HAPTIC FEEDBACK FOR REHABILITATION SYSTEMS

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Acknowledgements

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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To the dark nights which stayed with me

Abstract

The human sense of touch is an integral part of daily life; the loss of which puts the person at a severe disadvantage. Without this, tasks of grasping and manipulation of objects are next to impossible because feedback of force is a key requirement for them. While most of the systems give contact point or complete grasping force feedback, for precision grasping and other physical interactions finger awareness and force feedback from independent fingers is essential. In this study a wearable vibrotactile haptic feedback (Vi-HaB) system is designed to give individual finger awareness and multiple levels of force feedback from each fingertip for upper limb rehabilitation and teleoperation systems. The system provides simultaneous force feedback from multiple fingers/complete grasping force feedback as well. For testing the system accuracy, classical psychophysical methods were used on a group of 28 voluntary disabled subjects, out of which 14 were able bodied and 14 were disabled. The tests were conducted in both, ideal and real-world conditions i.e. without and with distractions and accuracies were calculated accordingly. A p-test was also conducted to observe significance between the data samples of with and without distraction datasets. The system performed with an overall accuracy of 78.97% with able bodies subjects and 82.04% with disabled subjects which are well above the min. performance measure of 60%. Vi-HaB is standalone system and can be mounted on any upper limb rehabilitation (upper limb prosthesis, exoskeleton) and teleoperation system for finger awareness and force feedback.

Key Words: *Haptic, Wearable, Vibrotactile, Force feedback, Rehabilitation,*

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CHAPTER 1: INTRODUCTION

1.1 Background

The importance of haptic force feedback in rehabilitation systems has been universally accepted and acknowledged [1] [2]. It has been proven to reduce their rejection ratio [3] [4] and increase the success rate in grasping and manipulation tasks [5]. It also results in alleviating both cognitive and muscular strain and induces a sense of embodiment [6] [7]. A lot of work is being done to replicate this uncanny, bio-inspired, trait for disable people using various techniques which are broadly classified as

1. Invasive
2. Non-invasive.

While reviewing both techniques in detail, both Antfolk et al. [8] and Li et al. [9] spoke in favour of non-invasive methods, arguing that invasive stimulation suffers from risks of infection and rejection, poor knowledge of neural decoding, technical issues of surgery, electrode replacement, and so on. Thus, non-invasive methods found way in most of the applications globally.

One of the oldest non-invasive techniques to be employed is the modality matched, mechanotactile feedback but with shifting trends Richard et al. [10], Antfolk et al. [8] and Li et al. [9] argued that to provide force feedback without sacrificing freedom of motion, the haptic interfaces have to be portable, light and prevent user fatigue. This sent mechanotactile methods in background due to their relatively large size, weight and high energy consumption, [8] [9] and sensory substitution methods came forward.

Sensory substitution revolutionized the field of wearable haptics with two key non-invasive techniques: electrotactile and vibrotactile feedback. Between these two, although electrotactile stimulation has the advantage of smaller size and relatively lower power consumption but small electrodes result in certain unexpected sensations such as burning pain; to counter which larger electrodes need to be used. Another drawback is its interference with EMG and EEG signals [8] [9] due to which vibrotactile stimulation, being free of the said issues, finds precedence in most applications.

Other reasons of the wide use of vibrotactile techniques are the ease of availability and

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integration with systems. Their light weight has opened new doors for wearable haptic devices [11] [12]. They are easily scalable; thus, are capable of displaying potentially larger amounts of data as compared to mechanical systems. [13] [8] [9] This scalability also results in the cost-effectiveness of the overall system [14]. Vibrotactile feedback is being used, both partially [15] [16] and independently [17] [18], in haptic systems as a force feedback channel.

Without haptic feedback, executing tasks involving physical interaction with objects, specially of grasping and manipulation, are next to impossible [1]. It is argued that not just the overall grasping force but without awareness of individual fingers and independent force feedback from each, dexterity and precision in grasping cannot be achieved [19] [20]. Thus, it is imperative for the disabled person to have an awareness of each finger independently and then of the forces being applied from each [21] [22].

For individual finger awareness/stimuli localization, most of the existing systems utilize the phantom hand map as target points to deliver sensory feedback [23] [24] [25] [26] regardless of the fact that substantial number of amputees and all congenital amputees lack phantom hand map thus leaving it as a feedback path with a dead end [27]. To work around this limitation different studies, using electrotactile [28] [29], vibrotactile and mechanotactile stimuli [28], have shown with promising results that predefined areas on the skin can be learned to be associated with predefined stimulation areas.

In a recent, first of its kind study [30], this concept was explored by associating predefined locations on the forearm with specific fingers using mechanotactile stimuli. Although the concept was verified but one major disadvantage of the system was that it was bulky owing to the five servo motors and thus is not a wearable system. The authors also declared mechanical noise due to servo motors as another limitation which may have negatively impacted the learning process. Moreover, the system was only tested on able-bodies subjects hence there is no insight as to how it would perform with amputees and in case of anything more than a trans-radial amputation, the system's response is undefined because it was only tested on the forearm.

