Proprioceptive Improvements of Lower-Limb Amputees under Training with a Vibrotactile Device – A Pilot Study

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***Abstract*— Limited mobility severely impacts the quality of life of persons with lower-limb amputations. Therefore, it is imperative to develop proper rehabilitation techniques to prevent falls and injuries. A vibrotactile device was developed as a training tool to enhance the rehabilitation of persons with recent lower-limb amputations. Stimuli provided by the device trains the user to sense discrete perturbations and then perform a corrective movement to reduce the chance of a fall. This pilot study was conducted to test the functionality of the device in improving the prosthetic proprioception of lower-limb amputees and the effect of the training instruction on motor learning. Two subjects were included in this study, one control and one receiving experimental training, with both subjects performing standing and walking tasks. Standing trials were used to evaluate the improvements in response and movement times and walking trials were tested for improvements in correct movement. In the standing task, the control and the experimental subject showed a 0.1% and 17% improvement in response time, respectively. In the walking task, both subjects showed improvements in making correct movement. Future work will focus on the design improvements of the device and the experiment protocols to further evaluate the effectiveness of the training.**

I. Introduction

Lower-limb amputees are at higher risk of falls if they cannot easily identify the state of their prosthesis when experiencing perturbations [1], [2]. The proprioception of a transtibial amputee's afflicted leg is limited to vibrational feedback felt through the prosthetic socket. Thus, persons with newly acquired prostheses may struggle identifying environmentally triggered perturbations without proper training.

Kaufman's work [3] in amputee rehabilitation has demonstrated the effectiveness of a task-specific fall prevention training program with transtibial amputees. Kaufman's methods involved training subjects to make recovery steps in response to imposed postural perturbations created by a treadmill. Peak trunk flexion and velocity were monitored since they have been shown to be determinants of falls. Results showed improvements in both trunk flexion angle and velocity, indicating the usefulness of task-specific training.

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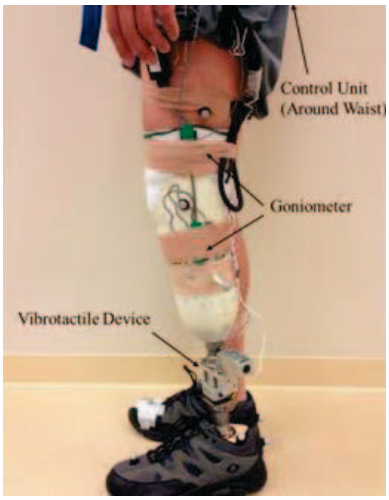

Figure 1. Overview of the vibrotactile device on a subject.

Sensory feedback as a form of rehabilitation for lower-limb amputees has been shown to increase postural control [4] and improve gait performance [5]. Rusaw and Crea [6] specifically used vibratory feedback in their experiments with transtibial amputees. The vibrating elements in both studies were placed in the thigh area.

In a series of studies, Wulf [7] showed that implementing an attentional focus during sport motor learning resulted in better performances. The transferability of the benefits of attentional focus to amputee rehabilitation is unknown.

This study implements attentional focus to the training of lower-limb amputees to compare the improvements of a subject with an attentional focus vs a control subject using a vibrotactile device. The vibrotactile device was developed to train lower-limb amputees to respond to imposed perturbations [8]. The device creates two distinct sensations with vibrating motors and a solenoid. It was designed to fit most standard lower-limb prostheses and can be fitted between the socket and pylon, allowing the vibrations to propagate up the prostheses simulating commonly experienced perturbations.

The three aims of this study were to (1) test the reactionary improvements to perturbations of subjects due to vibrotactile device training; (2) test the functionality of the vibrotactile device in delivering the sensations to subjects while standing and walking; (3) test the effects of attentional focus in task-specific vibrotactile training of lower-limb amputees.

