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A Wearable Skin Stretch Haptic Feedback Device: Towards Improving Balance Control in Lower Limb Amputees *

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Abstract— **Haptic feedback to lower limb amputees is essential to maximize the functionality of a prosthetic device by providing information to the user about the interaction with the environment and the position of the prostheses in space. Severed sensory pathway and the absence of connection between the prosthesis and the Central Nervous System (CNS) after lower limb amputation reduces balance control, increases visual dependency and increases risk of falls among amputees. This work describes the design of a wearable haptic feedback device for lower limb amputees using lateral skin-stretch modality intended to serve as a feedback cue during ambulation. A feedback scheme was proposed based on gait event detection for possible real-time postural adjustment. Preliminary perceptual test with healthy subjects in static condition was carried out and the results indicated over 98% accuracy in determining stimuli location around the upper leg region, suggesting good perceptibility of the delivered stimuli.**

I. INTRODUCTION

Limb loss has devastating effects and drastic changes to a person's life. It causes loss of function, loss of sensation and reduces quality of life due to imposed limitation to physical activities. It is estimated that lower limb amputees account for over 75% of the 32 million amputees' population worldwide [1], with vascular disease, trauma or congenital defects being the major cause. An important milestone in the rehabilitation stages for amputees is the prescription of prosthetic devices, which attempts to restore the functions of the missing limb. Despite surgical and technological advancements, person with lower limb amputation has been associated with low balance confidence, especially those suffering from vascular amputation [2]. Statistics have shown that half of the amputee community have reporting falling while close to half have reported fear of falling, with above knee amputees having higher risk of falling [3]. Loss of sensorimotor post amputation has been attributed to increase in the risk of falling due to lack of response from the amputated limb following external perturbation [4]. Several studies described reviving sensory pathway using improved surgical technique such as nerve transfers and targeted muscle reinnervation (TMR) and utilize the obtained signal to enhance control of prosthesis devices [5]. However, this technique is currently in its preliminary phase [6] which limits its application to wider amputee group. As an alternative, noninvasive sensory feedback have been suggested to compensate for human functional deficits. Of a particular interest is the use of tactile haptic feedback for prostheses users [7-12]. The use of haptic in upper limb powered prostheses have been widely studied in comparison to lower limb. This includes investigating its effect on improving grasping and lifting [8], enhancing grip force control [9], reducing slip [10], and creating edge perception [11]. Although limited, a handful of studies did focus on assessing the feasibility of applying haptic feedback for lower limb prosthesis users via modalities such as pneumatic balloon [7] and vibration [12]. Pneumatic feedback system requires specialized hardware and bulky apparatus which adds weight and reduces its viability for a portable system. Despite extensive use of vibrotactile actuators, skin stretch modality have been suggested as being superior to vibration as it activates both the slow acting (SA) and fast acting (FA) mechanoreceptors. In addition, it does not show adaptation effect and can be effective even in low velocities and small movements [13]. Specifically, on hairy skin (which dominates the lower limb), skin stretch applied in lateral direction was deemed as a preferable choice for developing tactile displays [14]. To our knowledge, a wearable device which applies lateral skin stretch feedback on lower limb has not been largely explored. This paper presents the design of a lightweight wearable lateral skin stretch haptic feedback system which aims to enhance balance control of lower limb prosthesis users by creating awareness of the foot position during ambulation. Overall feedback scheme, the haptic actuator design, and preliminary static testing with healthy subjects will be described accordingly.

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II. SYSTEM DESIGN

A. Feedback Scheme

A haptic feedback system for lower limb must consider intuitive mapping between the feedback and the ambulation events. Two mapping approaches have been adopted in the literature. First is the magnitude-based feedback where the feedback intensity changes with the intensity of the force measured at the foot-ground interface such as the one demonstrated in [7]. The second approach is an event-based feedback, in which the activation of the feedback corresponds to the gait events which are identified using sensors that measure gait kinematics parameters [12]. While the former approach is preferable to give perception of changing pressure, for continuous use, a discrete event-based (on-off) feedback was selected for our study. This feedback method has the advantages of reducing the complexity of the feedback algorithm and decreases the total skin-device contact period. Fig. 1 shows the feedback scheme for the overall system design.

