Providing Center of Pressure (CoP) Feedback for Transtibial Amputees: A Preliminary Exploration with Pancake Vibrators

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***Abstract*— This paper presents the preliminary exploration with a sensory feedback system to provide Center of Pressure (CoP) feedback for transtibial amputees. The CoP displacements in mediolateral (ML) and anterior-posterior (AP) directions are classified into different directional patterns, and we expressed these patterns with combinations of four pancake vibrators placed around the thigh. A pilot test was performed first to determine the stimulation threshold value that could be perceivable by the subjects. Two experiments including location and amplitude discrimination were then performed to determine the best stimulation parameters for pattern discrimination, and the average accurate recognition rates of 12 subjects were 99.3% and 97.7%, respectively. Based on the determined parameters, pattern discrimination experiments were performed to discriminate 12 patterns with different directional cueing, and experiments with 7 subjects achieved an accurate recognition rate of 95.4%.**

I. Introduction

Humans usually rely on the somatosensory feedback provided by muscle and skin receptors in the leg to control balance and movement [1]. Due to the amputation, however, an amputee has to rely on information which is conveyed through the prosthesis and detected via touch receptors along the socket-skin interface [2]. This altered sensory feedback results in poor balance and abnormal gait patterns compared to that of normal individuals [3]. Besides, the common skin irritation in the socket-skin areas attenuate the sensory feedback, and worsen the gait performance [4].

Along with the great advances in active lower-limb prostheses to restore the motor function of the amputees [5]–[8], increasing efforts are being made on sensory feedback to restore the perceptive function of the missing limb [9]–[13]. To provide sensory feedback, researchers need to map the locomotion information of the prosthetic limb to stimulation signals that can be perceived by muscle or skin receptors. According to the mapped feedback information, current sensory feedback studies can be classified into two categories: ankle-angle-based feedback, and foot-pressure-based feedback. As for the ankle-angle-based feedback, Chew *et al.* developed a vibrotactile display system to provide angle feedback to the amputee. Nine pancake motors were embedded into the socket to represent the ankle angle ranges from 0 to 90°. Location, amplitude, and gap modulation were used for haptic mapping, respectively. Experiments with three amputees being seated achieved an overall recognition rate of 85% [9], which was not high enough for practical application.

As for the foot-pressure-based feedback, Sabolich *et al.* presented a sensory feedback system that provides transcutaneous electrical neural stimulation to afferent sense organs located at the socket-skin interface. The stimulus magnitude was proportional to the pressure measured by force sensors under the prosthetic foot. Initial results showed that this system can restore a more symmetrical gait pattern [10]. Similarly, Fan *et al.* developed a wearable system to provide haptic feedback with pneumatically-controlled balloon actuators placed on the thigh. The system inputs discreet force levels from four force sensors mounted under the prosthetic foot and transmits the information into proportional discreet pressure levels to four corresponding balloon actuators [11]. Usability of this system was validated with six healthy subjects, and a pilot test was carried out with an amputee [12]. Different from the previous studies, Crea *et al.* presented a system to provide time-discrete gait information for lower-limb amputees. Three vibrators placed on the thigh were used to represent the gait phase transition between heel-strike, flat-foot, and toe-off. An experimental validation involving ten healthy volunteers proved the usability and effectiveness of the proposed system [13].

Although the ankle angle and foot pressure are important limb perceptions, they are not directly related to the dynamical stability of the amputees, and the stability improvements brought by these information feedback haven't been studied. Instead, Center of Pressure (CoP) under foot is the synthesis of foot contact area with the ground and foot pressure amplitude. It reflects ankle movement adjustments that change the center of mass (CoM) position and return the CoM back to a more stable position [14]. CoP follows a smooth progression in able-bodied gait, and its displacements in mediolateral (ML) and anterior-posterior (AP) directions have been used as stability indicators [15]–[17]. Our study aims at providing CoP feedback for transtibial amputees to improve their dynamic stability, and this paper is a preliminary exploration. In this paper, we classified the CoP displacements in AP and ML into different directional patterns, and expressed these patterns with four pancake vibrators placed around the thigh. The location and amplitude discrimination experiments were performed prior to the pattern discrimination experiments

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to determine the corresponding stimulation parameters, and these experiments with 7-12 able-bodied subjects achieved mean correct recognition rates of 99.3%, 97.7%, and 95.4%, respectively.

