PROSTHETIC LIMBS THAT REDUCE THE ENERGY COST OF WALKING TO BELOW NON-AMPUTEE LEVELS ARE POSSIBLE BUT HARD TO DISCOVER

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INTRODUCTION

This symposium addresses the question: Can active or passive prosthetic legs augment performance in people with amputation? In terms of reducing the energy cost of locomotion, all signs point to 'yes'. In principle, walking at constant speed on level ground requires no energy input. In practice, both powered [1] and unpowered [2] ankle exoskeletons can reduce the energy cost of unimpaired human walking to below normal levels. Powered prostheses can reduce the energy cost of walking compared to passive devices [3, 4] and passive prostheses can allow the same cost of transport as for unimpaired controls [5]. Ankle-foot prosthesis controllers can even reduce the energy used for active balance [6]. It is likely that powered, semi-active and unpowered prostheses will eventually lead to more economical gait than possible with biological legs.

Despite these positive signs, we cannot predict now the formula for success. Many devices expected to augment gait, powered or passive, have failed. The benefits of powered prostheses, and their effects on gait mechanics, have not been consistent [4], and many studies have found performance deficits with passive prostheses. Some amputees experience lower metabolic rate or increased satisfaction with emulations of robotic prostheses, while others respond better to emulations of passive devices [7]. Net work performed during ankle push-off might be responsible for the benefits of active prostheses, where present, but has not been studied in isolation from other prosthesis features. In non-amputee subjects wearing amputation-simulating boots, increasing prosthetic ankle push-off work in isolation leads to decreased metabolic rate [8], but only if push-off occurs late in stance [9] and without hypothesized reductions in center of mass work.

In this presentation, we will review recent studies that address the theme of augmenting locomotor performance and present the results of a new study intended to isolate the effects of ankle push-off work on the energetics of amputee walking [10].

METHODS

Participants with unilateral, trans-tibial amputation (N = 6, 47 ± 6 yrs, 1.79 ± 0.04 m, 88 ± 8 kg) with congenital (N = 1) or traumatic (N = 5) causes, at least one year post amputation (1-45 yrs) provided written informed consent to a protocol approved by the Carnegie Mellon Institutional Review Board.

Subjects wore an ankle-foot prosthesis emulator [11] in place of their prescribed foot. This tethered, robotic device can apply higher mechanical power than mobile prostheses or the biological ankle joint, without varying other prosthesis features such as mass, stiffness or contact geometry. We applied seven push-off conditions in which net ankle work ranged from -2 to 8 times of the value observed during normal walking at 1.25 $m \cdot s^{-1}$. Mechanics during the lead-up to push-off were held constant. Subjects underwent three acclimation days, three training days, and one collection day.

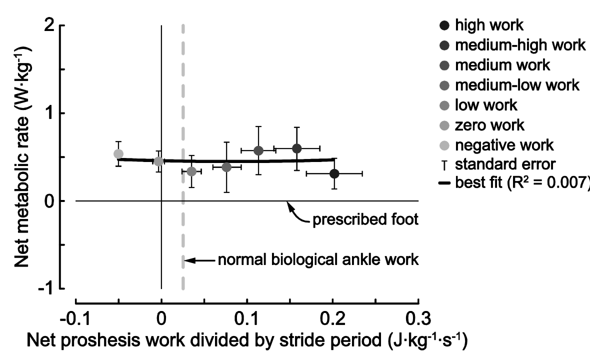

Figure 1: Metabolic rate was not significantly affected by net ankle-foot prosthesis push-off work on average.

We measured lower-limb joint mechanics, muscle activity, center of mass mechanics, and metabolic rate, and performed ANOVA to test for an effect of push-off work on each outcome. We fit quadratic relationships between net ankle work and metabolic rate on average and for each subject.

RESULTS AND DISCUSSION

On average, work input from the prosthesis did not affect metabolic rate (Fig. 1; $P = 0.2$; $R^2 = 0.03$). Effects were inconsistent between subjects (Fig. 2). Negative, low, or moderate net ankle work seemed to minimize metabolic cost in most cases, and no subjects trended towards lower metabolic rate with higher push-off work. Only one subject had lower metabolic rate than with their prescribed foot, achieved at about zero net work. Subjects also preferred medium-low net work ($P = 3 \cdot 10^{-4}$).

Push-off work affected some mechanics and muscle activity outcomes during the period of active push-off, but with inconsistent implications for metabolic rate. With increasing push-off work, prosthesis-side hip work decreased (H3; $P = 8 \cdot 10^{-5}$), prosthesis-side negative knee work increased (K3; $P = 6 \cdot 10^{-4}$), and intact biceps femoris activity decreased ($P = 3 \cdot 10^{-4}$). Contrary to predictions based on simple dynamic models of walking, increased trailing-limb push-off work did not reduce leading-limb collision work.

CONCLUSIONS

Augmenting gait is not simple. Net work input is thought to be responsible for reduced metabolic rate with powered prostheses, but humans are complex and it is very doubtful that this is the only factor. Subtle mechanical details may have unexpected effects on, e.g., muscle-tendon dynamics. Details of prosthesis control may also be important, and can reduce or increase energy cost without changing average work input [6]. These and other aspects of prosthesis function are most efficiently studied in experiments with versatile emulator systems [11], which allow single factors to be isolated, rather than comparisons of multi-featured devices.

It is certain that individual differences play an important role in selecting user-optimal device characteristics, illustrated here by the range of responses to increased push-off work. Optimization on an individual basis is challenging for many reasons, but is possible [12] and will be critical to augmentation of amputee locomotion.

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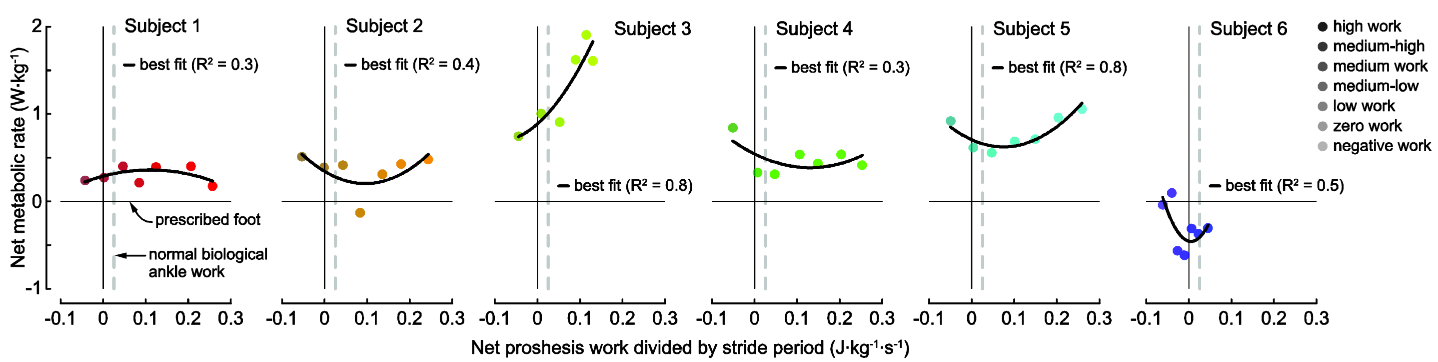

Figure 2: Subjects exhibited widely varying trends in metabolic rate as net work from the ankle-foot prosthesis was increased.