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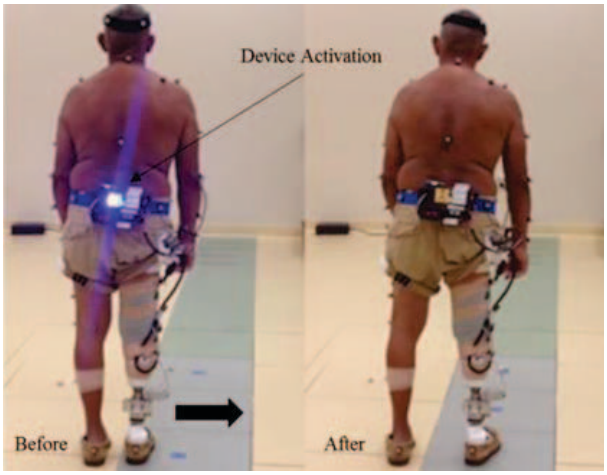

Figure 2. Before and after movement during a standing task with the vibrotactile device showing device activation and reactionary outwards step.

II. System Overview

The vibrotactile device provided two types of vibrational feedback to the user during the terminal swing phase. It was designed to be a low-cost, low-maintenance and universally fitting device for most transtibial prostheses. The two main components are the vibrotactile unit and control unit, shown in Fig 1. [8].

A. Vibrotactile Unit

The unit simulated external perturbations commonly experienced by lower-limb amputees using two Precision Microdrive vibrational motors and a Ledex push-type tubular solenoid. The vibrational motors were used to simulate the sensation of the user dragging his/her prosthetic foot and the solenoid was used to simulate a knocking sensation created by a foreign object striking the prosthetic limb.

The device was attached in line with the user's prostheses; between the pylon and socket. This setup allowed the vibrational feedback to be transmitted through the user's socket. Both vibrational motors were powered by three AA rechargeable batteries and the solenoid was powered by two 9V batteries. All batteries were mounted on the control unit.

B. Control Unit

The control unit contained circuit boards, LED lights, batteries and a goniometer. The batteries, LED lights, an IR receiver and a microcontroller (Arduino ATMega328) are all housed in a 3D printed box and worn around the user's waist. The infrared LEDs were used to synchronize with the motion analysis system and goniometer to signal the successful activation of the vibrotactile device as shown in Fig. 2.

Connected to the control unit, a goniometer was used to activate the vibrotactile device by identifying terminal swing phases based on the knee flexion angles. A remote control was used to initiate the angle detection of the goniometer during a subject's walk. This allows for randomized activations of the vibrotactile device by the care provider.

Table 1. Schedule of tests and training sessions

Legend: S = Standing and W = Walking		
Visit (Week)	Activity (Duration)	Description (Feedback)
1 (Week 1)	Baseline Test (2 hrs.)	S and W Trials (Vibration)
	Training Session 1 (1 hr.)	S and W Training (Vibration)
2 (Week 1)	Training Session 2 (1 hr.)	S and W Training (Vibration)
3 (Week 2)	Training Session 3 (1 hr.)	S and W Training (Vibration)
4 (Week 2)	Training Session 4 (1 hr.)	S and W Training (Vibration)
5 (Week 3)	Final Test (2 hrs.)	S and W Retention Trials (Vibration)
		W Transfer Trials (Knock)

III. Experiment

Two lower-limb amputees were recruited from the Long Beach VA Healthcare System to participate in this pilot study. Subject 1's physical characteristics were; age: 49 years, weight: 220lbs, height: 6ft and 2in, afflicted side: left. Subject 2's physical characteristics were; age: 67 years, weight: 164lbs, height: 5ft and 5in, afflicted side: right.

A. Experiment Protocols

The user study was conducted at the VA Long Beach Healthcare System Motion Analysis Laboratory equipped with an 8-camera VICON motion capture system and AMTI force plates. The experiment included standing and walking trials. In the standing trials, subjects were instructed to stand still with their prosthetic foot on a force plate, and to step outwards with their afflicted leg when they felt the stimulus, as shown in Fig. 2. The ground reaction forces were collected at 1000Hz. In the walking trials, subjects were instructed to walk across the room and to step outwards with their afflicted leg when they felt the vibrotactile feedback. They were not required to remain on the force plates. Ground reaction forces were not collected in the walking trials. Positional marker data were collected for both trial types at 100Hz using the VICON motion analysis system.

