Step-to-step ankle push-off work modulation can reduce balance-related effort in a robotic ankle-foot prosthesis

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Individuals with below-knee amputation often experience difficulty in balancing, despite great progress in ankle-foot prostheses. We explored a method to assist with balance, starting from a simulation study using a three-dimensional limit-cycle walking model. This study showed that step-to-step ankle push-off work modulation can be as effective as foot placement in restoring balance. Guided by this simulation study, we implemented step-to-step ankle push-off work controllers on a robotic ankle-foot prosthesis emulator. The controllers applied higher push-off work when subject's lateral velocity was lower than a nominal velocity at heel strike instant (stabilizing controllers) and lower push-off work for destabilizing controllers. A neutral controller maintained a nominal push-off work. Then, we conducted human subject experiments both with able-bodied subjects using simulated amputation device (N=10) and with individuals with below-knee amputation (N = 6) with a forced exploration period. Both groups presented a reduction in metabolic rate for the stabilizing controller compared to the neutral controller, with the simulated amputee subjects showing a reduction of 5.5% ($p= 0.003$), and the amputee subjects showing a reduction of 11% ($p = 0.13$). This reduction in metabolic expenditure is likely related to efforts to restore balance including foot placement, which was reduced by 10% ($p = 0.009$) for simulated amputees, and intact limb control effort during a stance phase, which was reduced by 13% for amputees ($p = 0.01$). We also observed that subjects tended to rate the stabilizing controllers as more comfortable and easier to balance on, especially after forced exploration for amputees. Step-to-step push-off work modulation has the potential to reduce balance-related effort in a commercial device, especially with an effective training method.

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