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MECHANICS & ENERGETICS OF WALKING WITH REDUCED ANKLE PLANTARFLEXTION

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INTRODUCTION

The ankle accounts for the largest burst of joint power of human walking, during push-off near the end of stance. The ability to produce ankle push-off can be impeded by neurological and muscular pathologies or because of injury [1], and is accompanied by greater metabolic energy expenditure [4]. Ankle push-off may also be impeded by some ankle-foot-orthoses (AFO) that physically restrict ankle motion to prevent foot-drop [2]. If push-off is indeed restricted, there may be an energetic penalty regardless of the condition causing foot-drop. This suggests that even healthy persons may expend more energy to walk when ankle motion is restricted.

Simple dynamic walking models show why reduced push-off may result in poor economy. If the legs behave like pendulums, energy is dissipated when the swing leg collides with the ground. That loss normally appears to be reduced by pushing off with the trailing leg just prior to heel strike, Fig 1.a (left side) [3]. A reduced push-off at the trailing leg (Fig 1.a, smaller blue arrow) is therefore expected to result in a larger-than-normal collision at the leading leg (Fig 1.a, larger red arrow). The models predict that gait with the reduced push-off will require more total positive work, which in turn leads to a higher energetic cost.

In this work we use a modified AFO to restrict bilateral plantarflexor motion at the ankle joint, to limit push-off in healthy adult subjects. We hypothesize that (1) Reduced ankle plantarflexion motion will result in less positive push-off work and more negative collision work. (2) The resulting gait will require more positive work with each step, and require greater energy expenditure.

METHODS

We modified a commercially available AFO (Bledsoe, EZ Set Hinge) to constrain ankle plantarflexion. We used steel cables of varying lengths, connected to the AFO, to restrict motion (Figure 1.c). Gait was examined during six walking conditions, four with reduced ankle motion, an unconstrained condition with no cable, and finally a normal shod condition with normal street shoes rather than the AFO. The cables were of a range of lengths and reduced the peak ankle plantarflexion by up to about 30 deg relative to normal walking. Eight healthy adults participated as subjects (6 males and 2 females, age 18-33, weight 76.6±8.8 kg). All trials were conducted on an instrumented treadmill (Bertec, Instrumented treadmill) at 1.4 m/s walking speed (Fig 1.b). In addition to the ground reaction forces captured by the treadmill, we measured the metabolic energy expenditure (Carefusion, Oxycon mobile) and lower limb kinematics (Phasespace, Impulse X2) of each subject.

From these data we calculated ankle knee and hip joint angles, moments, powers, and joint work. To characterize the effect of the constraint we have defined plantarflexiona (PF) reduction as the reduction of peak plantarflexion relative to that observed for walking in the unconstrained condition.

We also characterized work performed on the COM as follows. COM work rate ($\dot{W}_{com}$) was defined as the dot product of the ground reaction forces ($\vec{F}$) of each leg and COM velocity ($\vec{v}_{com}$),

$$\dot{W}_{com} = \vec{F} \cdot \vec{v}_{com} \, . \qquad (2)$$

COM work rate was plotted as against time (percent gait cycle), and also integrated during the Collision and Push-off phases, defined as the negative and positive bursts of power at beginning and end of stance, respectively. We examined COM work during Collision and Push-off as a function of PF reduction. As a simple summary of joint work, we defined the total positive joint work per step as the integrated positive joint power for each joint, summed over ankle, knee, and hip. Total negative joint work was defined similarly and examined as a function of PF reduction.

