Psychophysical Evaluation of A Mechanotactile Haptic Feedback Device

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***Abstract*—Sensory feedback enhances the intuitive operation of upper limb prostheses. However, most modern commercial prosthetic devices lack sensory feedback mechanisms due to the difficulty of integration and added complexity. Mechanotactile haptic feedback provides a non-invasive and low-cost alternative to traditional electromechanical haptic feedback modalities. While mechanotactile haptic feedback systems have been studied for their mechanical behaviour, their practical integration in prosthetic devices and associated human factors still remain to be investigated. Therefore, in this paper, we perform a psychophysics study to investigate the perceptual thresholds associated with a mechanotactile feedback system. We use a mechanotactile sensory system and feedback device to provide force feedback on the forearm of healthy volunteers. We systematically assess the optimal placement of the feedback devices and the minimum perceptible forces at each position. We found that the minimum perceptible force that a user can perceive range lies in the range of 0.39 N to 1.36 N at various points on the forearm. The distal forearm was found to have higher perception sensitivity compared to the proximal forearm. Our results shed light on the perception thresholds achievable with mechanotactile haptic elements. Results also indicate that proper placement and site selection of the mechanotactile feedback elements are crucial to enhance force perception accuracy.**

***Index Terms*—Mechano-tactile feedback, psychophysical measurement**

I. Introduction

The human hand is one of the most complex structures in nature, showcasing remarkable flexibility, dexterity, and sensory capabilities. It operates within a closed-loop sensory feedback system that is essential for maintaining precise control over its movements and interactions with the environment [1]. The sense of touch in the human hand is achieved by different types of mechanoreceptors present in the skin [2]. However, individuals with upper-extremity amputation who utilize upper limb prosthetic devices lack the ability to perceive sensory information related to touch. Therefore, crucial information required to execute simple tasks, grasping and holding objects without slipping or crushing them often exhibits poor force modulation and high failure rates [3], [4]. As a result, a vast majority of prosthetic users end up abandoning their devices and often cite the lack of sensory feedback as a key determinant [5], [6].

Several techniques have been adopted to sense distal tactile interactions and to provide haptic feedback to users to restore the sense of touch in prosthetic devices [7]. Several groups have reported resistive, capacitive and optical systems to sense the interaction forces on the fingertips of prosthetic devices and robotic grippers. BioTac, employed a conductive fluid enclosed in an elastomeric chamber to measure changes in electrical impedance due to tactile interactions [8].

On the other hand, sensory feedback can also be delivered through multiple modalities, including vibration, compressive and shear forces (skin stretch) and electrotactile feedback [9]. Invasive methods involving the implantation of neural interfaces have been successful in eliciting illusory sensory percepts in phantom limbs, providing highly realistic feedback to individuals with amputation [10]. However, the high risk of surgery and coupled with poor long-term stability of neural interfaces, has led to limited adoption [11].

Shi et al. developed a purely mechanical haptic feedback and sensing system [12], [13]. Briefly, the system utilizes a fluid-filled mechanotactile system, which has three main components: a fingertip sensor, an actuator, and a tube. This system senses the force on the fingertip sensor and transfers the force through the fluid to the actuator to produce modality-matched tactile stimuli. Unlike traditional approaches, the sensing element and the haptic feedback element are purely mechanical in nature, obviating the need for electrical connections or signal processing. Therefore, mechanotactile haptic systems are uniquely suited for integration into passive prosthetic devices and devices with limited electrical and electronic hardware resources. However, a systematic psychophysical measurement is required to understand the relationship between sensory input and perceived stimuli, i.e. the perception thresholds for mechanotactile haptic systems [14], [15].