The rest of this paper is organized as follows. Section II introduces the composition of the sensory feedback system. Section III introduces the experimental methods including different discrimination sessions and the pattern programming. IV presents the experimental results of different discrimination sessions. We discuss and conclude in Section V and Section VI, respectively.

II. Sensory feedback system

The sensory feedback system mainly consists of four pancake vibrators, four drivers, and one control board. The four miniaturized vibrators each had a pancake shape with 12-*mm* diameter, 3.4-*mm* height, 1.7-*g* weight, and identical force amplitude. They were placed on the front, back, left, and right side of the subject's thigh with an elastic bandage, as shown in Fig. 1.

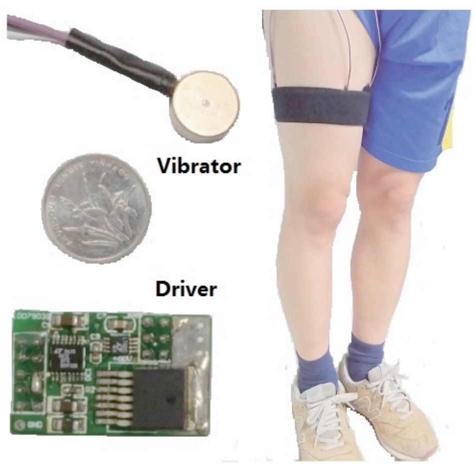

Fig. 1. The sensory feedback system (vibrator, driver) and the system wearing.

Four electronic drivers are designed to activate the vibrators. Each driver consists of an operational amplifier to modulate the signal amplitude and a transistor-based follower to increase the output current of the driver. The designed driver can output signals with the maximal voltage of 12V and maximal current of 500 mA.

The control board consists of a 32-bit microcontroller and four digital-analog converters (DAC) to generate different kinds driving signals such as sinusoidal as well as direct-current (DC) signals. The microcontroller was controlled by a Personal Computer through a RS232 serial interface, communicating with it through a custom communication protocol at the speed of 256000 bits per second.

III. Methods

During locomotion, the CoP moves in both AP and ML directions, and movements on these two directions happen simultaneously. To express the CoP effectively, we classified the CoP movements into different directional patterns, and map these patterns to different stimulations with the sensory feedback system. The location and amplitude discrimination experiments were performed prior to the pattern discrimination experiments to determine the corresponding stimulation parameters.

Customized program was designed for conducting the experiment. It consists of a controller program, written with assembly commands, for delivering tactile display and a graphical user interface (GUI), written in Matlab 2014a, for providing instructions to the subjects. The GUI provided the subjects with written instruction on the screen (for all three experiments), visual representations of stimuli, (for experiment one and three), and interactive learning interface (for experiment three; see below). All the behavioral data was automatically recorded and brief interviews were conducted after the experiments.

A. Pilot tests

The purpose of pilot tests is to choose appropriate stimulus amplitudes that are distinguishable at the skin locations we chose. Thus, we did not use psychophysical procedures to evaluate the JND (Just Noticeable Difference) and equal-sensation contour. Absolute threshold for tactile stimuli was measured at four vibrator locations with two stimulus durations each (150ms and 300ms). A classical 1-up 3-down staircase procedure was applied to the test [21]. Four vibrator locations were consecutively tested in a random order.

According to the test results, the average threshold for 150ms stimuli was 36.4±5% of full amplitude (FA) over all locations, and 27.3±4% FA for 300ms stimuli. No significant difference was found between locations. Eleven amplitude values were selected between absolute threshold and FA, and six amplitude values were chosen for the following experiment after a simple two alternatives forced choice discrimination test: for 150ms signal set, the amplitude values were 49.1% FA, 65.5% FA and 100% FA; for 300ms signal set, they were 36.4% FA, 54.5% FA and 100% FA. All the amplitude values had the same distance in log scale.