So far, in light of the existing literature, no wearable system for providing finger awareness to amputees lacking phantom hand map is available. Thus, in this study we work along the lines of the above concept and associate fingers to predefined locations on the upper arm using vibrotactile stimulations.

In terms of force feedback, in recent years a lot of work has been done on force feedback from

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upper limb prosthesis using vibrotactile stimulation [31] [32]. Most of the systems have used either one [33] [34] [35] or two [36] [37] vibrotactile elements along with a single force sensor to convey complete grasping force and make or break contact information [38]. In case of single inducer, variation in frequency and amplitude represented different levels of force while with multiple inducers, each element represented a respective force level e.g. low and high. As the need for finer force level distinction increased, the number of vibrotactile elements was also seen rising from 3 [39] [40] to 8 [41] to an extent of 12 [42] in some cases. But since the target was to display complete grasping force so the number of force sensing element remained at a constant of one.

As seen from the existing literature review, studies have focused mostly on conveying complete grasping force feedback. In cases where the purpose is not to grasp the object but to use individual fingers, such feedback systems fail the user [43] [44].

This study focuses on the field of teleoperation as well. Teleoperation is the remote controlling of robotic system. In telerobotic, various systems have been developed in an effort to convey force feedback information. Most of the current systems are utilizing mechanical inducers such as servo-powered joysticks as feedback to the operator. One such commercial product is the “Phantom Omni /3D touch” which is widely used in various researches. But these systems pose certain disadvantages as well i.e. being bulky and costly. Also, only a limited number of tactile cues can be conveyed through them. Most of the vibro-haptic system in telerobotic, deliver feedback on the user’s palm. This limits the use of systems to only teleoperation applications and they cannot be utilized in rehabilitation systems where the user has some sort of nerve damage of hand or complete amputation.

1.2 Scope

This study focuses on development and testing a wearable vibrotactile haptic feedback (Vi-HaB) system, which provides individual finger awareness and multiple levels of force feedback from individual fingers for upper limb rehabilitation and teleoperation systems.

Five force sensitive resistors FSRs, are mounted on a plastic, dummy hand; one FSR on each fingertip. This is to test the static interaction of the system for tactile sensory evaluation. Force feedback from these sensors is conveyed to the user through five vibrotactile motors within the wearable Vi-HaB band, thus establishing a one to one mapping between the slave and master

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sides. This one to one mapping also enables the system to generate an awareness of the individual fingers thus making the disable person identify and differentiate between the respective (thumb, index, middle, ring and little) fingers on which forces are being applied. As each FSR – motor pair operate independently thus multiple stimulations can also be processed thus the system can provide multiple forces simultaneously and complete grasping force as well.

In short, Vi-HaB combines three types of haptic information; individual finger awareness, force level detection at each finger and simultaneous force level detection, all in a single system. The static system is tested using tactile sensory evaluators to check whether the user is able to process and understand the provided haptic feedback information using the wearable band. The accuracy is calculated by conducting activities based on classical psychophysical methods on a group of 28 nsubjects. The results are compared with predefined performance measures. A Wilcoxon signed rank test/ p-test is also conducted using MATLAB on the data samples.

The developed system is a wearable, low power consuming system which is free of mechanical noise, does not interfere with EMG and EEG signals and is independent of phantom hand map limitations. It is standalone system and can be mounted on any upper limb rehabilitation (upper limb prosthesis, therapeutic exoskeletons) system and teleoperation systems for finger awareness and force feedback. It can also be used for virtual reality applications.

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CHAPTER 2: SYSTEM DETAILS AND DEVELOPMENT

2.1 Development of Haptic Feedback System

The Vi-HaB system is developed to conveys force level information along with awareness of the finger they are being applied to, when static interaction takes places between the FSRs, on fingertips of a plastic hand, and tactile sensory evaluators. The system runs at an input power of 5V and has three distinct units as shown in Fig. 1