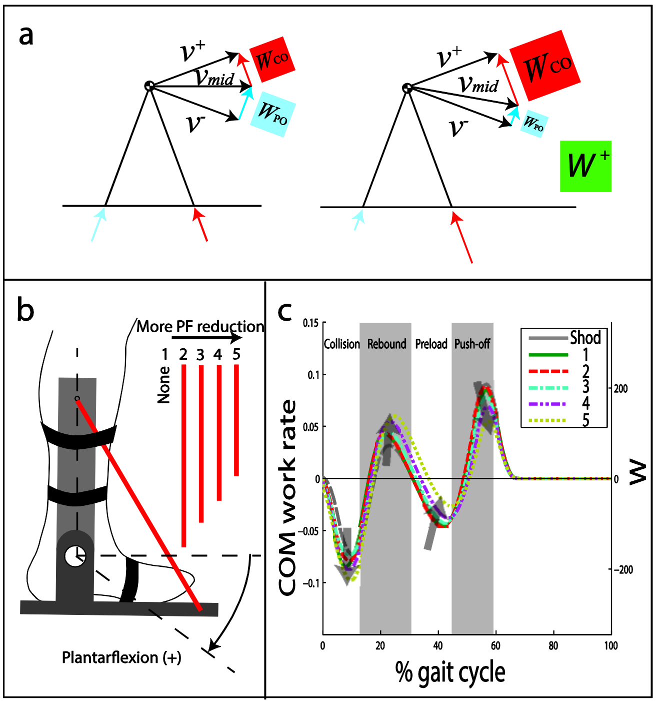

Figure 1: (a) Simple model predicts effect of reduced push-off. Shown are velocities of COM before, after, and at mid-point of the transition between stance legs. Positive push-off work (blue area) precedes negative collision work (red area). When push-off is reduced (at right), the collision is greater and more positive work is needed elsewhere in the gait cycle (green) to maintain walking speed. (b) Modified AFO for reducing normal ankle plantarflexion. Steel cables (red lines) attached to the AFO caused ankle motion to be limited. (c) Average COM work rate vs. time, over a stride, with increasing amplitude with increasing ankle restriction (1: no restriction, 2 – 5: increasing restriction)

RESULTS AND DISCUSSION

We found artificially reduced ankle motion to result in greater metabolic energy expenditure. Net metabolic rate (gross rate minus standing rate) increased approximately linearly with PF reduction (Fig. 2a). This was accompanied by increasing magnitude of negative collision work, and decreasing push-off work (Fig. 2b).

Examining the work performed by the joints, ankle restriction resulted in greater amounts of total positive joint work, and total negative joint work (Fig. 2c). The individual effects on the joints were as follows. Reduced ankle plantarflexion resulted in decreasing amounts of both positive and negative ankle work. The larger collisions at heel-strike appeared to be absorbed by the knee, with increasing amounts of negative work. The knee also performed more positive work, perhaps to compensate for the dissipated energy. There was a small but significant increase in negative hip work, and no significant change in hip positive work (Figure 2.c). The increase in total positive joint work is consistent with the increased net metabolic rate as maximum plantarflexion was reduced.

Although greater energy expenditure was required with reduced ankle plantarflexion, subjects were able to compensate by performing more work at the knee (and more joint work overall) and thus maintain steady 1.4 m/s walking speed. The metabolic penalty appeared to be due to the greater collisions resulting from reduced push-off.

CONCLUSIONS

Healthy adults with artificially reduced ankle plantarflexion walked with increasing metabolic rate. The restriction resulted in reduced push-off and greater collision work. This required greater joint work overall, especially at the knee. This study may be relevant to design of AFOs and to treatment of some pathologies that cause reduced ankle strength. Commonly prescribed AFO such as the posterior leaf spring AFO may reduce ankle push-off, and could cause greater metabolic energy expenditure from the restriction alone and independent of health condition. Our results may also illustrate why patients with reduced ankle plantarflexion often expend more energy to walk.

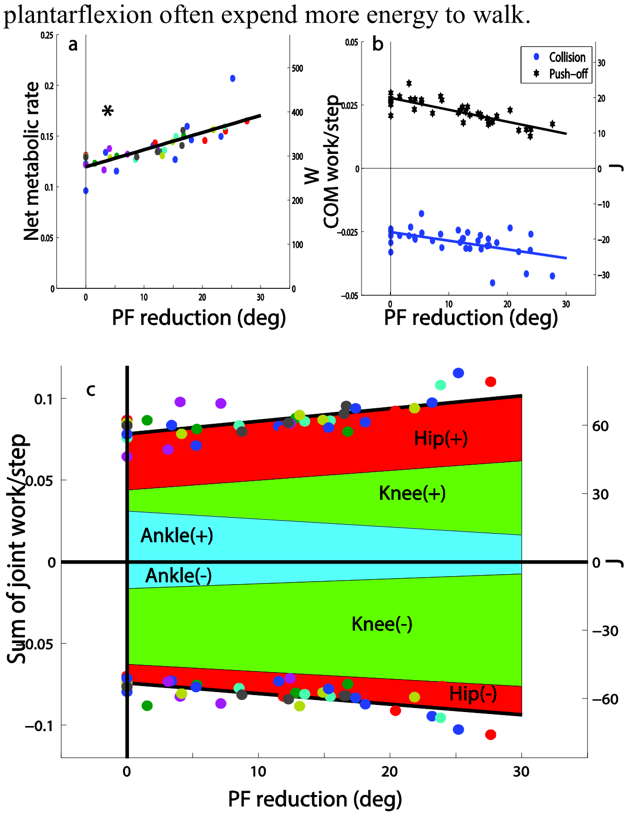

Figure 2: (a) Net metabolic rate estimated from oxygen consumption and carbon dioxide production, as a function of plantarflexion (PF) reduction. With increasing restriction of ankle motion, subjects expended more energy to walk, and (b) produced greater amounts of negative collision work and decreasing amounts of positive push-off work, computed from COM work per step. (c) Sum of positive and negative joint work per step also increased. Colored regions represent positive or negative work of ankle, knee, and hip. All work and energy quantities are in dimensionless units, with base units defined by gravitational acceleration *g*, body mass *M* and leg length *l*. *: The slope is significant ($P < 0.05$).

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