B. Experiment 1: location discrimination

Location discrimination is essential for haptic spatial and directional cueing [22]–[24]. This experiment was designed to evaluate location discrimination on the thigh.

1) Stimuli: Four vibrators were placed on the Front (Vibrator 1), Left (Vibrator 2), Right (Vibrator 3), Back (Vibrator 4) side of the right upper leg. A 300ms, 50% FA stimulation was applied to all locations in this experiment. We also provided visual cues during tactile stimulation. Four grey dots with text labels were displayed on the computer screen as visual representations of the vibrators. When the tactile stimulus was delivered to the thigh, the corresponding dot would change its color to green while others remained the same.

2) Subjects: Seven able-bodied subjects (4 males, 3 females) aged between 23 and 28 years old participated in the location experiment. All the subjects were graduate students in the Department of Psychology and College of Engineering at Peking University, and none of these participants had abnormalities of the tactile sensory system. We adjusted the elastic bandage according to the circumference of individual subjects to make it comfortable.

3) Procedure: In this experiment, subjects were asked to indicate which of the four vibrators had been activated. The experiment consists of a learning session, a reinforced learning session with visual feedback, and a test session without feedback.

In the first session, the subjects were familiarized with the stimulation delivered by each vibrator. Each stimulation was presented three times in a random order, and the dot representing the activated vibrator turned green for 0.2s as a visual notification. In the reinforced learning session, a red cross fixation was presented before each trial, and stimulation was presented at a random time between 0.5 and 0.8s after the fixation. Subjects were told to click the corresponded dot with a mouse. They were given the visual feedback of their performance: the chosen dot would turn green if the answer was correct, otherwise the dot corresponding to the correct stimulation would turn red for 0.3s. This session consisted of a nonspecific number of blocks depending on subjects' learning performance. In each block, there were 20 trials (4 locations with 5 repetitions). The session would complete if the subject reach 80% overall accuracy and 60% accuracy for each location. The test session followed after a short break. The four locations were presented ten times in a random order. The procedure was similar to the second session but no visual feedback was provided.

TABLE I
AMPLITUDE-DURATION COMBINATIONS

		Amplitude combinations		
		Low-Moderate	Low-High	Moderate-High
Duration	150ms	49.1%-65.5%	49.1%-100%	65.5%-100%
	300ms	36.4%-54.5%	36.4%-100%	54.5%-100%

C. Experiment 2: amplitude discrimination

The aim of this experiment was to evaluate amplitude discrimination of stimuli with different intensity (low, moderate and high). We investigate this discrimination within two duration conditions separately (150ms and 300ms). We are particularly interested in whether subjects can distinguish the two stimuli with similar intensities.

1) Stimuli: There were 6 amplitude-duration combinations in total, as shown in Table I. We asked subjects to judge which stimulus, within a comparison pair, was stronger.

2) Subjects: The same subjects from experiment one participated in this experiment. Three of the subjects participated this experiment first, while others participated in Experiment 1 first.

3) Procedure: Six duration-intensity combinations defined above were tested in this experiment, and we were interested in pair-wise comparisons between stimuli with similar intensities. The experiment followed a classical 2 alternatives forced choice paradigm, which has been widely used in intensity discrimination tasks. The experiment task was to judge which stimulus is stronger among the presented pair. A red-cross fixation was presented 0.5-0.8s before each trial. After that, a stimulation combination was presented. To avoid the masking effect [27], two stimulations were delivered in a random order with a 5s interval. Subjects