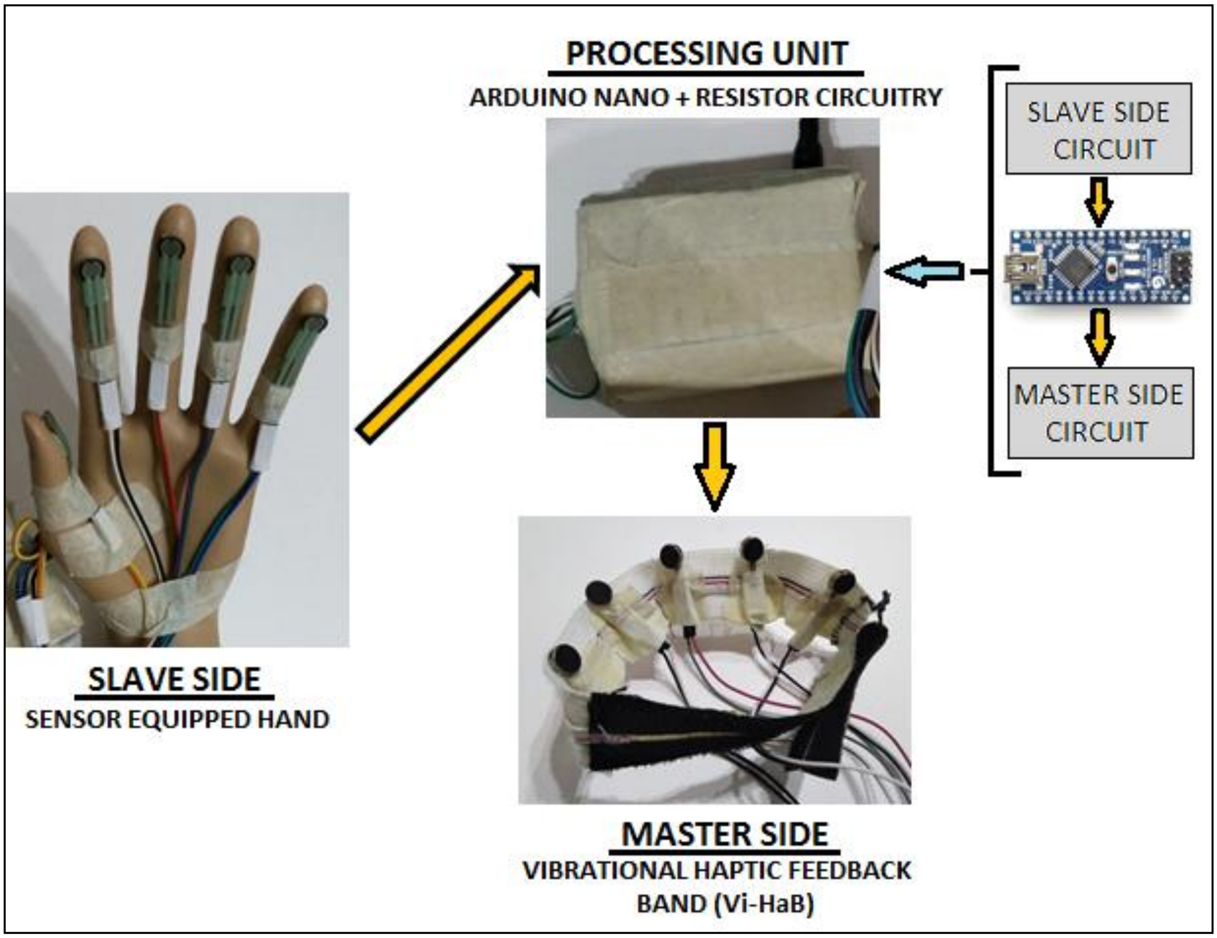

Figure 1 System Block Diagram

1. Slave side.
2. Processing unit.
3. Master side.

The static slave side serves as a mount for the force sensors. Using different tactile sensory

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evaluators, static interaction is generated which results in data output from the sensors. The data from these sensors is fed to a processing unit where it is converted into the respective force levels. These levels are mapped one on one, through the processor, to the vibrotactile haptic feedback band on the master side. The wearable band serves to generate the cutaneous signals as feedback from the sensors. Multiple vibrotactile motors are embedded within the band for this purpose where each motor represents one finger and force levels are discriminated by variations in frequency and amplitude of vibrations.

The details of these three units are given in following subsections.

2.1.1 Slave Side

This side has five force sensitive resistors (FSRs) which are a link between the master side and the environment. These sensors are mounted on a plastic dummy hand; one sensor on each fingertip for testing static interactions and generation of force levels.

The FSRs used here are "Force Sensitive Resistors [45] – Small (SEN-09673 RoHS)" from Sparkfun [46] and were selected while keeping in view some key features. Each sensor has a 4mm (0.16 in.) diameter active sensing area/spatial resolution. According to Li et al. [9] for tactile elements, a spatial resolution of 5-40mm could be satisfactory. What we have here is better than satisfactory.

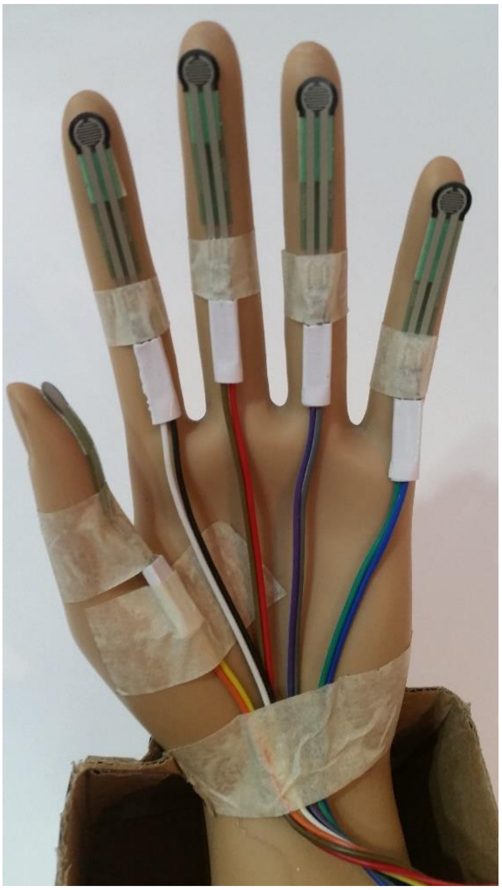

Figure 2 Slave Side

Li et al. also states that the force sensitivity should be within a range of 0.3 to 10 Newtons. Moreover, in another review article, Prachi Patel [47] states that according to the Revolutionizing Prosthetics Program (RPP), funded by DARPA, a bionic hand needs to feel a minimum of 0.1 newtons of force over a fingertip. The actuation force of the FSRs used here is 0.1N with a sensitivity range of 0.1 to 10 ± 2% N, thus the rage of these sensors is meeting

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international standards.