Therefore, in this paper, we perform a thorough psychophysical evaluation of the mechanotactile systems reported by Shi et. al [12], [13]. First, we conducted an experiment to identify

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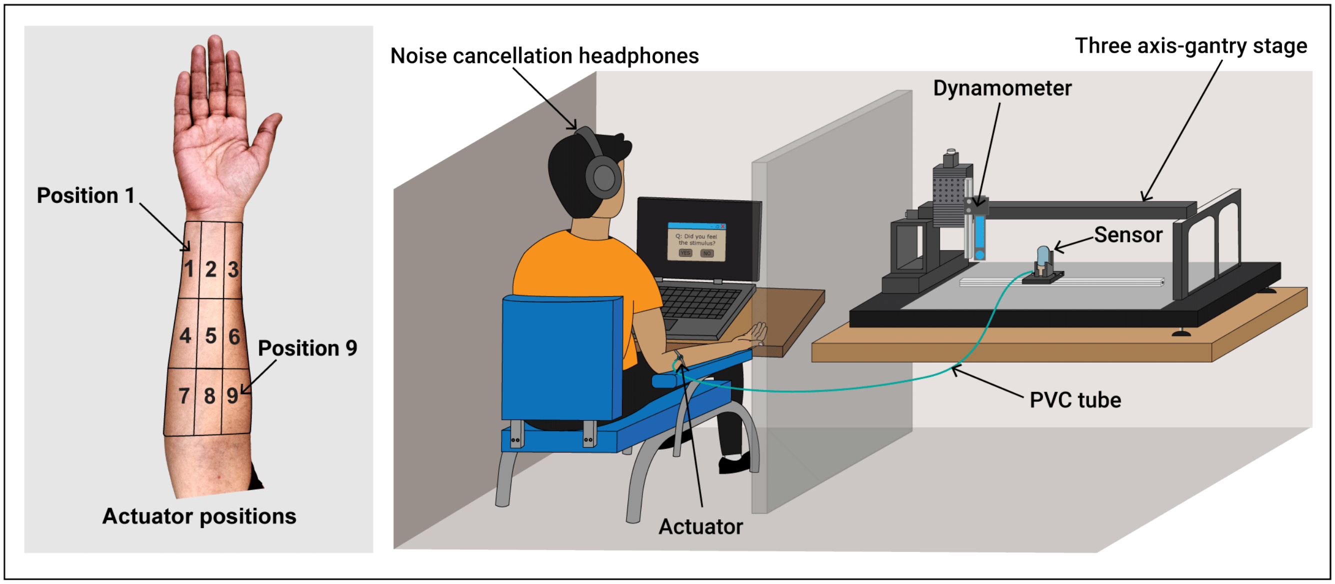

Fig. 1. The experimental setup for the psychophysical evaluation of mechano-tactile haptic device. The feedback actuator was placed on the Participant's forearm, and the fingertip sensor was fixed on the gantry. A curtain was placed between the gantry setup and the subject, and noise-cancellation headphones were used to avoid visual and audio bias.

the most suitable position for placing the mechanotactile actuator on the forearm. In a follow-up experiment we also assess the smallest perceptible force.

II. Methods

A. Participants

We recruited six non-disabled participants for this study. The mean age of all participants was 27±6. All the participants self-reported being right-hand dominant with no history of injury to the dominant arm. All procedures reported here were approved by the Institute's ethics committee (IEC) at the Indian Institute of Technology, Delhi, New Delhi. Participants provided written consent prior to participating in the study.

B. Experimental setup

The main components of the experimental setup include a three-axis-gantry stage (by Holmarc), dynamometer (Go Direct by Vernier), mechanotactile haptic system [12], Laptop with intel i7 processor 32 GB RAM Windows 11 64-bit, one external monitor, noise cancellation headphones. The mechanotactile sensing system was filled with water and assembled. The fingertip sensor was fixed on the gantry platform with the help of the custom-designed 3D printed holder, as shown in Fig. 2. The use of the gantry in the experiment ensures precise control and repeatably for every trial and across the subjects. The dynamometer was attached to the moving arm of the gantry such that it could be pressed against the sensing element with a pre-calibrated force. The actuator of the mechanotactile system was placed on the forearm of the participant at various locations (discussed in the next section).The outer diameter of the actuator is 20 mm, and the membrane diameter is 12 mm, the thickness of the actuator is 8mm. From the palmer side of the fingertip sensor, the width of the sensor is around 12mm, height is around 32 mm, and the thickness of the sensor is around 20 to 25 mm. The sensor and actuator are connected via a water-filled 3mm diameter PVC pipe, which transfers the force. The three-axis-gantry stage and dynamometer are connected to the Laptop using USB. The experiment was run on a custom-developed MATLAB script (The MathWorks, Inc., Natick, MA).

