ENERGY COST OF WALKING IN A PASSIVE-ELASTIC ANKLE-METATARSOPHALANGEAL EXOSKELETON

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INTRODUCTION

Passive-elastic lower-limb exoskeletons aim to reduce metabolic costs by taking advantage of elastic springs that provide both assistive passive torque and mechanical work. While there have been approaches to store and return energy passively across the entire limb [1], the majority of passive-elastic exoskeletons have drawn inspiration from the spring-like mechanics of the human triceps surae. These devices are typically designed with an external spring that parallels the Achilles tendon that stores and returns energy during the stance-phase of walking or hopping.

Emulating the elastic role of the human triceps surae is proving a successful means by which to augment human walking. Indeed, the metabolic energy saving of one such lightweight passive-elastic ankle exoskeleton has recently been shown to lower the metabolic cost of walking below that of normal, instrumented, walking [2]. Here we propose that further advances in passive-elastic assistive exoskeletons may be achieved by drawing inspiration from non-human species that exemplify elastic gait mechanics. Unlike humans that move in a plantigrade posture, the majority of cursorial species walk and run in a digitigrade posture (toe running). This mode of locomotion facilitates elastic energy storage and return in multi-joint muscle-tendon units that cross both the ankle and the metatarsophalangeal (MP) joint. For example, the ostrich has been shown to produce nearly fifty percent of the positive mechanical work of the stance phase of running through elastic recoil at the tarso-metatarsophalangeal joint [3]. This feature of ostrich running is thought to be the main explanation for how they run with half of the metabolic energy compared to humans [3].

The purpose of the present study was to design and test a biologically-inspired human exoskeleton that emulates the storage and return of elastic energy at both the ankle and MP joints typical of the gait mechanics of efficient non-human cursorial species.

METHODS

Exoskeleton Design:

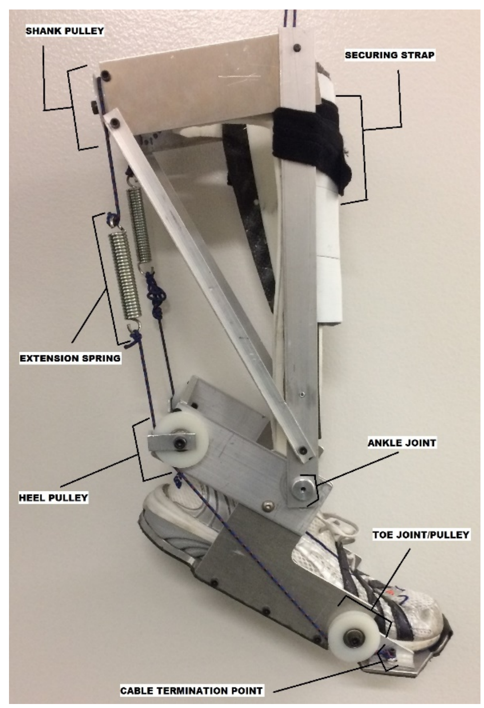

Figure 1: Passive-elastic ankle-MP exoskeleton

We designed a passive-elastic exoskeleton (EXO) that was based on a two-joint (ankle and MP) passive spring design. The EXO consisted of three segments fabricated out of carbon fiber and aluminum: (1) a shank frame; (2) a rear-foot frame mounted directly to a lightweight running shoe that articulated with the shank frame; and (3) a fore-foot plate that was mounted to the sole of the running shoe under the toe box (Fig. 1).

The proximal section of the spring cord (Paracord) was aligned in parallel with the triceps surae muscles and ran to a pulley situated on the rear-foot frame behind the ankle. The distal section of the spring continued to a second pulley mounted on the rear-foot frame near the MP joint and terminated on the fore-foot plate. The spring cord looped between the left and right side of the EXO across two pulleys mounted at the top of the shank frame. Two parallel linear steel springs (7 kN/m each) were positioned in the spring cord line behind the calf. This design provided a simultaneous passive-elastic joint moment at the ankle and MP joints and was capable of transferring energy between the joints.

Metabolic Testing: Pilot experiments measured rates of oxygen consumption (Vista VO2 Lab, Ventura California) in multiple walking trials (1.25 m/s) under three conditions; (1) a control walking condition without the EXO; (2) walking with the EXO but without the passive elastic component engaged; and (3) walking with the EXO fully functional. Standing trials, both under normal and EXO conditions, were collected to determine the net cost of walking (gross metabolic rate minus standing rate). A training period of 20 minutes was used to allow for familiarization with walking in the device both with the spring engaged and when the spring was disengaged.

RESULTS AND DISCUSSION

The metabolic rates (ml O_2/kg/min) for walking and standing in the control (no EXO) condition, in the EXO with the spring disengaged, and in the EXO with the spring engaged are presented in Fig. 2

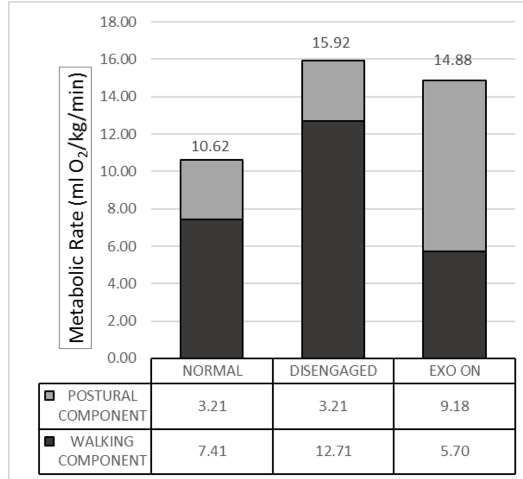

Figure 2: The gross oxygen cost measured during walking is represented by the sum of the black and grey bars (standing postural cost). The black bars represent the net oxygen cost of walking.

The gross oxygen cost of walking with the EXO was substantially elevated over the control condition, and is likely explained by the substantial mass of the EXO. Nevertheless, the gross cost of walking in the EXO with the spring engaged was reduced by 6.5%, indicating that the two-joint passive-elastic spring mechanism can reduce walking cost. The net oxygen cost of walking was, surprisingly, 23% lower than the control condition. This value is impressive, but must be viewed cautiously since this arises due to the high cost of standing in the EXO. It is unclear if the same postural/balance cost is present during gait. In summary, pilot data indicate that a biologically-inspired ankle-MP EXO may provide a novel approach for reducing the metabolic cost of human walking.

REFERENCES

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