The sensors are configured in a directly proportional configuration where the output voltage increases with increase in the applied force [48]. The output voltages of sensors are fed, through a supporting circuitry, to a microcontroller in the processing unit, where they are converted into respective force levels.

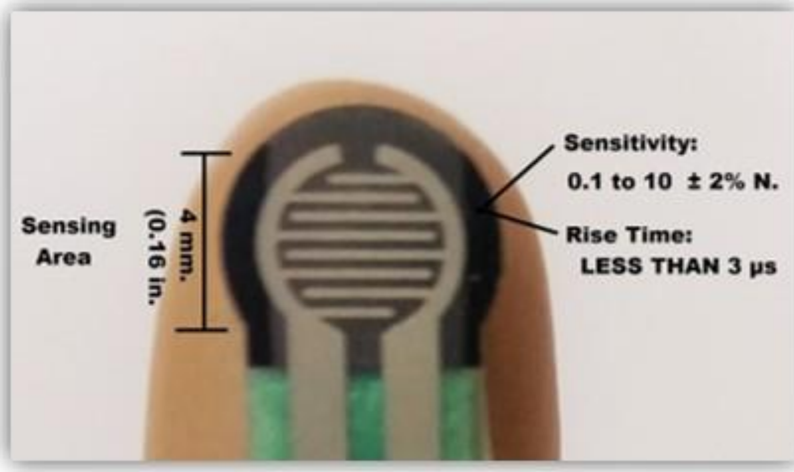

Figure 3: FSR

2.1.2 Processing Unit

The processing unit is a square cardboard box which houses the slave side circuitry, the master side circuitry and a microcontroller. It is a small 3.5 x 2.5 x 1.8-inch unit with an operating voltage of 5V.

An Arduino Nano microcontroller serves as the link between the slave and master sides. Its small size and low power consumption best fulfill the requirements of the system.

The outputs from FSRs are received by the microcontroller. It converts the sensor voltages and maps them, one on one, to the master side vibrotactile motors through the connecting circuitry.

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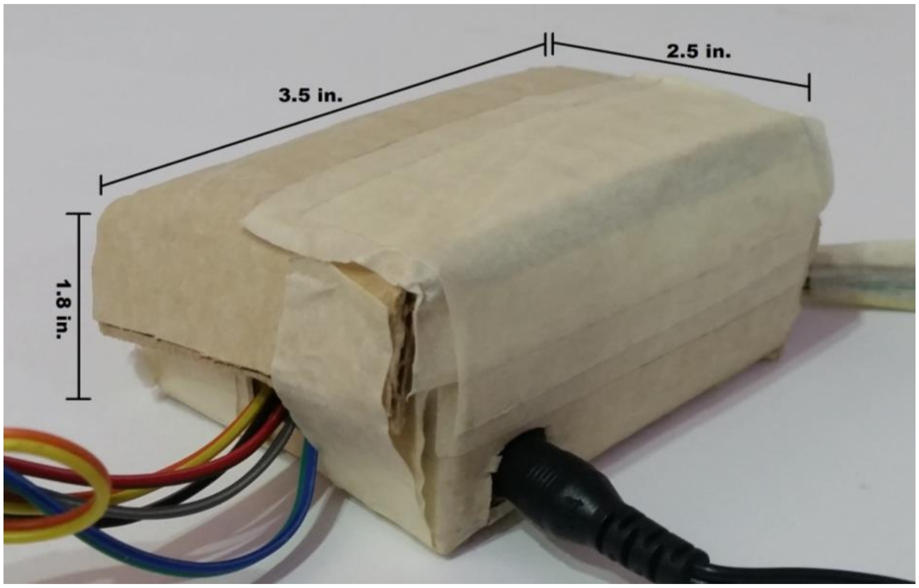

Figure 4: Processing Unit

2.1.3 Master Side

The Master side consists of the main, wearable Vibrotactile haptic feedback band (Vi-HaB) as shown in Fig. 2. It is a 15 x 1 in. band, in which 7.5 in. is nylon elastic while the remaining is adjustable Velcro so that it can be set according to the ease of different users.

This band wraps around the upper arm thus is capable of facilitating all amputees below shoulder disarticulation. Moreover, in a study conducted by P. Chaubey et al. the results showed that the biceps region was most preferred in terms of resolution and user preference for placement of a vibrotactile feedback device [49].

