached linear tension springs (Mc Master-Carr Inc.) between two metal brackets on the posterior of the exoskeletons. To vary ankle exoskeleton compliance we used springs with different linear stiffness values (compliant=2.1 kN/m; stiff = 5.1 kN/m). The moment arm length for the spring attachment was 14.0 cm, yielding ankle exoskeleton torsional stiffness values of 0.71 N-m/deg (compliant) and 1.75 N-m/deg (stiff). The subject hopped on two-legs at 2.0, 2.2 and 2.4 Hz donning exoskeletons without springs (NS), with compliant springs (CS) and with stiff springs (SS). Each trial lasted 4 minutes with 7 minutes rest between trials. To test our primary hypotheses, we calculated the net metabolic power (gross minus resting) (watts) using rates of oxygen consumption and carbon dioxide production measured with indirect

calorimetry. We used inverse dynamics to calculate the ankle muscle-tendon average positive mechanical power over the hopping cycle (watts). To assess the mechanical contribution of the exoskeletons we used force recordings from a load cell attached in series with the springs to determine the average positive mechanical power delivered during recoil (watts)

RESULTS

Preliminary results ($n = 1$) indicate that bilateral elastic ankle exoskeletons can reduce net metabolic power over a wide range of two-legged hopping frequencies and exoskeleton stiffness values. Net metabolic power was reduced in *all* hopping conditions with parallel exoskeleton springs (CS and SS) when compared to no springs (NS) (Fig. 1, top). Metabolic savings ranged from 8% (at 2.4 Hz, CS) all the way up to 25% (at 2.0 Hz, SS). Contrary to our hypothesis, our largest reduction (25% at 2.0 Hz, SS) was close to what Grabowski et al. reported (27%) in similar conditions with a *compliant, full-leg* exoskeleton. Our mechanics data support the result that stiff

springs are more effective than compliant ones. The biological muscle-tendon contribution to ankle positive work was always lower in the SS versus CS condition (Fig. 1, bottom).

DISCUSSION

Our device provides parallel stiffness at the ankle joint *only*, but can achieve reductions in metabolic cost that are similar to a full-leg exoskeleton. It is possible that assistance at one joint could cause postural changes and influence the mechanical demands at other joints. In addition, the effective exoskeleton stiffness seems to be a critical design variable that deserves further attention. Other future work will attempt to extend the concept of ‘energy-neutral’ passive exoskeleton assistance to other locomotion tasks (e.g. running, walking).

REFERENCES

1. Ferris DP et al., *J Appl Physiol*, **100**(1), 163-70, 2005.
2. Grabowski AM et al., *J Appl Physiol*, **107**(3), 670-8, 2009.

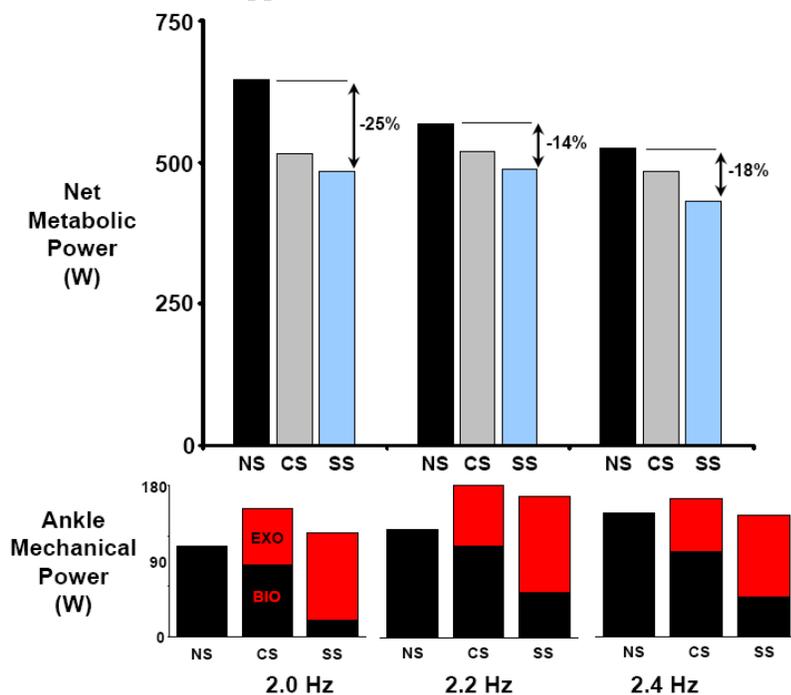


Figure 1: (Top) Net metabolic power (W) for one subject during two-legged hopping at 2.0, 2.2, and 2.4 Hz (left to right) in three conditions: wearing bilateral elastic exoskeletons without springs (black, NS), with compliant springs (gray, CS) and with stiff springs (light blue, SS). Percentages are reductions between NS and SS conditions. **(Bottom)** Average ankle positive mechanical power (W) over a hopping cycle. In each condition, red portion of the bar is the exoskeleton contribution and black portion is the biological muscle-tendon contribution to the overall ankle joint power output. The stiff exoskeleton delivered more positive mechanical power (on recoil) and reduced net metabolic power more than compliant at all frequencies.