Step-to-step ankle in/eversion torque control in a robotic ankle-foot prosthesis may reduce balance-related effort during walking

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1 Introduction

Individuals with below knee amputation exert more effort during walking than their able-bodied counterparts [1]. This increased effort may partially be due to increased balance-related effort, especially while walking on challenging terrain [2]. Recently, we found that balance-related effort can be reduced by modulating ankle push-off work with a robotic ankle-foot prosthesis [3]. In doing so, we also realized the unexplored potential of other balance resources in robotic prostheses, such as active ankle in/eversion control.

Active ankle in/eversion control may help stabilize lateral motion during walking. Human walking seems to be the least stable in the medio-lateral direction [4]. Recovering from disturbances in the medio-lateral direction requires more balance-related effort for individuals with below knee amputation [5]. With the aim of improving balance in the medio-lateral direction, researchers have started developing prostheses with in/eversion compliance [6]. However, under specific types of lateral disturbances, passive prostheses with different in/eversion stiffness properties did not improve balance [5]. Rather than passive in/eversion actuation, humans seem to utilize active in/eversion control after foot placement control [7] to facilitate in redirecting the center of mass velocity. This action can be achieved with a robotic ankle-foot prosthesis by modulating ankle in/eversion torque at each step.

Feasibility of the step-to-step ankle in/eversion torque controller to restore balance could be revealed in a simulation study before it is validated by a human-subject experiment. A simulation study provides a platform to rigorously compare the effect of the proposed controller with other lateral stabilization methods [8]. If the performance of the in/eversion torque controller is comparable to other stabilization methods, such as foot placement control and ankle push-off work modulation, then active in/eversion torque control could be a viable solution to improve balance. Due to assumptions and simplifications used in the simulation, it is also important to run an experimental study exploring the effect of ankle in/eversion torque control on stability. The effectiveness of the controller could be revealed by a reduction in balance-related effort during walking [3].

In this study, we explore the effect of step-to-step ankle in/eversion torque control on balance in a simulation study and experimental study. We hypothesized that active ankle in/eversion control at each step would be relatively effective compared to other stabilization control methods. We also hypothesized that stabilizing step-to-step ankle in/eversion torque modulation in a robotic ankle-foot prosthesis would reduce balance-related effort in individuals with below knee amputation, while a destabilizing controller will increase effort. We discuss preliminary simulation results and propose experimental methods.

2 Methods

2.1 Simulation methods

We used a three-dimensional limit cycle walking model with hip and ankle joints to compare the effect of different modes of actuation at each of the joints on balance recovery [8]. The ankle in/eversion joint was actuated to apply a constant torque during the stance period, while the foot was flat on the ground. The ankle plantarflexion joint was controlled to provide push-off work. The abduction joint was modulated quasi-statistically to change step-width, and the hip flexion joint was actuated to track desired step length.

To stabilize the model during walking, we designed discrete linear feedback controllers, which altered actuation parameters once per step. We controlled parameters with high control authority in the medio-lateral direction: the magnitude of in/eversion torque, the magnitude of push-off work, step-width, and the combination of step-width and in/eversion torque. The gain of the controller was optimized using LQR. We will further optimize the gain using CMA-ES to account for a non-linear region. The performance of each controller was quantified by evaluating two measures while the model walked one hundred steps without falling: 1) the maximum tolerable random disturbance in lateral velocity and 2) the maximum tolerable random disturbance in ground height.

2.2 Experimental methods

We will implement the step-to-step ankle in/eversion torque controller on a recently developed prosthesis with two degrees of freedom [9]. This tethered device has two independently actuated toes, which allow for control of ankle plantarflexion and in/eversion. The step-to-step controller will choose an ankle in/eversion torque on each step as a linear function of the estimated medio-lateral velocity. The decision will occur at the instant of toe-off of the contralateral limb. The device will be controlled to generate this desired in/eversion torque while