Five vibrational coin motors are equally spaced on the 7.5 in. elastic portion with a gap of approx. 25.4 mm (edge to edge) between each. This distance is in conformity with the human detection thresholds. For single stimuli at a time, J. Rantala [50] stated the minimum point localization distance to be 15mm while in case of multiple stimuli, Michael et al. [51] identified the minimum distance for two-point discrimination to be more than 20 mm. Hoffmann et al. [52] states the closest distance physically possible is 10mm for vibrotactile elements. They accessed vibrotactile spatial acuity at both 20mm and 10 mm distance; the 20mm distance lead to about 64% discrimination accuracy. As the vibrotactile motor's distance in Vi-HaB is more than the minimum mentioned here so an accuracy of at least above 65% was predicted.

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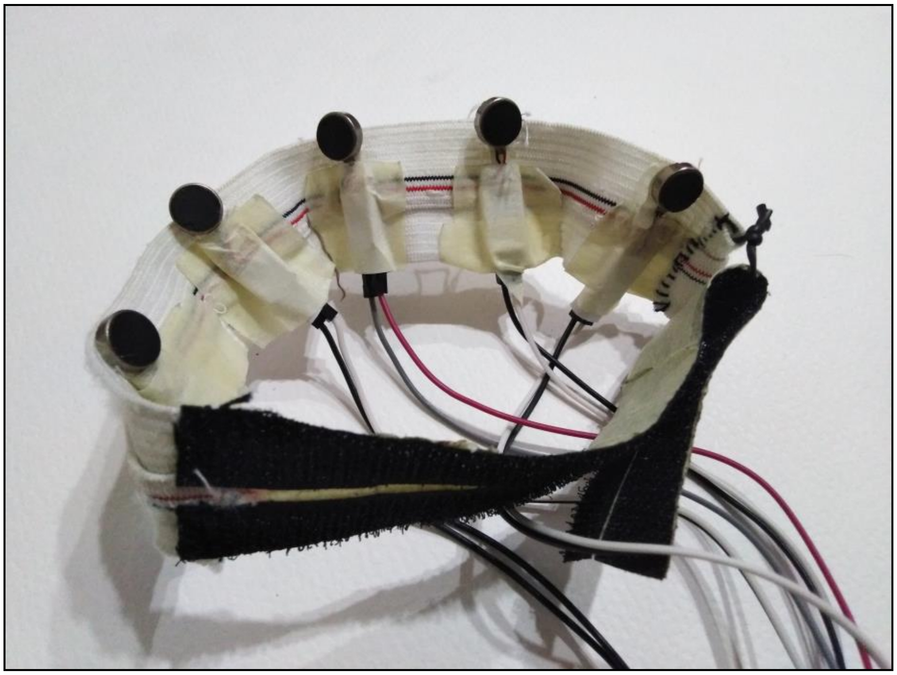

Figure 5: Wearable vibrotactile haptic feedback band (Vi-HaB)

The motors used in Vi-HaB have a diameter of 10.0 mm and 3.0 mm height. The operating voltage is 1.5 - 4V and a stall current of 0.06 A [53]. Each motor is linked to one FSR from the slave side through the Arduino board via the supporting circuitry. Each motor, thus, represents one finger of the hand. Simultaneous variations in both frequency and amplitude of the motor represent the force levels being applied on the fingertips of the dummy hand. The ranges for frequency and amplitude variation of motors are [~95 - ~240] Hz and [~0.2 - ~0.65] g respectively. [54] [55] [56]

These motors activate the Pacinian corpuscles, FA II type mechanoreceptors, in the skin as the frequency range is well within the range detected by the Pacinian corpuscles i.e. ~40 to ~400 Hz. According to Lederman et al. [57] the advantage of operating in the FA II type range is that their adaption time is fast. This reduces the overall system training time.

2.2 Vi-HaB

The three modules discussed above, slave side, processing unit and master side combine to form the complete Vi-HaB system as shown in Fig. 3. Five FSRs and motors are mapped, one on one, onto each other thus each motor represents an individual finger of the dummy hand and each motor's variation in intensity of vibration represent different force feedback levels. The

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relation between motor vibrations and applied force is directly proportional and is given by the following formula:

$$V_{out} = V_{in}/[1 + (R_{FSR}/R_M)] \quad (1)$$

Where $V_{in} = 5V$ and $R_M = 3.3k\Omega$

The wearable band wraps around the upper arm such that each motor falls in line with the natural position of the fingers as shown with red arrows in Fig. 3. thus, it helps in the development of mapping within the user's mind.