C. Experiment Procedure

Experiment one was conducted to obtain the minimum perceptible forces at each position and identify the most suitable position for placing the mechanotactile actuator on the forearm. One mechanotactile actuator element is placed in nine different positions on the glabrous side of the forearm (palmar aspect). The feedback actuators were placed on the forearm by measuring the length of the forearm and dividing it into three equal portions from distal to proximal with a 2 cm margin from wrist and elbow joints.

A noise-cancellation headphones (Bose Quiet Comfort 15, Bose Corporation, USA) with brown noise sound was used to avoid any external disturbance. Additionally, an opaque curtain was used between the subject and the gantry to remove any effect of direct visual feedback.

The experiment sequence used in this experiment was as follows: the actuator was placed at one of the positions on the forearm and secured using a velcro strap. The random sequence of the six different force levels (0, 0.4, 1, 1.2, 2, 2.2) N, including sham, are presented one by one. All these forces are pre-measured by indentation of the fingertip sensors from 1 mm to 3.5 mm displacement with a difference of 0.5 mm by moving the dynamometer with the speed of 16 mm/s. The range of displacement for this experiment was restricted to

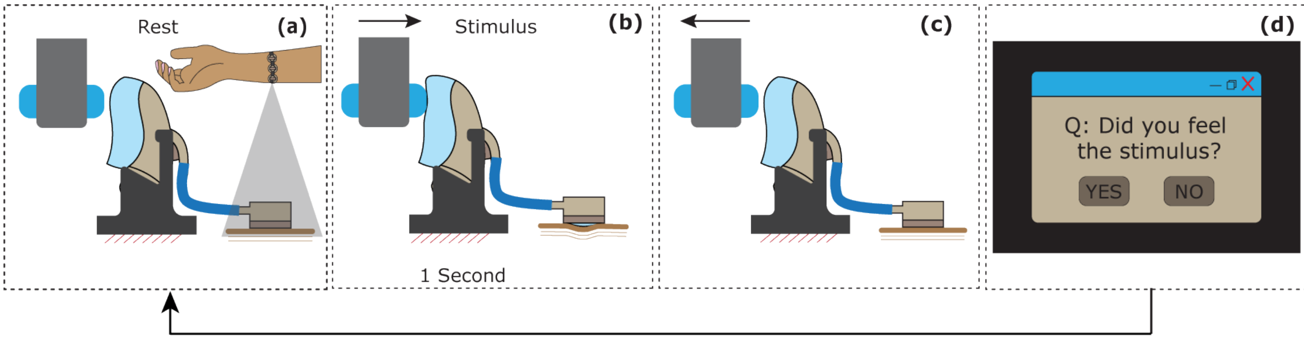

Fig. 2. Experiment sequence. (a) The dynamometer is in rest condition (no tactile feedback on the forearm). (b) The dynamometer moves and applies force on the fingertip sensor, holding it for one second. (c) The dynamometer returns to its resting condition. (d) A pop-up window appears on the screen with the question, "Did you feel the stimulus? Yes/ No".

3.5 mm to prevent the fingertip sensor from any physical damage.

