A Lower Limb Prosthesis Haptic Feedback System for Stair Descent

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1 Background

Though there are a variety of prosthetic limbs that address the motor deficits associated with amputation, there has been relatively little progress in restoring sensation. Prosthetic limbs provide little direct sensory feedback of the forces they encounter in the environment, but "closing the loop" between sensation and action can make a great difference in performance [1].

For users of lower limb prostheses, stair descent is a difficult and dangerous task. The difficulty in stair descent can be attributed to three different factors: 1) Absence of tactile and haptic sensations at the bottom of the foot. Although force on the prosthetic socket provides some haptic feedback of the terrain being stepped on, this feedback does not provide information on the location of the staircase edge. 2) Insufficient ankle flexion of lower limb prostheses. Dorsiflexion of the physiological ankle during stair descent is about 27°. Even prostheses that provide active dorsiflexion provide less than this number, and regular prostheses provide almost no ankle dorsiflexion. The first two factors are analogous to the sensation of stair descent for someone without amputation wearing ski boots. 3) Prosthetic feet are optimized for flat-ground walking, offering undesirable energy storage at ankle flexion and energy return at toe-off. This can result in unwanted extra energy at the end of stance phase, propelling the user forward down the stairs.

Most research in lower limb prosthesis design focus on flat ground walking, but there has been less progress in addressing the challenges of stair descent. One technique that users of prosthetic lower limbs can use for addressing these challenges is to employ an "overhanging toe" foot placement strategy. Under this strategy, the edge of the staircase is used as a pivot point for the foot to roll over the stair. This reduces the need for ankle flexion by allowing the knee and hip to compensate, and avoids storing energy in the prosthetic spring. This strategy is dynamic, and requires the user to know the amount of toe overhang to adjust the movement of the rest of the body. Most haptic devices built to assist individuals wearing prostheses focus on upper extremity tasks [2–4] or standing and walking [5,6]. Here, we describe a system for stair descent. The system provides information on the location of the edge of the staircase as vibrotactile stimulations on the thigh.

2 Methods

The haptic device consists of an insole, a wearable thigh band, and an embedded system.

Sensory Insole. The insole (Figure 1) has 6 pressure sensitive piezoelectric resistors (FlexiForce A401, Teckscan, South Boston, MA, USA) concentrated at the middle of the insole along the proximal-distal direction. The insole can be made in multiple sizes and worn inside any shoes underneath any prosthetic limbs.

Figure 1: Sensory insole. Not pictured is another layer of sisal webbed textile.

Each piezoelectric resistor senses the presence of staircase step underneath the foot based on the stepping force. This information is sent to the embedded computer which communicates with the actuators.

The A401 piezoelectric resistive force sensor was chosen as it is flexible and can be easily attached to the insole. It is low-cost and widely available, but any similar sensors could be used. The sensors are connected to separate voltage divider circuits acquired at 500Hz. In future designs, we wish to increase the number of force sensors especially towards the middle of the insole for increased sensing resolution. This can be done by using similar piezoelectric resistive sensors with smaller diameter and by increasing the number of channels of the multiplexer. These design criteria will become clearer as user studies progress.

Wearable Thigh Band Actuator. The wearable thigh band (Figure 2) consists of 6 piezoelectric actuators that are sewn onto an elastic band, equally spaced at 1.5in. The wearable is worn on the thigh along the medio-lateral direction, with the actuators coming into contact with the skin. The band is fastened using Velcro and the size can be easily adjusted. To provide comfortable contact with the skin and eliminate sharp vibrating edges, we designed a cap that houses the actuator. The cap is 3D printed in PLA plastic.

Figure 2: Wearable thigh band with the vibrotactile arrays (top), actuator cap (down left), and the piezoelectric actuator and driver (down right)

The actuators receive signals from the sensors through the embedded computer. Each actuator corresponds to each sensor, as shown in Figure 3. Proximal-distal information at the foot is mapped medio-laterally on the thigh. This is because the thigh is more sensitive towards point discrimination along the medio-lateral direction.