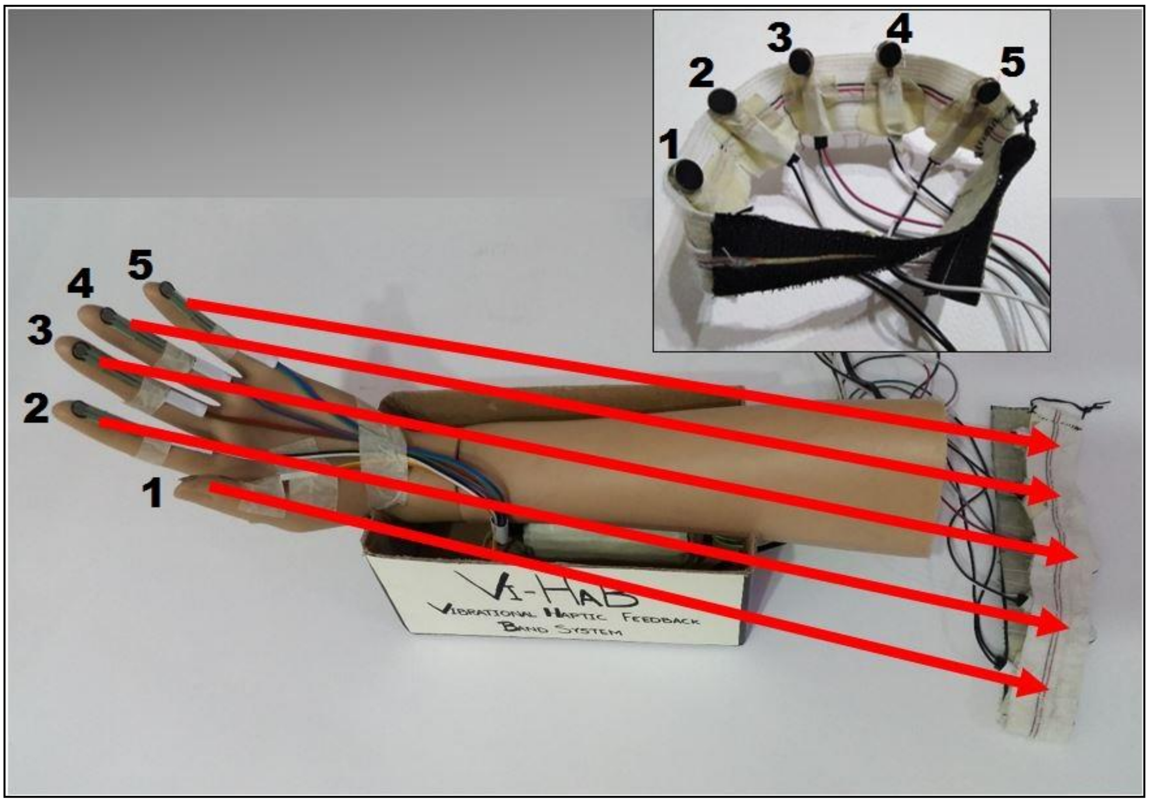

Figure 6: Vi-HaB System

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CHAPTER 3: SYSTE TESTING

3.1 Subjects

For system testing, a total of 28 subjects were divided into two groups. They were briefed about the details of system, the testing process and a consent form was signed by them, prior to the activity. All tests were conducted in accordance with the rules and guidelines of ethics committee at AFIRM and the Declaration of Helsinki.

3.1.1 GROUP I

In group I, system was tested on 14 disabled subjects in collaboration with Armed Forces Institute of Rehabilitation Medicine (AFIRM). The subject's ages ranged between 15 to 41 years with 3 females and remaining males. All the subjects had some form of disability i.e. amputation or nerve injury. Details about their type of disability, effected hand and dominant hand are given in Table I.

3.1.2 GROUP II

In group II, system was tested on 14 able bodies subjects at RISE Lab, SMME, NUST. The subject's ages ranged between 18 to 30 years. Details about their gender, testing hand and dominant hand are given in Table II.

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Table I
GROUP I SUBJECTS DETAILS

Subject Number (S)	**Gender (M/F)**	**Age**	**Disability**	**Testing/ effected Arm**	**Dominant hand**
1	F	15	Wrist amputation	Right	Right
2	M	17	Trans-radial congenital amputation	Left	Right
3	M	19	Wrist amputation	Right	Right
4	F	21	Trans-radial amputation	Left	Left
5	M	24	Trans-carpal amputation	Right	Right
6	M	26	Trans-humeral amputation	Left	Right
7	M	27	Brachial Plexus injury	Right	Left
8	F	30	Trans-radial amputation	Left	Right
9	M	31	Trans-radial amputation	Left	Left
10	M	31	Nerve injury	Left	Right
11	M	32	Trans-radial amputation	Right	Right
12	M	32	Brachial Plexus injury	Right	Right
13	M	34	Trans-humeral amputation	Left	Right
14	M	41	Trans-radial amputation	Right	Right

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Table II
GROUP II SUBJECTS DETAILS

Subject Number (S)	Gender (M/F)	Age	Amputee/ Healthy	Testing Arm (Right/Left)	Dominant hand
1	F	18	Healthy	Left	Right
2	M	21	Healthy	Left	Left
3	M	22	Healthy	Left	Right
4	F	22	Healthy	Right	Right
5	F	22	Healthy	Right	Right
6	F	22	Healthy	Right	Right
7	F	24	Healthy	Right	Left
8	M	25	Healthy	Left	Right
9	M	26	Healthy	Left	Right
10	M	26	Healthy	Right	Right
11	M	27	Healthy	Right	Right
12	F	27	Healthy	Left	Left
13	F	29	Healthy	Right	Right
14	M	30	Healthy	Left	Right

3.2 Testing of Vi-HaB

Once the system was ready, it was necessary to test whether the claimed types of haptic information were distinguishable by the user or not. And if, as theoretically expected, the user is perceiving the feedback correctly then what level of accuracy is being achieved. If the system accuracy is not above a certain predefined performance measure then it summarizes that it cannot be used in practical life.

