INTRODUCTION

With the continuous evolution of lower limb prosthetics, existing designs have diverged into two general categories: 1) passive systems composed of elastic materials, and 2) active systems composed of motors and inertial sensors [1]. A central goal between these contrasting approaches is to replicate the mechanical energy profiles of the natural ankle-foot system (NAFS) to restore normal gait. The prevalent theory in the field, stemming from the knowledge that the ankle joint musculature produces greater positive work than negative work during stance [2], is that an active prosthetic system is required to replicate the work-related efficiency of the NAFS [1]. However, structures like the plantar soft tissue and ligaments deform [3], and the toe joint musculature contracts eccentrically [4], such that these ‘distal foot structures’ collectively function to remove energy from the system.

As prosthetic ankle-foot systems are intended to restore the functions of all anatomical structures within the NAFS, there is a desire to quantify the combined effects of the ankle joint musculature and all distal foot structures in normal gait. Therefore, the purpose of this study was to quantify the net efficiency of the NAFS during stance across a full range of walking velocities.

METHODS

Eleven healthy subjects (ages 24.2 ± 2.9yrs, height 1.72 ± 0.08m, and body mass 75.3 ± 21.8kg) participated in a fully-instrumented gait analysis. The subjects walked barefoot at four scaled walking velocities: 0.4, 0.6, 0.8, and 1.0 statures/s (0.8 is considered the normal velocity for a healthy adult [5]). Kinematic data were collected using a six-camera motion capturing system (Motion Analysis Corp., Santa Rosa, CA), and kinetic data were collected from a strain gauge force platforms (AMTI, Watertown, MA). All data were analyzed using Visual3D software (C-Motion Inc., Germantown, MD). The combined ankle-foot power ($P_{CAF}$), normalized by body mass (W/kg), was quantified by the summation of the ankle joint power ($P_{ank}$) and the distal foot segmental power ($P_{fd}$). $P_{ank}$, indicative of the total power due to ankle musculature, was quantified using a 6 degree-of-freedom joint model [6]. $P_{fd}$, indicative of the total power due to the combined actions of all distal foot structures (e.g., plantar soft tissue, ligaments and intrinsic foot musculatures), was quantified using a deformable foot model [3]. Altogether, $P_{CAF}$ signifies the total power due to the combined effect of all anatomical structures within the NAFS.

The total work done by the ankle joint and the combined ankle-foot system were quantified by integrating $P_{ank}$ and $P_{CAF}$, respectively. The efficiencies of the ankle joint ($E_{ank}$), and the combined ankle-foot system ($E_{CAF}$) were calculated as the ratio of positive to negative work. The effect of walking velocity on $E_{ank}$ and $E_{CAF}$ was assessed, using a one-factor repeated measures ANOVA with Bonferroni corrections for pair-wise comparisons ($\alpha=0.05$).

RESULTS AND DISCUSSION

The ankle joint primarily added energy to the body, while the distal foot structures primarily removed energy from the body (Figure 1). Accounting for the simultaneous influences, the $P_{CAF}$ was generally characterized by a period of negative power from early to mid-stance, followed by a period of positive power (Figure 1).

There was a significant effect of walking velocity for both $E_{ank}$ and $E_{CAF}$ ($p < 0.05$). Across the four walking velocities, $E_{ank}$ values were 1.46 ± 0.37,
Figure 2: Mean ± std of mechanical efficiencies of ankle joint (blue) and combined ankle-foot system (red). All pair-wise comparisons for ankle joint were significant (p < 0.05), except for 0.4 vs 0.6 statures/s. For the combined ankle-foot, pair-wise comparisons between 0.4 vs 1.0, 0.6 vs 0.8, and 0.6 vs 1.0 statures/s were significantly different (p < 0.05).

CONCLUSIONS

In normal gait, the ankle joint musculature and all distal foot structures collectively function to produce a net negative work during stance over a range of walking velocities. Thus, a passive prosthesis might replicate the net efficiency of the NAFS during level-ground steady state walking. Future efforts may consider the precise customization of mechanical properties of passive prostheses to optimize energy storage and return characteristics.

REFERENCES