COMPENSATORY MECHANISMS IN BELOW-KNEE AMPUTEE GAIT IN RESPONSE TO INCREASING STEADY-STATE WALKING SPEEDS.

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INTRODUCTION

Below-knee amputee walking is often characterized by bilateral asymmetry (Arya et al., 1995; Sanderson and Martin, 1997) such as increased intact leg loading, which can lead to a higher risk of developing musculoskeletal disorders in the intact leg (e.g., Lemaire and Fisher, 1994). Much of this asymmetry is due to the functional loss of the ankle plantar flexors, which have been shown to be critical in providing body support, forward propulsion, and leg swing initiation during normal walking (e.g., Neptune et al., 2004). Thus, significant compensatory mechanisms are necessary to fulfill the role of the lost ankle muscles. However, it is not clear if these compensatory mechanisms remain invariant with changes in task demands, such as walking over a wide range of walking speeds.

Since walking at faster speeds requires greater propulsion, it may be expected that amputees depend more on the intact leg for propulsion with increasing speed. We hypothesized that GRF asymmetry between the intact and residual legs would increase with walking speed. To test this hypothesis, we examined the braking and propulsive impulses and impulse ratios, as well as joint kinetics to identify how amputees modulate propulsion with increasing speed.

METHODS AND PROCEDURES

Kinematic and kinetic data were collected from 14 amputees and 10 control subjects at four walking speeds: 0.6, 0.9, 1.2 and 1.5 m/s. Kinematic data were captured using a motion capture system (Vicon, Oxford Metrics) while GRFs were collected using four force plates (Advanced Mechanical Technology, Inc.) imbedded in a 10-m walkway. Average speed was measured with two infrared timing gates at each end of the walkway. The kinematic and kinetic data were processed in Visual 3D (C-Motion, Inc.). Propulsive and braking GRF impulses were calculated as the positive and negative time-integral of the anterior/posterior (A/P) GRF, respectively. The impulse ratio was calculated as a measure of loading asymmetry. For the amputee subjects, the propulsive and braking impulse ratios were computed as the residual leg impulse divided by the intact leg impulse. In control subjects, the impulse ratios were computed as the left leg impulse divided by the right leg impulse. Positive and negative joint work was determined as the time-integral of the joint power.

Statistical analyses included three, two-factor, repeated measures ANOVAs for the impulse and work calculations. A one-factor repeated measures ANOVA was used for the impulse ratios. When significant differences were found, Bonferroni pairwise comparisons were used to determine which values were significantly different ($p \leq 0.05$).

RESULTS

Both the intact and control legs generated significantly more propulsion than the residual leg at every speed ($p<0.001$). The amputee propulsive impulse ratio at 0.9 m/s was significantly different than at 1.2 and 1.5 m/s ($p \leq 0.025$), but a clear increasing or decreasing trend was not observed. The residual leg had significantly less braking than the control subjects at the three highest speeds ($p \leq 0.050$; Fig. 1). Neither the amputee nor control braking impulse ratio significantly changed with walking speed.

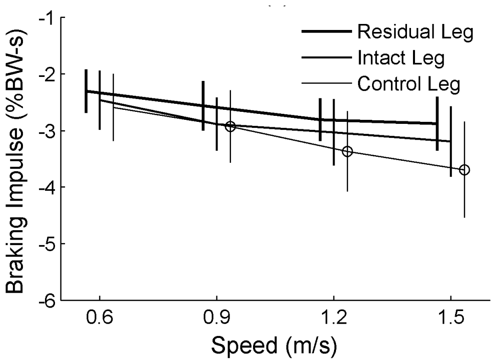

Figure 1. Residual, intact and control braking impulses. '○' indicates a significant difference with the residual leg.

In general, positive and negative joint work increased with increasing speed for all three leg conditions. The residual leg positive hip work was significantly greater than the control subjects at the three highest speeds ($p \leq 0.016$). The intact leg positive hip work was significantly greater than the control subjects as well, but only at the two highest speeds ($p \leq 0.040$). Residual positive knee work was significantly less than the intact leg (0.6, 1.2, and 1.5 m/s; $p \leq 0.001$) and control subjects (1.2 and 1.5 m/s; $p \leq 0.003$). Positive joint work at the residual ankle was significantly less than the intact leg and control subjects ($p<0.001$).

DISCUSSION

Our hypothesis that the intact leg would generate a greater portion of the necessary propulsion as walking speed increased was not supported, as the propulsive impulse ratio did not decrease with speed. This shows that the residual leg can effectively modulate propulsion when varying task demands are placed on the body.

As walking speed increased, the residual leg reduced residual braking and increased positive hip work. It's likely that the residual hip extensors act to provide propulsion in early stance, thus reducing the net braking impulse. The hip extensors have been shown to provide propulsion in simulations of able-bodied walking (Neptune et al., 2004), and so may be used in the absence of the ankle plantar flexors. The reduced knee work observed also supports this conclusion, as the biarticular hip extensor (hamstring) muscles would act to provide a knee flexor moment, and therefore reduce the net knee extensor moment during this period.

SUMMARY

Amputee subjects maintained their initial loading asymmetry as walking speed increased. The most prominent compensatory mechanism was increased positive hip work in early stance, which led to reduced residual braking. Rehabilitation strategies that increase the residual hip extensor output may help to improve loading asymmetry in amputee walking.

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