The universally accepted techniques for testing the sensitivity and accuracy of haptic systems are the Psychophysical Methods. In this study, one of the techniques from the classical psychophysical methods has been used. [58] [59]

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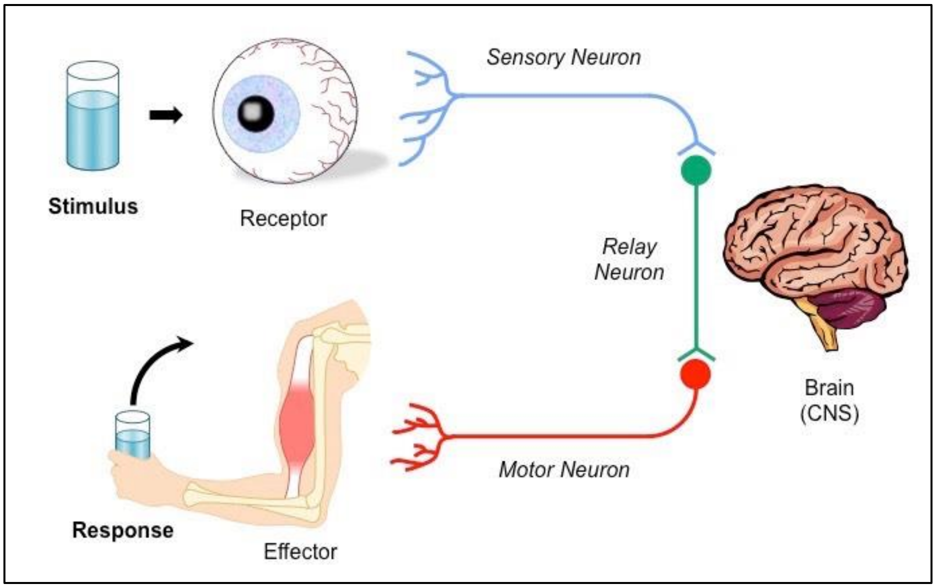

Figure 7: Haptic perception path

As mentioned, Vi-HaB is aimed to deliver three types of haptic information, thus the accuracy of system for each type was tested by conducting individual activities for each. For testing the system, three sets of activities were designed using the "Method of Constant Stimuli". This method has two further variations. The first two activities followed the "Absolute Threshold (RL)" test i.e. "Method of successive Constant Stimuli" while the third activity followed the "Differential Threshold (DL)" test i.e. "Method of simultaneous Constant Stimuli." [60].

These activities were conducted with each subject individually. The system setup for testing can be seen in Fig. 4. The subject's disabled/residual arm was places parallel to the stump of dummy hand. A black cloth was used to cover the stumps so as to induce a sense of embodiment. Vi-HaB band was wrapped around the subject's upper arm. A removable opaque white flexible screen was used to hide the hand from the subject's view.

A predefined set of stimuli were presented to the user by static interaction of dummy hand and tactile sensory evaluators (Fig.5). Tactile sensory evaluators were used to maintain uniformity of stimuli across all subjects.

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Figure 8: Vi-HaB system testing setup

They were first trained on the system and then the activities were conducted. Each activity was further divided into two cases. In first case, the activity was conducted in a quiet and distraction free environment using noise cancellation headphones. A 5-minute time gap was added to check whether the subject retains the developed mapping. Then the subject's environment was introduced with audiovisual distraction by playing an animated video on a laptop screen and headphones were used as audio output. The distractions were to check the effect of external disturbances on Subject's perception ability because real world environments are full of distractions. Thus, for a system to be effective, it should either work equally well or outperform in a distractive environment.

The complete test with one individual was for a duration ranging from 3 minutes to 1 hour, depending on subject's adaptability to the system. The subjects were to give verbal responses during the activities, which were recorded in tabular forms.

A standardized scoring method for activities was set to calculate the system accuracy. The results were then compared with predefined performance measure/minimum accuracy requirements.

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Details of tactile sensory evaluators, activities, how they were conducted and scored, and the Wilcoxon double-sided signed rank test are given in following subsections.

3.2.1 Tactile Sensory Evaluators

Data generated from human observers are often highly variable; like other analytical test procedures, sensory evaluation is concerned with precision, accuracy, sensitivity and the avoidance of false positive results [61]. In field of touch, tactile sensory evaluators are used to determine specific relationship between stimuli and human perception [62] [63] [64] [65].

In this study, three clip type tactile evaluators were used where each induced a specific stimuli i.e. low, medium and strong level force. The evaluator clips can be seen in Fig. 5. Each clip has a specific spring strength thus when placed on the fingertip, it induces a specific level of force. Low-level clip induces a force of approx. 1 – 2N, medium-level clip induces a force of approx. 4 – 5N and strong-level clip induces a force of approx. 7 – 8 N. Each clip's contact area, 10.2 mm x 0.9 mm, with the FSR is fairly small which ensures repeatability and uniformity of contact points every time it is placed over the sensor.