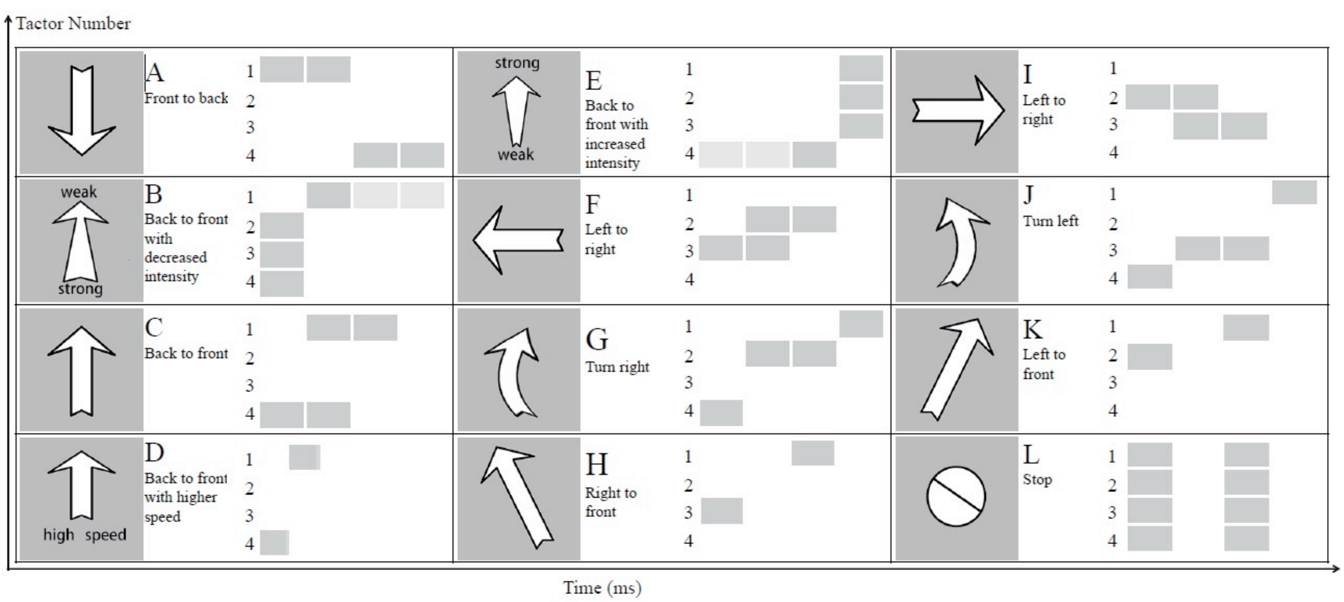

Fig. 2. Summary of tactile pattern used in Experiment 3. There are a total of 12 types of walking patterns to be shown to the subject. Each cell indicate one type of tactile pattern (right) and its corresponding visual feedback to the subject (left). The tactile pattern is a combination of vibrations of 1 4 vibrators. Each grey rectangle represents a 150ms vibration (except for pattern D which is 100ms). Light grey represents lower intensity at 49.1% FA and dark grey represents higher intensity at 100% FA. There is no lag between adjacent vibrations.

were asked to judge which stimulation (first or second) was perceived with higher intensity by clicking a virtual button on the screen. All the combinations were repeated ten times and all trials were randomized.

D. Experiment 3: pattern discrimination

The results of Experiment 1 and Experiment 2 provided a basis for our further investigation for designing more complex tactile patterns. In this experiment, we designed tactile signal patterns that are spatially and temporally congruent to the walking pattern. We then tested whether subjects can learn the association between tactile stimuli and their intended walking patterns within a short training period. Successful and fast learning of 12 associations will be an indicator of our method's validity.

1) Stimuli: We defined 12 possible patterns. Fig. 2 summarized these patterns with their vibrator programming, corresponding walking patterns, and their visual representations on the screen. For example, pattern C stands for a back to front motion. Vibrator 4 (on the back of thigh) and 1 (on the front of thigh) are activated successively with a duration of 300ms. Their duration overlaps for 150ms (stimulus onset asynchrony, SOA).