As shown in Fig. 2(a), the dynamometer is on rest condition (no stimulus is applied); after 2 s, the dynamometer is translated by the gantry and exerted the pre-determined force on the actuator and was held for a period of 1 s as shown in Fig. 2(b). The gantry was then moved back to its original position to release the force stimulus, as shown in Fig. 1(c). Immediately following the release of the stimulus, the MATLAB control interface was programmed to pose the following question to the user: "Did you feel the stimulus?". The user was allowed to verbally respond - 'Yes' or 'No', as shown in Fig. 2 (d). the verbal response was recorded by the experimenter. After entering the response, the next force stimulus in the random sequence was presented, and the process was repeated till all force values had been presented. A total of ten trials were conducted at each position on the forearm.

The experiment two is the follow-up experiment of the first study. This study only includes the proximal position on the forearm. The mechanotectile actuator was placed in the best suitable position that was found in experiment one. The criteria for choosing the most suitable position on the proximal side was based on the minimum absolute force value on the forearm out of three positions from medial to lateral. In this study, another force value, 1.6 N, was introduced between 1.2 N and 2 N to improve the resolution of the psychometric curve above the 90% of the proportion of perceived stimuli. The experiment setup of this experiment is shown in Fig. 1. The noise-cancellation headphones and the opaque curtain were used the same as the previous experiment, as shown in Fig. 1. The sequence used in this experiment was as follows: the mechanotactile actuator was placed on position 8 (between medial and lateral on the proximal side) shown in the Fig. 1. The random sequence of the six different force levels (0, 0.4, 1, 1.2, 1.6, 2) N, including sham, are presented one by one. As illustrated in Fig. 2 (a), the dynamometer is on rest condition (no stimulus is applied); after 2 s, the dynamometer is translated by the gantry and exerted the pre-determined force on the actuator and was held for a period of 1 s as shown in Fig. 2(b). The gantry was then moved back to its original position to release the force stimulus, as shown in Fig. 1(c). Immediately following the release of the stimulus, the MATLAB control interface was programmed to pose the following question to the user: "Did you feel the stimulus?". The user was allowed to verbally respond - 'Yes' or 'No', as shown in Fig. 2 (d). the verbal response was recorded by the experimenter. After entering the response, the next force stimulus in the random sequence was presented, and the process was repeated till all force values had been presented. A total of ten trials were conducted on signal position.

III. Result

The recorded response data for all the positions were processed through a custom MATLAB script by taking the mean and standard deviation of all ten trials for each force level. The sigmoidal model with the logistic fit function was used to fit the psychometric curve. The psychometric curve was generated with 95% confidence interval for each position. The logistic fit function is mentioned in the Equation (1) [16].

$$y = \frac{A_1 - A_2}{1 + \left(\frac{x}{x_0}\right)^p} + A_2 \tag{1}$$

Where y is the proportion of perceived stimuli, x is the force in Newton (N) , A_1 and A_2 represent the initial and final values of the proportion of perceived stimuli, x_o is the centre or midpoint between minimum and maximum values of response, and p is the power it determines slope of the curve. The absolute force thresholds were calculated by taking the force value at 50% of the proportion of perceived stimuli. The equation for calculating absolute force thresholds is given in Eq (2) by rearranging Eq (1)

$$x = x_0 \cdot \left[\frac{A_1 - A_2}{y - A_2} - 1\right]^{1/p} \tag{2}$$

where: $y = (A_1 + A_2)/2$ for 50% of the proportion of perceived stimuli.

The absolute force distribution for all nine positions on the forearm is shown in Fig. 3. The results show that the minimum and maximum absolute force thresholds on the forearm are 0.39 N (0.14 N, 0.43 N: 95% CI) and 1.36 N (0.99 N, 1.46 N: 95% CI) at positions 2 and 5 respectively (see Fig. 1).

However, considering our target population of individuals with amputation, distal placement of actuators may not be possible depending on the length of the residuum. At the proximal end, position 8, demonstrated the lowest absolute force perception threshold of 0.51 N (0.43 N, 0.63 N: 95% CI). Therefore, we conducted experiment 2, at position 8, by repeating the psychophysical evaluation with 5 additional participants.