Piezoelectric actuators were chosen over linear resonant actuators (LRA) and eccentric rotating mass (ERM) motors because the frequency and amplitude of actuation can be controlled independently. This is important to produce effective sensory feedback. Here we use amplitude-modulated stimulation at 250 Hz [7].

Embedded System and Electronics. The insole and wearable band are controlled using the BeagleBone Black (BeagleBoard.org, Oakland, MI, USA). An embedded electronics board that consists of voltage divider amplifiers, a multiplexer, and an inter-integrated circuit (I^2C) bus is used to acquire the signal from the force sensors, and to read and write from the analog channels.

Methods of Actuation. We propose two modes of actuation for the wearable thigh band. In the first mode, the magnitude of the vibration from the piezoelectric actuator is proportional to the force signal sensed by the sensor. Higher force corresponds to higher vibration magnitude. The user will feel vibration signals on the thigh as a faithful representation of the forces under the foot. This mode is designed to provide a sense of sensory embodiment, in which the user feels a sense of body ownership over the device.

In the second mode, the actuator will only vibrate if the sensor senses an edge. Only the single actuator that corresponds to the sensor at the edge boundary vibrates. This mode is designed to provide the user with the most useful haptic information, but not necessarily to recreate the sensory experience of the amputated limb.

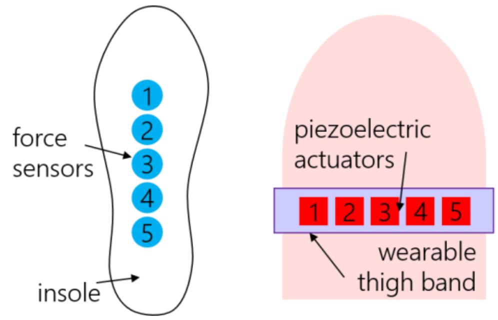

Figure 3: Insole (left) and wearable thigh band (right)

3 Results

The haptic feedback system, including the insole, the wearable thigh band, and the embedded systems and electronics are described in Section 2 and illustrated in Figures 1-3.

4 Interpretation

This novel feedback device is expected to make the task of descending the stairs less challenging for users of lower limb prostheses, while allowing for a relatively easy introduction to the market and low cost.

References

[1] Saunders, I., and Vijayakumar, S., 2011, "The role of feed-forward and feedback processes for closed-loop prosthesis control," J. Neuroeng. Rehabil., **8**(1), p. 60.

[2] Kim, K., Colgate, J. E., Santos-munn, J. J., Makhlin, A., and Peshkin, M. A., 2009, "On the Design of Miniature Haptic Devices for Upper Extremity Prosthetics," pp. 1–12.

[3] Damian, D. D., Ludersdorfer, M., Kim, Y., Hernandez Arieta, A., Pfeifer, R., and Okamura, A. M., 2012, "Wearable haptic device for cutaneous force and slip speed display," Proc. - IEEE Int. Conf. Robot. Autom., pp. 1038–1043.

[4] Huang, H., Enz, C., Grambone, M., Justiz, J., Li, T., Unsal, O., and Koch, V. M., 2014, "Data fusion for a hand prosthesis tactile feedback system," IEEE 2014 Biomed. Circuits Syst. Conf. BioCAS 2014 - Proc., pp. 604–607.

[5] Fan, R. E., Culjat, M. O., King, C.-H., Franco, M. L., Boryk, R., Bisley, J. W., Dutson, E., and Grundfest, W. S., 2008, "A haptic feedback system for lower-limb prostheses.," IEEE Trans. Neural Syst. Rehabil. Eng., **16**(3), pp. 270–277.

[6] Rusaw, D., Hagberg, K., Nolan, L., Ramstrand, N., and others, 2012, "Can vibratory feedback be used to improve postural stability in persons with transtibial limb loss," J Rehabil Res Dev, **49**(8), pp. 1239–1254.

[7] Stepp, C. E., and Matsuoka, Y., 2012, "Vibrotactile Sensory Substitution for Object Manipulation: Amplitude Versus Pulse Train Frequency Modulation," IEEE Trans. Neural Syst. Rehabil. Eng., **20**(1), pp. 31–37.