Table 1 provides the summary of the experiment protocols. The experiment was divided into three phases; a baseline test, training session and final test. The baseline test included both standing and walking trials. The baseline test was followed by a total of four training sessions in which subjects practiced responding to the vibrational feedback while standing and walking. The final test included a test of retention and a test of transferability of the training. Retention of the skills developed during training was assessed in final standing and walking trials. The transferability of the training was assessed using the knocking feedback instead of the vibrational feedback.

Table 2. Instructions received during the study

Subject	Standing Instruction	Walking Instruction
Subject 1 (Control)	"Stand in place. Step out to the side as fast as you can when you feel the stimulus."	"Walk down the green and grey path. Step out to the side with your prosthesis as soon as you feel the stimulus and stop"
Subject 2 (External)	"… In order to do this, concentrate on moving your prosthetic foot out to the side, think hard about your prosthetic foot and moving it out."	"… In order to do this, concentrate on moving your prosthetic foot out to the side, think hard about your prosthetic foot and moving it out."

B. *Training Instructions*

Wulf's studies involving attentional focuses in motor learning exercises showed that in most cases external focus groups yielded better learning results than internal focus and control groups. An external focus directs a subject's attention to the effects of their movement on the environment. Based on these results, an external focus group and control group were used in this study. Subject 1 was in the control group and Subject 2 was in the external focus group. Table 2 shows the training instructions that were provided to each subject. Subject 2 received the same instructions as Subject 1 but with additional external focus instructions.

IV. Data Analysis & Results

The kinematic data collected from the motion analysis system were post-processed using the VICON Nexus software. Ground force data were processed and analyzed using MATLAB. The following sub-sections describe the methods used for data analysis in the standing and walking task.

A. *Standing Trials*

Improvements in reaction time (RT) and movement time (MT) were used to evaluate the effectiveness of the training within standing trials. As seen in Fig. 3A, RT is defined as the time interval between the activation of the vibrating motors (MA: motor activation) and the initialization of the subject's outwards step (IS: initialization of step). MA time stamps were manually defined from the force plate data for each standing trial; initial forces created by the vibrations were easily distinguishable in the force plots. The IS time stamp was calculated as the instant the subject's ground reaction force in the vertical (Z) direction increased by 5% above the average stationary force. The average stationary force was determined by taking the average of vertical forces in a 50 milliseconds window before MA.

MT is defined as the time interval between IS and the instant the subject regained his/her balance after the outwards step marking the equilibrium point (EP). EP was calculated using the center of pressure (COP) data in the x-direction (mediolateral direction), shown in Fig. 3B. Starting from the return of the outward step, averages and standard deviations of the COP were calculated for consecutive 0.25 second windows. We assumed the subject regained their balance when the standard deviation became less than 1 mm. This instance was marked as EP.

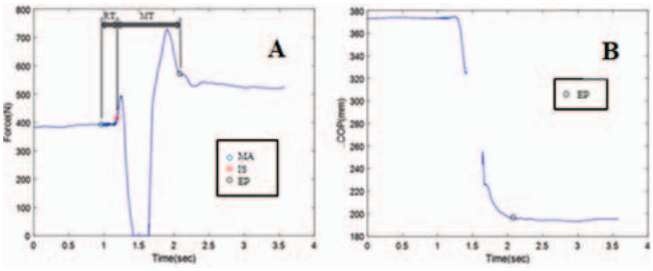

Figure 3. Determination of RT and MT in standing trials. A) Ground reaction force vs time. B) COP vs time. The COPs are in the mediolateral direction

B. *Walking Trials*

For walking trials, we analyzed the trials for which the LED light from the control unit was visible to the VICON to ensure the activation and synchronization of the tactile feedback with the motion analysis system. From the trials with successful device activations, trials were categorized as either correct or incorrect trials. A trial was considered correct if the subject reacted to the stimulus by stepping outwards during the swing phase that followed the device activation. Incorrect trials were trials in which subjects made an incorrect movement or had no reaction to the stimulus. The number of trials in which a subject correctly responded to the device was observed for improvements between baseline and final trials. In addition to the baseline and final tests for walking trials, a separate test was conducted to evaluate the transferability of the training to a different stimulus, a discrete knock. These transfer tests were completed on the same day as the final tests. Reactionary movements were observed and post-processed using the VICON Nexus software.

