A bird-inspired Passive-elastic Ankle-toe Exoskeleton Induces Digitigrade (toe) Walking in Humans

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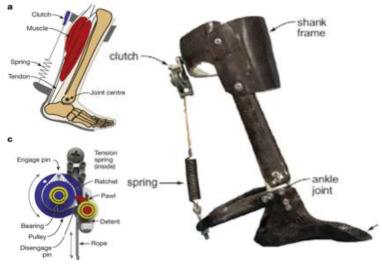
Background & Objective

Recent developments in lower-limb wearable robotics have achieved human locomotor augmentation with a reduction in metabolic energy cost[1,2].



Lower-limb passive-elastic exoskeletons typically take advantage of elastic springs that parallel the Achilles tendon. These 'exotendons' provide both assistive passive torque and storage and release mechanical work. (Fig. 1)

Figure 1. Cost-reducing passive-elastic exoskeleton with spring/clutch mechanism[1]

A challenge of a lower limb 'exotendon' application is achieving effective assistance with minimal interference. For example, effective energy reduction through plantar flexion assistance requires a clutch that minimizes dorsiflexion resistance in swing (Fig. 1).

Biological Inspiration

We propose that further advances in passive-elastic assistive exoskeletons may be achieved by drawing inspiration from non-human species. A digitigrade (toe) posture facilitates torque generation and elastic energy storage and return in multi-joint muscle-tendon units that cross the ankle, metatarsophalangeal (MP) and interphalangeal (IP) joints [3] (Fig. 2).

Three features of digitigrade locomotion that may confer an advantage for energy reduction in a human exoskeleton design include:

1) **Increased contribution of passive-elastic mechanical work.**
2) **Passive torque assistance at the MP joint.**
3) **A 'biological' clutch mechanism for unloading the exotendon during swing (MP plantar flexion).**

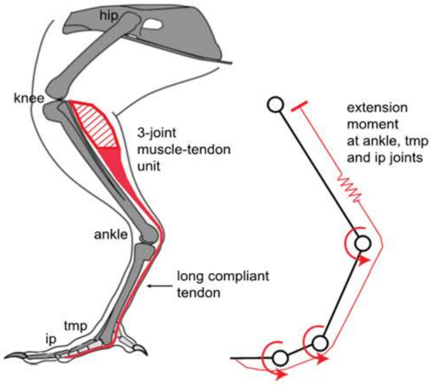


Figure 2. Digitigrade muscle-tendon architecture

Study Objective

To design and test a biologically-inspired passive-elastic exoskeleton prototype that uses an elastic exotendon to provide passive assistive torque and mechanical work at the ankle and MP during walking. Specifically, we examined whether digitigrade walking is achievable and its effect on joint mechanics and locomotor energetics.

Methods

Passive-elastic Exoskeleton Design

- Three segment design: (1) Shank (2) Rear-Foot (3) Forefoot
- Aluminum frame. Carbon-fiber shank brace. Weight: 5.0 lbs.
- Continuous exotendon connecting shank to forefoot; fitted with two (medial and lateral) parallel springs (7kN/m).
- Ankle moment arm = 0.12m
- MP moment arm = 0.02m
- Instrumented with load cells (OMEGA) proximal and distal to rearfoot pulley.
- Cable and spring unit engages at 48° plantar flexion

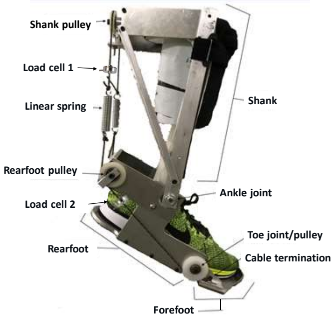


Figure 3. Exoskeleton Design

Methods

Study Design

- N = 7 subjects (4M, 3F).
- Testing Conditions (randomized order); 1) Normal standing, 2) Exoskeleton standing with spring assist, 3) Walking no Exoskeleton, 4) Walking with Exoskeleton and spring assist, 5) Walking with Exoskeleton without spring assist. (Additional trials with no Exoskeleton but with matched leg mass.)
- Oxygen consumption (COSMED K4 / K5); treadmill walking (7 minutes at 1.25m/s).
- 3D Gait mechanics (8-camera Motion Analysis Corp; two AMTI force-plates); overground walking (1.25 m/s ± 5%). Minimum 5 trials @ each condition. Joint mechanics calculated using custom MATLAB scripts.

Results & Conclusions

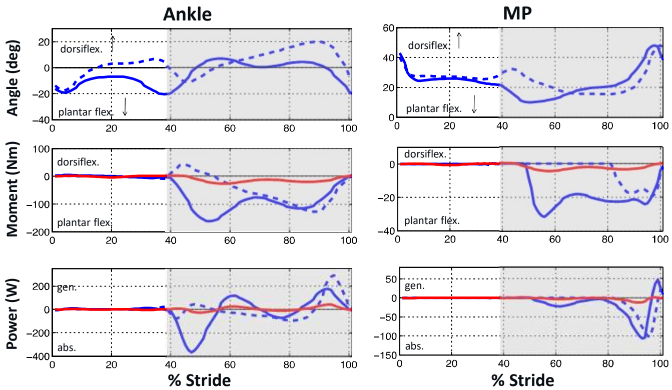


Figure 4. Exoskeleton with spring assist (solid blue) exoskeleton without spring assist (dashed blue) and exoskeleton spring contribution (red)

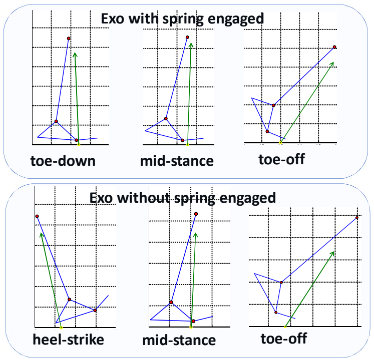


Figure 5. COP position during stride

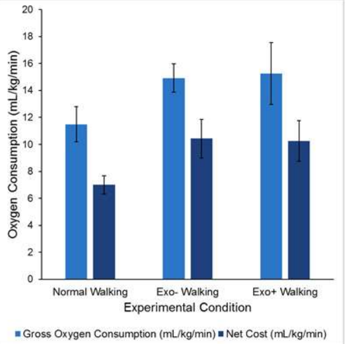


Figure 6. Mean oxygen consumption during walking in normal, Exo- (without spring assist), and Exo+ (with spring assist) conditions.

- 18% passive spring contribution to peak ankle moment
- 14% passive spring contribution to peak toe moment
- 7 J passive +'ve ankle work; 23% contribution to ankle +'ve work

Conclusion

- **2-joint Ankle – MP passive-elastic exoskeleton = digitigrade walking**
- **Bi-phasic ankle power abs. – gen. distributes positive ankle work when spring engaged, but retains similar total positive work.**
- **Despite early and large ankle and MP loading, the Ankle-MP passive elastic exoskeleton resulted in minimal changes in the energy cost of walking (compared to walking with the exoskeleton minus spring). The cost-neutral effect may be explained by the large passive contribution to +'ve ankle work in addition to passive moment contribution.**

References

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