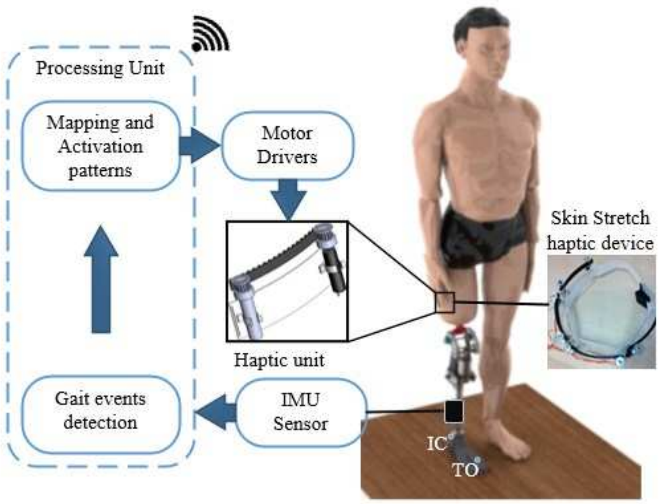

Figure 1. Conceptual feedback scheme showing the sensor and actuation unit. IC: Initial Contact, TO: Toe Off, IMU: Inertial Measurement Unit

Single wireless Inertial Measurement Unit (IMU) attached on the shank developed in our previous work [15, 16] will be used to identify gait events. The system demonstrated successful real-time detection of toe-off (TO) and initial contact (IC) events (Fig. 2) by applying rule-based algorithm on the gyroscope signal obtained during level ground walking and ramp ascending/descending for healthy and amputee subjects.

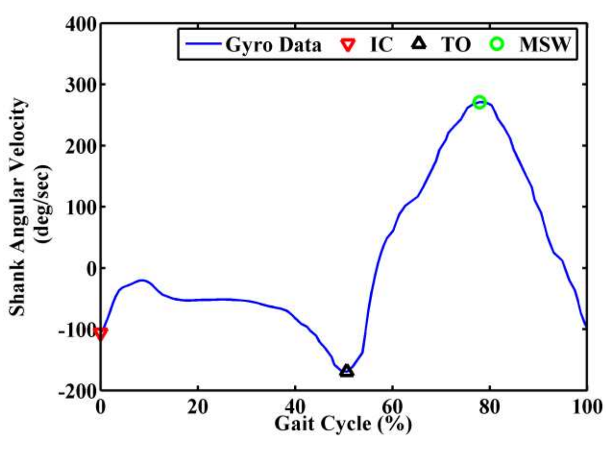

Figure 2. Sample of gyroscope signal showing detection of gait events for one gait cycle. IC: initial contact, TO: toe-off, MSW: mid-swing. Details in [15, 16]

Placement of haptic actuator will require different strategies based on various amputation level. For transtibial amputee, it is possible to place the actuator on the residual limb around the thigh area. For transfemoral amputee, socket modification could be made to allow integration of the actuators in the same area of the residual limb. The identified events will be intuitively mapped to corresponding segments of the haptic actuators. This arrangement is postulated to benefit the amputees by having the awareness of the limb placement during ambulation and enabling real-time postural adjustment.

B. Haptic Actuator Design

Fig. 3 shows the design of the haptic device. The actuator is driven by a miniature DC motor (RE10, Maxon, Sachseln, Switzerland) attached to a 16:1 gearbox (GP10A, Maxon, Sachseln, Switzerland). The motor was coupled to a 10.6 mm diameter pulley and is capable of delivering 4.5N continuous force and up to 9.3N at its nominal speed. Stretch stimuli are delivered via a flexible grooved timing belt with 15 stimuli spaced at 4.5 mm attached to the DC motor on one end and to a fixed shaft on the other end. The belt was adjusted to be in curved manner such that it can be stretched when the motor is activated. Each haptic actuator segment was fixed on a flexible plastic sheet, enabling it to take the shape of the limb curvature. To allow simultaneous placement of multiple devices on the limb, these actuator segment units were linked using a fabric elastic strap. The motor is driven using electronic circuitry at 5V and interfaced to a computer with data acquisition (DAQ) card (NI-USB 6225, National Instruments, Austin, Texas). A Graphical User Interface (GUI) programmed in LabView software (National Instruments, Austin, Texas) was used to control the motor activation sequence and display the active actuator segment. Upon each activation, the motor will make a limited turn (restricted by the length of the grooved belt), effectively stretching the skin in the lateral direction. Motors in all segments were supplied with the same voltage and were assumed to produce the same stretching effect.