C. *Results*

The standing trials results are seen in Table 3 for Subject 1 and 2. An improvement in both subjects was observed with the response time. Subject 1 showed a 0.0024 sec improvement and Subject 2 showed a 0.0351 sec in response times. There was no improvement for movement times within any subject. Surprisingly, both subjects show a slightly higher average movement time in the post-test. Statistical analysis was not performed on the results due to the limited number of subjects. The results shown only provide a preliminary evaluation of device and the training.

The walking trials results are seen in Table 4 [9]. There was an improvement of percentages of correct trials for both subjects between the baseline and the final tests. Additionally, in the transfer test with the knocking stimulus, Subject 1 and Subject 2 showed success ratios of 74% and 72%, respectively.

V. Discussion

This preliminary study focused on the proprioceptive improvements of two transtibial amputees that were trained with a vibrotactile device. We hypothesized that training transtibial amputees with the device would improve reaction times and movement times in the standing task and correct trial ratios in the walking task. Also, we hypothesize that the subject who received an external-focused training instruction would show larger improvements in motor skills compared to the control subject. We observed this trend for reaction times

Table 3. Results for response times and movement times in standing trials.

Standing Trials	Subject 1 (Control)		Subject 2 (External)	
	RT(sec)	MT(sec)	RT(sec)	MT(sec)
Baseline	0.2430	0.6421	0.2306	0.4877
Final	0.2406	0.6772	0.1909	0.5737

Table 4. Results for success ratios in walking trials.

Walking Trials	Subject 1 (Control)		Subject 2 (External)	
Baseline	0/24	0%	0/54	0%
Final	3/9	33%	5/22	23%
Transfer	23/31	74%	26/36	72%

in the standing task, in which Subject 1 and Subject 2 showed a 0.1% and 17% improvement, respectively. Subject 2's larger improvement suggests the potential benefit of the training instruction on the motor learning. However, there were no improvements observed for movement times. In fact, both subjects show slightly longer average movement time in the post-test. This may be due to the movement variability that the subjects can make following the stimulus. For example, the subjects may step outwards at a shorter or a longer distance.

In the walking task, both subjects detected the feedback and made appropriate corrective movements at a higher rate after the training. Both were also able to transfer the trained motor skills in the transfer test. The control subject yielded a significantly higher correct trial ratio in the final test and slightly higher in the transfer test. The results do not support the benefit of the device and the training instruction. However, we believe that the significance of these results may have been affected by the design issues of the vibrotactile device. During the walking trials, we observed issues with motor activation delay, inaccuracy of the knee angle detection from the goniometer, and the synchronization that limit the number of trials that can be included for data analysis. These issues may affect the user's experience with the feedback and the training. Based on the experiment and subject feedback, the vibrotactile device will be redesigned to improve its accuracy and reliability.

VI. Conclusion and Future Work

In this pilot study, we introduced a novel vibrotactile device and an investigation into the effect of the training instruction. We also developed methods of analyzing the kinematics of transtibial amputees reacting to perturbations. After training with the device, both subjects showed improvements in reaction times in standing trials and correct trial ratios in the walking trials. Subject 2, who received external-focus training, performed better in the reaction time than the control subject. The user experiment also provides insights to the design improvement needed for the vibrotactile device. Since the completion of the experiment, the vibrotactile device has had and will have additional design changes. The activation delay and synchronization will be minimized using a wireless transmission. The goniometer will be replaced by Inertia Measurement Units (IMU) to more accurately detect the gait cycle for feedback activation. A new hardware design contains a clamping mechanism that fits over standard-sized pylons, eliminating the requirement to disassemble the prosthesis in the old design. Four vibrating motors, two pairs of different motor types, with faster activation were added to the device, resulting in stronger vibrations and varying frequencies. Different frequencies may allow subjects with different vibrational sensitivity to detect the device's activation. A spring-activated actuation unit replaced the solenoid to deliver a stronger striking force. Future studies will include more subjects to statistically verify the effectiveness of the vibrotactile device and the training instruction in training transtibial amputees.

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