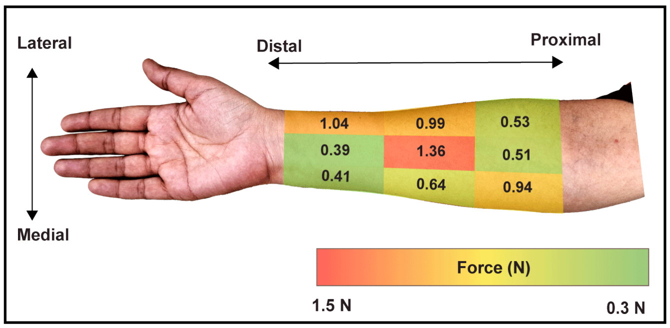

Fig. 3. Absolute force discrimination threshold obtained with the mechanotactile haptic feedback unit across the volar aspect of the forearm .

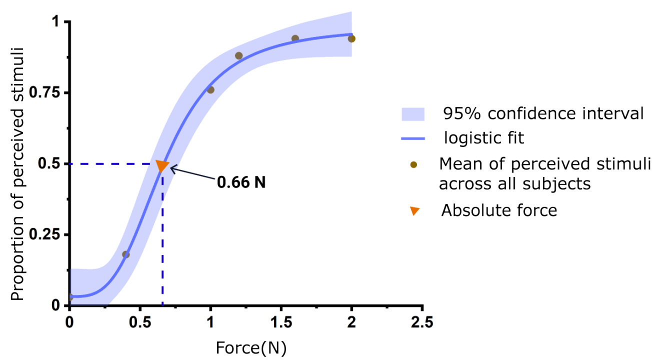

Fig. 4. Psychometric curve showing responses to the absolute force discrimination task of Experiment 2.

For Experiment 2, all five subject responses were processed through a custom MATLAB script, and the mean and standard deviation across all ten trials for each subject were calculated individually. A psychometric curve was plotted using the sigmoidal model with a logistic fit function as mentioned in Eq 1. The psychometric curve with 95% of CI for position eight is shown in Fig. 4. The absolute force threshold was calculated by taking the force at 50% of the proportion of perceived stimuli. As mentioned in the Fig. 4 the calculated absolute force threshold is 0.66 N (0.56 N, 0.77 N: 95% CI).

IV. Discussion and Future Work

In this study, we conducted two experiments. In the first experiment, a pilot study was conducted to determine the distribution of the absolute force perception threshold of the mechanotactile haptic unit for the volar aspect of the forearm. Our findings indicate that while the distal regions of the forearm exhibit perception thresholds as low as 0.39 N, the proximal portion of the forearm may be more appropriate for individuals with an upper limb amputation. In the follow-up experiment, we also investigated the minimum perceptible force values that the user could perceive at a single position with five subjects. For experiment 2, we found that at the proximal forearm, the minimum force perceptible was approximately 0.66 N.

This study has a few critical limitations. The study was conducted with a sample size of six, one for the initial and five for the follow-up experiment. Further, we used only one mechanotactile device for this study, requiring repositioning of the feedback actuator at each step possibly leading to minor errors in placement over repeated trials. In future work, more mechanotactile devices will be used to reduce the duration of the experiment. In a follow-up study, we also intend to determine the discriminability of two closely matched forces exerted through the mechanotactile units. This experiment will further shed light on the minimum achievable and perceptible force resolution with the mechanotactile haptic units.

V. Conclusion

In this paper, we performed a psychophysical evaluation to investigate the relationship between physical force and perceived force in mechanotactile haptic devices. First, we placed feedback actuators at various positions along the forearm and applied different force stimuli randomly. Based on the participants' responses, we determined the perceptible minimum force values at each position and found that the distal sensitivity was as low as 0.39 N while the perceptibility was 0.51 N at the proximal forearm.

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