Ankle push-off is equally important to foot placement in stabilizing three-dimensional walking

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1. Introduction

Individuals with below knee amputation experience a higher risk of falling and fear of falling [1], perhaps due to reduced balance, which may be caused by lost ankle actuation. The effect of ankle actuation on walking stability, however, is unclear. If ankle control, especially push-off work modulation, proved to be an effective disturbance rejection method as compared with other stabilization methods, we might have an opportunity to help with stability using robotic prostheses.

Hip actuation and ankle actuation seem to be useful control resources for balanced walking. A foot placement control using hip joint actuation can effectively recover balance [2]. Individuals with below knee amputation, however, still retain normal hip function, which suggests that lost ankle function could be the cause of the reduced stability. In humanoids, many researchers have directly controlled center of pressure using ankle actuation. Realizing this strategy in a robotic ankle might be hard due to the under-actuation phase in human locomotion. Controlling push-off work once per step is another method, effect at stabilizing 2D walking robot [3]. Although the scheme is implementable on a robotic ankle, ankle push-off control effect on stability for 3D locomotion has not yet been studied. If the strategy were found to be relatively effective in 3D locomotion, a stabilizing robotic ankle may improve disturbance recovery.

The purpose of this study is to investigate the relative importance of ankle push-off control for stabilizing 3D walking by simulating a limit cycle walking model with step-to-step controllers.

2. Methods

We developed a 3D limit cycle walking model with ankle plantar-flexion and inversion joints as well as hip flexion and abduction joints to compare how actuation of these joints affected balance recovery. The hip joint was actuated to obtain a desired step length using high gain PD control of the flexion joint and a desired step width using a quasi-statistical control of the abduction joint. The ankle joint was actuated to generate ankle roll resistance using a low gain PD control of the ankle inversion joint, and push-off work using impedance control of the ankle plantar-flexion joint.

Once per step, a high level controller modulated the joint actuation parameters, step length, step width, ankle roll resistance, and push-off work to enhance stability. At each step, this discrete controller generated new actuation parameters by multiplying the control gain by the state error between the measured states and nominal states. The hip and ankle joints were actuated using the new parameters during the following step. We used a fixed gain, gained by CMA-ES using an initial seed, found by LQR and line search methods.

We examined the balance restoration ability of each discrete controller by measuring the maximum tolerable floor height disturbance the model could withstand while walking 100 steps (Fig. 1). We investigated the following five conditions: 1) step width control, 2) step width and step length modulation – foot stepping, 3) ankle resistance control via PD gain control, 4) ankle push-off work control, and 5) combined control.

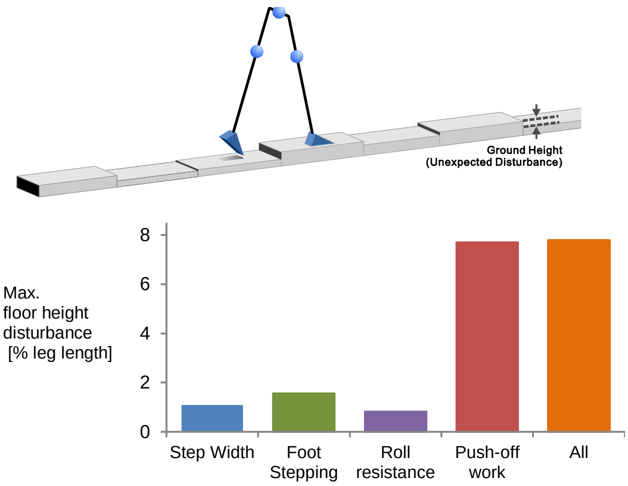

Fig 1. Ground height disturbance modeling (top) and stability result for each discrete controller, which modulated an actuation parameter once per step (bottom). Stability was described as the max. random disturbance magnitude for which the model walked 100 steps without falling. We divided the value by the leg length to normalize. The model with ankle push-off control overcame five times more disturbances compared with the foot placement strategy.

3. Results and Discussion

Surprisingly, ankle push-off work control most effectively stabilized the model using the developed controller (Fig. 1). Balance recovery ability of hip and ankle roll control, however, might be expanded by using different controllers. Hence, we examined a combination of linear controllers and measured the maximum step disturbance. Using an early-stage controller, both foot stepping and push-off control enabled the model to walk more than 10 steps after a 9cm step down disturbance (8.3 % leg length), the maximum possible disturbance for our limit cycle and once-a-step control design. These results suggest that linear ankle push-off work control might be as effective as foot stepping control to stabilize walking motion from small disturbances. Hence, we might be able to improve balance using stabilizing robotic ankles for individuals with below knee amputation. Before implementing this strategy in practice, however, several challenges, including those related to human-robot interaction and sensory information, need to be addressed. The trade-off between energy usages is also unknown. These issues remain open questions.

[1] Miller, 2001, Arch. Phys. Med. Rehab.
[2] Donelan, 2001, Proc. Roy. Soc. Lon. B.
[3] Hobbelen, 2008, Int. J. Rob. Res.