A PASSIVE-ELASTIC ANKLE EXOSKELETON USING CONTROLLED ENERGY STORAGE AND RELEASE

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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. Recent designs have focused on portable devices that can mimic the normal torque output of the lower-limb joints over the full gait cycle using large, powerful motors under high gain force control. Powerful motors are heavy, require bulky gears and mounting frames, and rely on even larger power sources. Furthermore, we are unaware of any study to date that demonstrates a metabolic savings during walking with a *portable* lower-limb exoskeleton.

On the other hand, a recent study indicates that when humans don tethered (i.e. non-portable), bilateral, lightweight, pneumatically powered ankle exoskeletons that replace *only* ~63% of the ankle muscle-tendon mechanical work during push-off, they reduce their metabolic energy consumption by 10-12% during treadmill walking [1]. Thus, supplying mechanical energy at a single joint (i.e. the ankle) during a key propulsive phase of walking (i.e. push-off) can have appreciable metabolic benefits.

Our goal in this study was to develop a *portable* device capable of providing ankle joint mechanical assistance during walking *without using external power from onboard actuators* (i.e. an 'energy-neutral' solution). Human walkers exploit a key passive dynamic principle of locomotion: elastic energy storage and return. Early in stance, strain energy is stored in the Achilles' tendon and then it is recovered later, providing up to 60% of the ankle joint mechanical work during push-off [1, 2]. We hypothesize that a passive wearable device using parallel elastic elements during the walking cycle is capable of recycling a significant portion of the ankle joint mechanical work and could reduce the metabolic cost of walking by up to 18% [1].

METHODS

Our goal was to provide all of the benefits of an actively powered exoskeleton [1] but in a portable framework without motors or an external energy source. We set out to develop a passive, 'energy-neutral' system with the following key design objectives: (1) deliver torque to the ankle following a pattern similar to the normal joint moment during walking and (2) recycle elastic energy during the stance phase while allowing free ankle rotation during swing.

In order to generate torque in parallel with the ankle joint center and match the normal ankle joint moment we centered our design around a pair of highly elastic (k_{eff}=13.2 kN/m), commercially available leaf springs (length=26.6 cm) (TAC 15, PSE Inc., Tucson, AZ). The resulting stiffness (k_{eff}=26.4 kN/m or ~5 N-m/deg) of the combined springs allowed for a design with a compact moment arm length (12.6 cm). We calculated a suitable spring origin location; placing it below the ankle joint center (by ~1.5 cm) and forward (by ~14.0 cm), towards the ball of the foot (Fig. 1, top panel).

In order to store elastic energy and return it at the appropriate time during the gait cycle, we employed the principle of controlled energy storage and release [3]. We designed a system of springs, pins, and motion constraints to control the latch and release of a set of cams engaging and disengaging the leaf-springs during walking. This novel, adjustable 'smart-clutch' is advantageous because it uses the linear motion of the spring linkage, transmitted by changes in ankle joint angle, rather than electro-mechanical switching to set the timing of cam latch and release. In this way, we could disengage the springs at a critical ankle joint angle (i.e. max plantarflexion) to achieve free ankle rotation during swing.

RESULTS/DISCUSSION

Our design concept utilizes four key functional stages during walking gait to employ controlled energy storage and release: heel strike, foot flat, dorsiflexion, and push-off. At heel strike (Fig 1., orange) the clutch couples the cams to the spring linkage, but still allows for ratcheting upwards until foot flat. In stage 2, foot flat (Fig 1., green), the cams lock, allowing dorsiflexion to load the springs. During stage 3, the user's center of mass energy is stored as strain energy in the springs as the ankle dorsiflexes during mid stance (Fig 1., purple). During push-off, (stage 4) (Fig 1., light blue) energy is returned from the spring to propel the user's center of mass forward for the next step. Finally, the clutch releases the cams (Fig 1., dark blue), disengaging spring action for swing phase.

The current design configuration yields a maximum exoskeleton torque of ~105 N-m (Fig 1., red trace) and ~21 J of cycled spring energy. Future directions include device fabrication and human testing to determine whether an 'energy-neutral' passive elastic ankle exoskeleton using controlled energy storage and release can reduce metabolic cost during walking.

REFERENCES

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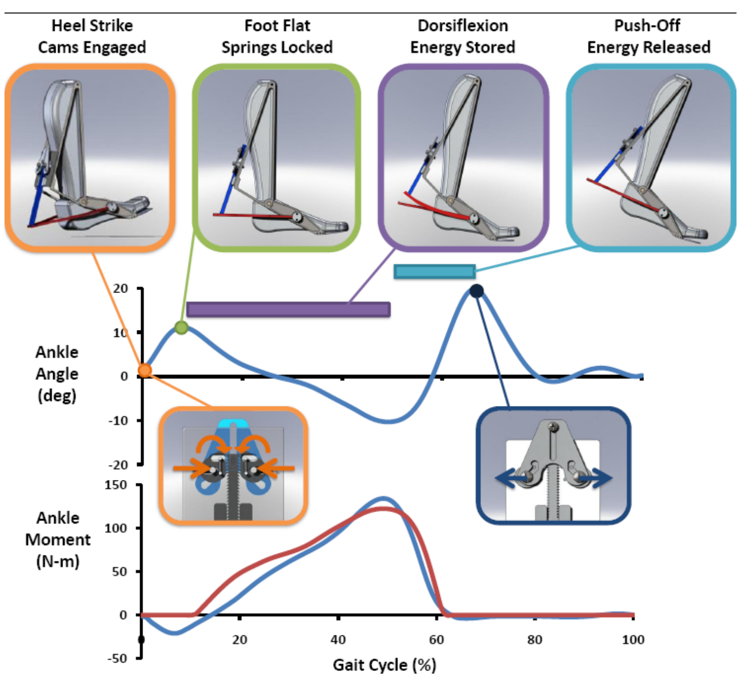

Figure 1: Passive-elastic ankle exoskeleton function during walking. Top row: Four key functional stages of controlled energy storage and release during stance (0-60%). Bottom rows: Light blue traces are representative walking data at 1.25 m/s for the ankle angle and ankle moment (plantar flexion +) over the stride from heel strike (0%) to heel strike of the same leg (100%). Red trace is the calculated torque contribution from the exoskeleton springs. Orange outlined panels show heel strike and cam/clutch engagement. Purple bar indicates period of spring energy storage. Light blue bar indicates period of spring energy recoil to aid push-off. Dark blue outlined panel shows cam/clutch release, disengaging the springs to allow for free swing.