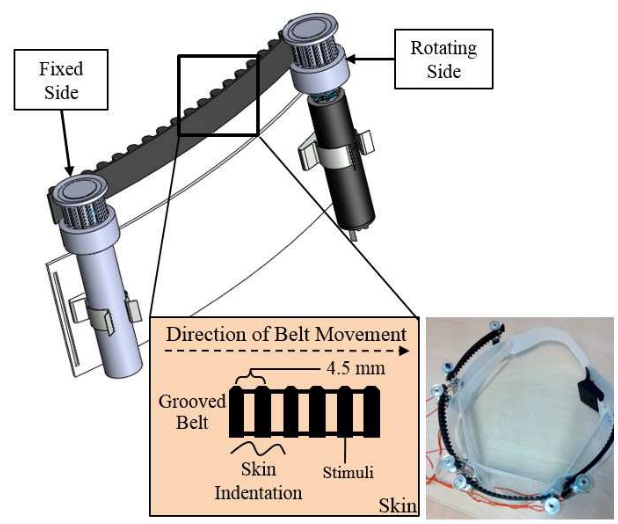

Figure 3. Haptic actuator design . Bottom right: Four linked haptic segments.

The total weight for a single haptic segment was 70 g (excluding power unit) with the size of 95 mm (width) × 63.5 mm (height). To allow easier adjustment and testing, the system was tethered to the DAQ card, while a wireless system will be used for final design to ensure portability. The haptic actuator unit was designed to be wearable around the limb. However, instead of facilitating single point tactile stimuli as demonstrated in [7], multiple stimuli simulated by the grooved belt make contact and move laterally against the skin to create a skin-stretch haptic effect. The purpose of this was twofold; firstly to allow larger skin area to experience the haptic sensation which can benefit amputees with reduced sensations post amputation. The second purpose was to take advantage of the fact that hair follicles can be trapped in between multiple stimuli, and movement of the haptic belt will cause movement of the hair follicles which elicits additional haptic sensation.

III. PRELIMINARY WORK

A pilot study in static mode was carried out to assess the effectiveness of haptic stimuli delivered by the device. The ability of the subjects to perceive the applied stimuli in static condition is important in ensuring the practicality of the device to be used during dynamic activities.

A. Subjects

Three healthy adult male subjects (H1, H2, H3, age: 26.7±4.2 years old) with no apparent gait abnormalities or lower limb vascular disease participated in this study. Subjects were provided with the information sheet and briefed about the experiments. Consent was obtained from the subjects and the Institution's Ethical Review Board approved the experimental procedures involving human carried out in this study.

B. Experimental Protocol

Fig. 4 shows the overall experimental setup. Subjects were seated in a comfortable position with the haptic device wrapped around middle thigh of the right leg at anterior, posterior, medial and lateral sides. For convenience, these locations were labelled as front, back, right and left respectively in the subject's response sheet. While placing the device, the belt was ensured to be positioned such that it made firm contact with the skin. White sound was played via headphone throughout the session to eliminate auditory cue coming from the motor. The subjects were also seated close to a table such that the apparatus was not visible to them, to avoid visual identification of the haptic actuator movement. A program was created in LabView to send an activation signal to one of the haptic device's locations in random manner for 10 times. Upon each activation, the device would stretch the skin for 50 ms, before returning to its original position. There was 5 seconds pause between each activation to allow the subjects to record their response in the response sheet. Subjects were instructed to indicate in the response sheet, the perceived stimuli locations (front, back, left, or right) or if the location cannot be determined if no stimuli was felt. The test was repeated with 150 ms, 300