Both intensity, duration and location cues were used to enhance distinctiveness among all the patterns. pattern B, C, D, E were similar in location cue (back to front motion) but differed in intensities for each vibrator. Pattern J, G, K, H were in the same intensity for each vibrator, but vibrator 2 (Left) and vibrator 3 (Right) were enhanced in each pattern.

2) Subjects: Twelve able-bodied subjects (6 males and 6 females), included six subjects in the first two experiments, participated in the pattern recognition experiment. All the subjects were graduate student at Peking University, none of these participants had abnormalities of the tactile sensory system.

3) Procedure: The experiment followed similar procedures as in Experiment 1. At the beginning of the learning session, the meaning of 12 tactile patterns were explained to the subject, accompanied by presenting their corresponding graphics (Fig. 2). Then subjects familiarized themselves by sensing the tactile patterns with simultaneous presentation of their graphics. Each pattern were presented 3 times in a random order. The reinforced learning session was followed after a short break. In this session, subjects were exposed to a tactile stimulus and then were asked to choose the corresponding picture among all 12 possible pictures shown on the screen using a mouse. A green frame around the picture was shown for 0.2s to signify the correct reaction, and a red one signified an error. The trials were organized in blocks of 48 trials with each pattern repeated for 4 times in a random order. Subjects could only proceed to the next session if they achieved at least 80% overall accuracy and 50% accuracy for each pattern within a single block. Before the test session, subjects took a 2-min break to prevent fatigue. During the test session, all the patterns were repeated ten times and no error feedback was given.

A brief interview was conducted after the experiment. Subjects were asked to describe the sensation of each pattern over the following questions: *'Can you clearly identify the series order and total vibrator number presented in this pattern?' 'Can this pattern be intuitively associated with the corresponded picture?'*

IV. Experimental Results

A. Location discrimination

Locating a single stimulation around the circumference of upper leg proved to be easy, with an overall response rate of 99.3% correct. Of the four vibrators, Vibrators 2 (Left Side) and 4 (Back) were identified with 100% accuracy and vibrators 1 (Front) and 3 (Right Side) were mislocalized only once. A repeated measures analysis of variance (ANOVA) showed there was no significant difference between four locations. A ceiling effect was clearly evident in the result from this experiment. The result indicated vibrators mounted around upper leg were able to provide location information with a single presentation of tactile stimulation, which was consistent with previous studies on other body sites as torso [23], upper arm [25] and abdomen [26].

B. Amplitude-duration discrimination

Fig. 3 shows the average accuracy rate for different condition. The accuracy rate was above 92.5% for all conditions and 97.7% overall. A 3-way repeated measures ANOVA indicated there was no significant interaction between durations and intensity combinations ($F(2,12)=1.322$, $p=0.303$), nor were there any significant interactions between vibrator locations and other two variables. There was no significant main effect of duration levels ($F(1,6)= 3.36$, $P=0.116$) and vibrator locations ($F(3,18)=0.452$, $p=0.719$). However, different intensity combinations were statistically different ($F(2,12)=6.072$, $p=0.015$). Pairwise comparisons (Bonferroni) indicated that low-moderate amplitude combination was associated with more errors than the low-high combinations ($p=0.034$), and there were no other significant differences between conditions.

This result is consistent with our hypothesis. Although reduction in duration would decrease sensation, the 3 intensity levels we tested could still be clearly distinguished.

The performance difference between low-moderate was unexpected, but a overall correct percentage of 96.4% for all the low-moderate combinations was acceptable for intensity discrimination tasks.

C. Pattern discrimination

On average, subjects familiarize themselves for about 2 minutes only. For the formal, reinforced learning session, all the subjects could reach the criterion within two blocks (7 subjects with one block and 5 with two blocks). The averaged confusion matrix over all subjects during the test session was shown (Table II). Letters on the horizontal and vertical axes denoted the signal patterns. The mean correct percentage for all patterns was 95.4%. This result is consistent with our first hypothesis. It appears thatsignal

TABLE II
CONFUSION MATRIX OF THE PATTERN RECOGNITION RESULTS.