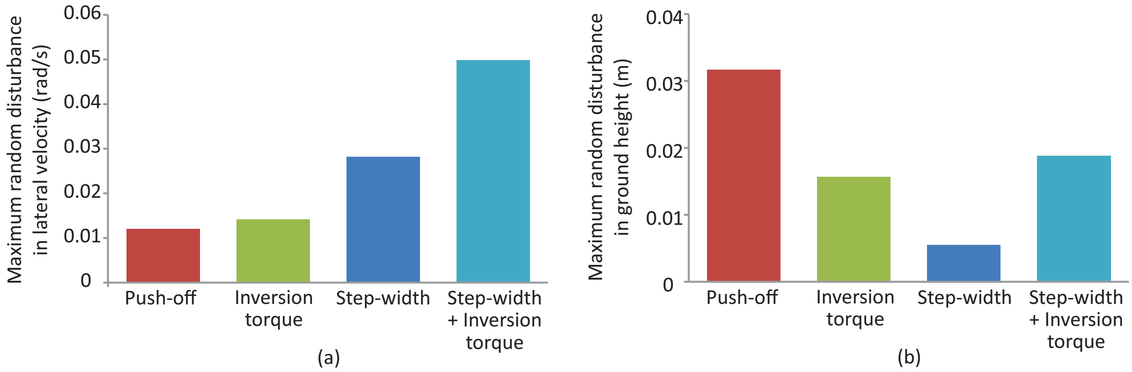

Figure 1: (a) Maximum tolerable disturbance in lateral disturbance and (b) maximum tolerable disturbance in ground height. Step-to-step ankle in/eversion torque control in combination with step width control increased the ability to restore balance after lateral velocity disturbances. The control method also moderately restored balance from both disturbances. Step-to-step ankle push-off work control was the best method to restore balance after ground height disturbances, and showed a reasonable performance to restore balance after lateral disturbance.

providing plantarflexion torque that corresponds to a piecewise, linear approximation of the human ankle work loop.

To test our hypothesis, we will perform a human-subject experiment using the developed controller. The experiment will include subjects walking in four conditions: step-to-step stabilizing controller; step-to-step de-stabilizing controller, which uses the same magnitude of the gain as the stabilizing controller but opposite sign; no step-to-step controller; and prescribed prosthesis. The balance-related effort will be measured via metabolic energy consumption, step width variability, average step width, center of pressure variability within a step, and user preference [3].

3 Preliminary results and future work

In our simulation study, once per step ankle in/eversion torque control moderately restored balance when the model was subjected to random disturbances in both lateral velocity and ground height (0.014 rad/s and 0.016 m, respectively, Fig. 1). For lateral velocity disturbances, when the in/eversion controller was used in conjunction with the step-width controller, balance restoring performance almost doubled (0.050 rad/s) compared to step-width control alone (0.028 rad/s, Fig. 1(a)). When ground height disturbances were applied, although the in/eversion controller was still effective at restoring balance, the best performance was achieved by the push-off work controller (0.032 m, Fig. 1(b)). These results suggest that each ankle in/eversion torque and push-off work controller has a different capability to handle a specific type of disturbance. Perhaps an appropriate combination of those controllers might further enhance balance to withstand disturbances, including a union of the lateral velocity and ground height disturbances.

Based on current simulation results, we expect that in our proposed experimental study, the step-to-step ankle in/eversion controller in a robotic ankle-foot prosthesis will reduce balance-related effort. We will also further perform simulation studies to explore the maximum balance restoring performance of each linear ankle controller by optimizing gains using CMA-ES. As the optimization is performed, we will apply three different types of disturbance: lateral velocity, ground height, and a combination of two. We expect these simulation and experimental results to offer insights into potential control methods for reducing the balance-related effort of individuals with below knee amputation.

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References

[1] Waters, R.L., Mulroy, S.: The energy expenditure of normal and pathologic gait. Gait Post. 1999, **9**: 207–231.

[2] Paysant, J., Beyaert, C., Dati, A., Martinet, N., Andr, J.: Influence of terrain on metabolic and temporal gait characteristics of unilateral transtibial amputees. J. Rehab. Res. Dev. 2006, **43**: 153.

[3] Kim, M., Collins, S.H.: Once-per-step control of ankle-foot prosthesis push-off work reduces effort associated with balance during walking. J. NeuroEng. Rehabil. 2014, **in review**:.

[4] Kuo, A.D.: Stabilization of lateral motion in passive dynamic walking. Int. J. Rob. Res. 1999, **18**: 917–930.

[5] Segal, A.D., Klute, G.K.: Lower-limb amputee recovery response to an imposed error in mediolateral foot placement 2014, **47**: 2911–2918.

[6] Gorges, J.J.: Controlled coronal stiffness prosthetic ankle for improving balance on uneven terrain. Master's thesis, University of Washington, Department of Mechanical Engineering (2013). Advisor: Glenn Klute

[7] Hof, A.L., Vermerris, S.M., Gjaltema, W.A.: Balance responses to lateral perturbations in human treadmill walking. J. Exp. Biol. 2010, **213**: 2655–64.

[8] Kim, M., Collins, S.H.: Once-per-step control of ankle push-off work improves balance in a three-dimensional simulation of bipedal walking 2014, **in review**:.

[9] Collins, S.H., Kim, M., Chen, T., Chen, T.: An ankle-foot prosthesis emulator with control of plantarflexion and inversion-eversion torque. In: Proc. Int. Conf. Rob. Autom.