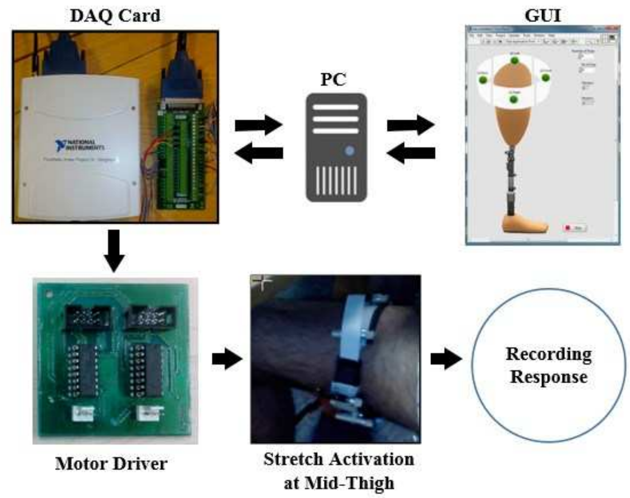

Figure 4. Experimental setup. DAQ: Data Acquisition, GUI: Graphical User Interface.

ms and 450 ms stretching period. A total of 120 responses (10 activation × 4 stretch period × 3 subjects) were recorded from the subjects. The perceptibility of the haptic stimuli was calculated by finding the percentage of correct responses over the total number of trials.

IV. RESULTS AND DISCUSSION

Fig. 5 shows the summary of the results achieved by each subject H1, H2 and H3 for all four stretching period. A 98.3% mean accuracy was achieved when perceiving the location of the stimuli. The results suggested that the skin-stretch feedback could be highly perceived regardless of the stimuli location around the thigh region, which is consistent with reports from other work [7].

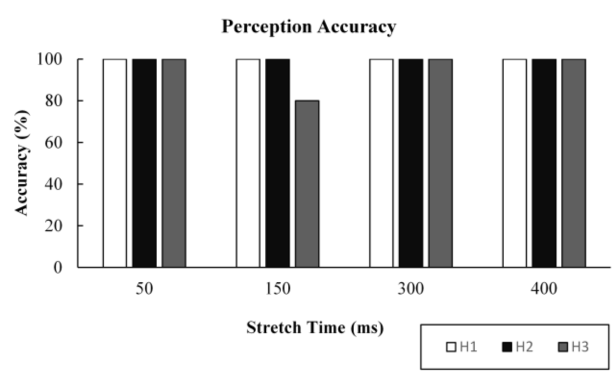

Figure 5. Subjects' accuracy for various stretch time.

The only error recorded was attributed to subjects H3 during 150 ms trial, where he indicated confusion about the terminologies used to indicate the location of the stimuli. The same subject scored perfectly for other trial set.

Previously, the use of tactile feedback for balance and postural control has been investigated for patients with vestibular disease where reduction of sway during locomotion [17] and postural stability improvement [18] were reported. At least one study [19] described work with above knee amputees to investigate the effect of providing IC and TO (detected using foot sensors) cues during ambulation, however, using visual and auditory feedback. The authors reported improvement in several dynamic gait performance measures. We deduced that similar improvements could be achieved using wearable skin-stretch device, which requires less intervention and can be used outside laboratory environment. To achieve this goal, however, the system must be robust enough to provide discernable stimuli in both gait events. For an average gait period of 1s during normal walk [20], stance phase takes place for about only 600 ms, which means a feedback stimuli that can be perceived in short duration will be beneficial for real-time application. It was noted that the perceived stretch stimuli during the experiment can be perceived accurately even in the lowest stretching period of 50 ms, which shall be useful in dynamic trials. Moreover, another important consideration in providing feedback during movement of the limb is to ensure that the delivered stimuli is not down weighted or masked by the sensory motor system [21]. This effect will be investigated in future work.

V. Conclusion

A wearable haptic device based on lateral skin-stretch feedback was presented in this paper. The device demonstrated the advantage of having high perceptibility at low magnitude and short stretching period. The outcome of the preliminary test motivated further research which includes investigating the device's perceptibility during dynamic activities such as walking and stair/ramp ascending and descending. Future work will also focus on complete integration of the feedback system (IMU sensor and haptic device) and evaluation with amputee group to investigate the effect of providing feedback cues in improving their balance control. A successful integration of haptic feedback scheme during ambulation is hoped to benefit the amputee community as a whole.

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