Confusion		Subject response											
		A	B	C	D	E	F	G	H	I	J	K	L
Actual pattern	A	**94.8%**	4.2%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	B	0.0%	**93.8%**	4.2%	0.0%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	C	0.0%	2.1%	**92.7%**	1.0%	4.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	D	1.0%	0.0%	2.1%	**94.8%**	0.0%	0.0%	0.0%	2.1%	0.0%	0.0%	0.0%	0.0%
	E	0.0%	4.2%	2.1%	0.0%	**91.7%**	0.0%	1.0%	1.0%	0.0%	0.0%	0.0%	0.0%
	F	1.0%	0.0%	1.0%	0.0%	0.0%	**96.9%**	0.0%	0.0%	2.1%	0.0%	0.0%	0.0%
	G	0.0%	0.0%	1.0%	0.0%	1.0%	0.0%	**97.9%**	0.0%	0.0%	1.0%	0.0%	0.0%
	H	1.0%	0.0%	1.0%	0.0%	0.0%	3.1%	0.0%	**95.8%**	0.0%	0.0%	0.0%	0.0%
	I	0.0%	0.0%	1.0%	0.0%	1.0%	3.1%	0.0%	0.0%	**91.7%**	0.0%	4.2%	0.0%
	J	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	2.1%	0.0%	**97.9%**	0.0%	0.0%
	K	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.0%	**99.0%**	0.0%
	L	0.0%	2.1%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**97.9%**

arrays with 50% overlapped vibration could provide clear spatial-temporal cues. Interestingly, some subjects (5 of 12) reported a sensation of continuous motion or the ”funneling illusion” [20] after the experiment, the effect of this illusion on pattern recognition will be studied in our further research.

Of the twelve patterns, pattern G, J, k and L resulted in better performance, with a accuracy above 97.9%, and patterns B, C, E, I showed slightly lower accuracy ranging from 91.7% to 93.8%. It showed patterns provided more location cues could be identified easier, and an enhanced vibration of key location features (Pattern G and J) could increase the distinctiveness between similar patterns.

Among all patterns, pattern B, C and E were the most confused signal set. We found that all of them were similar in terms of spatial and temporal profiles but varied in intensity and duration of specific vibrators. However, a repeated measures ANOVA revealed that there was no significant difference in the recognition rates across patterns. Our results indicate that location might be a more effective cue for pattern identification. Our results also suggest that intensity-duration combination can provide subjects valid cues for complex feedback which subjects can learn their meanings with minimal practice.

Six of our twelve subjects participated in the first two experiments. We then tested whether they have an advantage over the other six subjects owing to their extra exposure

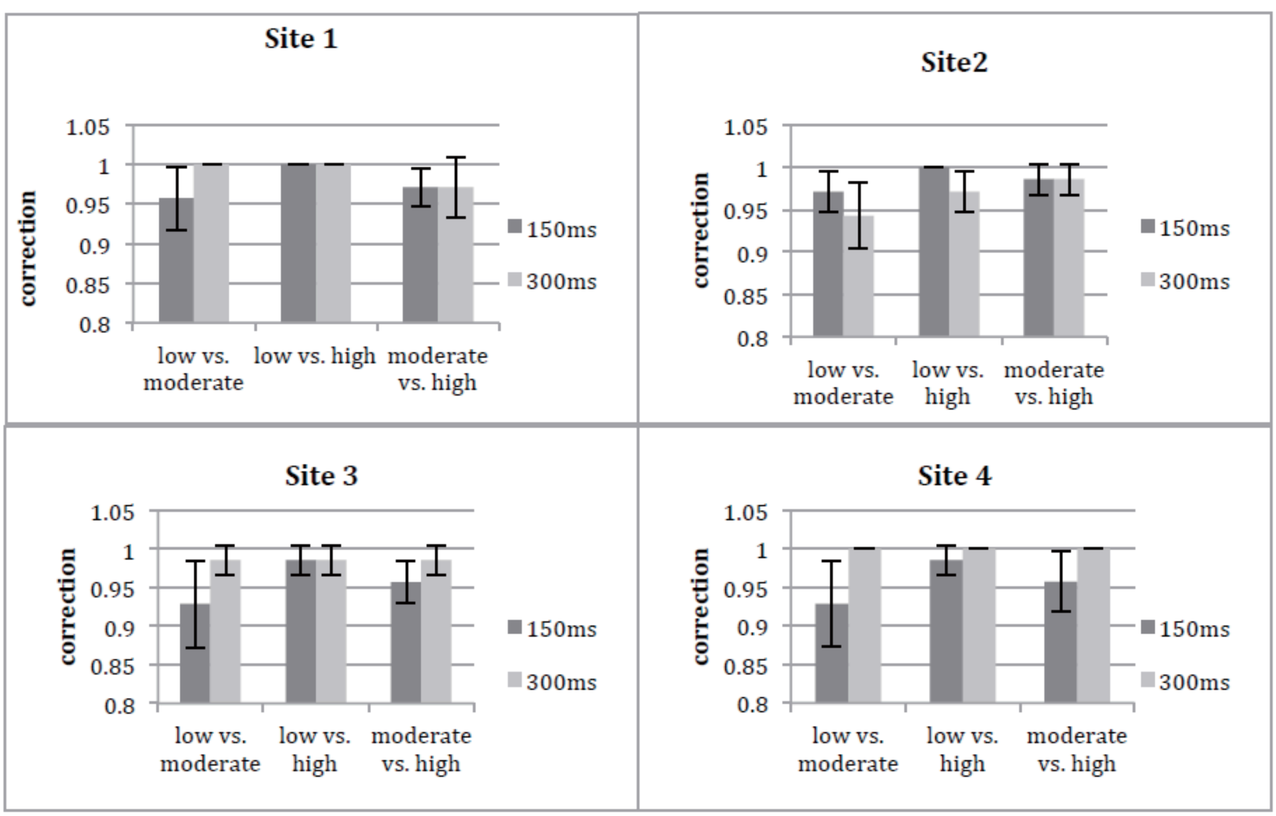

Fig. 3. Experimental results of the amplitude-duration discrimination.

to location and amplitude-duration discrimination task. It turned out that there was no significant difference between new subjects and those who had participated in all three experiments ($F(1,10)=1.38$, $p=0.268$). New subjects achieved above 94.6% overall accuracy while old subjects achieve 96.2%.

V. Discussion

Compared with previous studies of similar vibrators, our results indicated that the design of our tactile pattern set was highly intuitive. With only minimal training, mapping between the tactile patterns and its visual representation could be effectively learned. Namely, to the best of our knowledge, the average duration of signal patterns (450ms) were shorter than most studies and the variation in signal set (twelve patterns) were larger than common pattern recognition tasks ([18], [19], [23]). Besides, the designed locomotion pattern included the intensity change as well as the directional cueing, and can be used to either represent the foot pressure as the previous study did, or represent the locomotion of CoP.

The preliminary exploration didn't provide feedback of the complete CoP trajectory during one gait cycle, but the designed patterns had included most directional displacements of CoP, and our future work will extend the feedback pattern to the complete CoP trajectory. Besides, experiments were performed with the able-bodied subjects standing still instead of walking. But as the vibrators used in the experiments are of small size and can be easily embedded into the socket of amputees, performing experiment with the amputees during locomotion is feasible in the future.

VI. Conclusion

This paper presents the design and evaluation of a sensory feedback system that can provide CoP feedback for transtibial amputees. Three discrimination experiments including location, amplitude, and pattern discrimination were performed to evaluate the effectiveness of the proposed system. Experiments with 7-12 able-bodied subjects achieved average accurate recognition rate of 99.3%, 97.7%, and 95.4%, respectively. Future work includes mapping the complete CoP trajectory, embedding the vibrators into the socket, and performing experiments with the amputees during locomotion.

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