These ensured the presentation of uniform stimuli to all subjects.

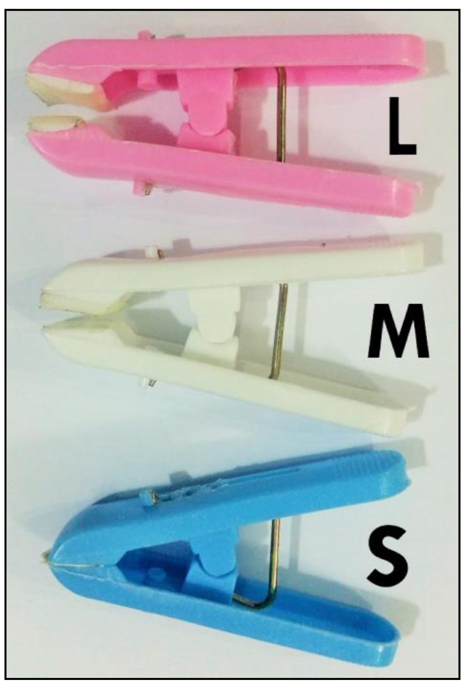

Figure 9: Tactile sensory evaluator clips

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3.2.2 Activity I: Individual Finger Detection

3.2.2.1 System Training

Subjects were given an initial training on Vi-HaB for individual finger identification of the dummy hand. A duration of 10 minutes was set as maximum for the training activity. The band was wrapped on subject’s arm and they were able to see dummy hand. Each finger was pressed sequentially using the medium-level tactile evaluator clip while the subject visually observed and developed a feel of the place of respective vibrating motors.

Before placing the clip on each fingertip, a cue was also given by announcing the finger being pressed i.e. thumb and then 1 to 4 for the remaining fingers respectively. The clip was left on the fingertip for 1 second before removing it. Each successive stimulus was presented with a gap of 5 second in between.

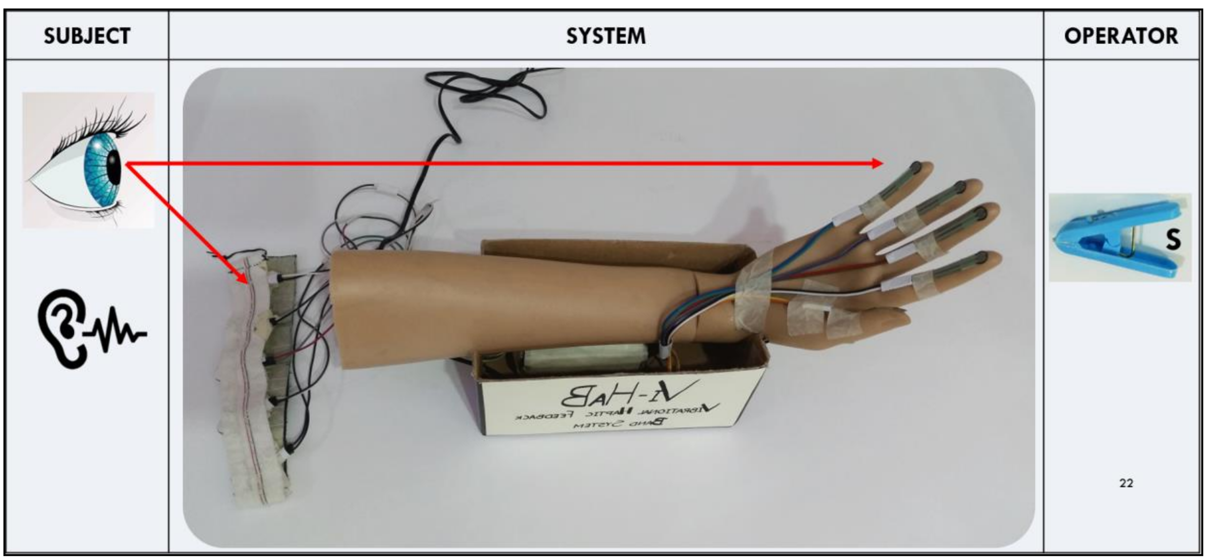

Figure 10: Activity I Training

The subject was first presented with 3 training cycles, where one training cycle is equal to a complete circuit of stimuli presented from thumb to last finger and then back to thumb.

After this, a random order was presented on subject’s request. The activity was conducted after the subject gave a go ahead, within the specified time of 10 mins.

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3.2.2.2 System Testing

3.2.2.2.1 Case I: Without Distraction

After the training session, the dummy hand was hidden from the subject's view by placing an opaque white sheet in front but the user could still look at the Vi-HaB band. A noise cancellation headphone was placed on the subject for distraction free environment. Using the medium-level evaluator clip a total of 30 stimuli were presented to each subject.

These 30 stimuli were divided into 6 groups where each group had the same set of stimuli but with different random order. Each group consisted of same five stimuli where 'Th' stands for 'Thumb', '1' for index finger, '2' for middle finger, '3' for ring finger and '4' for little finger. These groups are mentioned in the Table II(a).

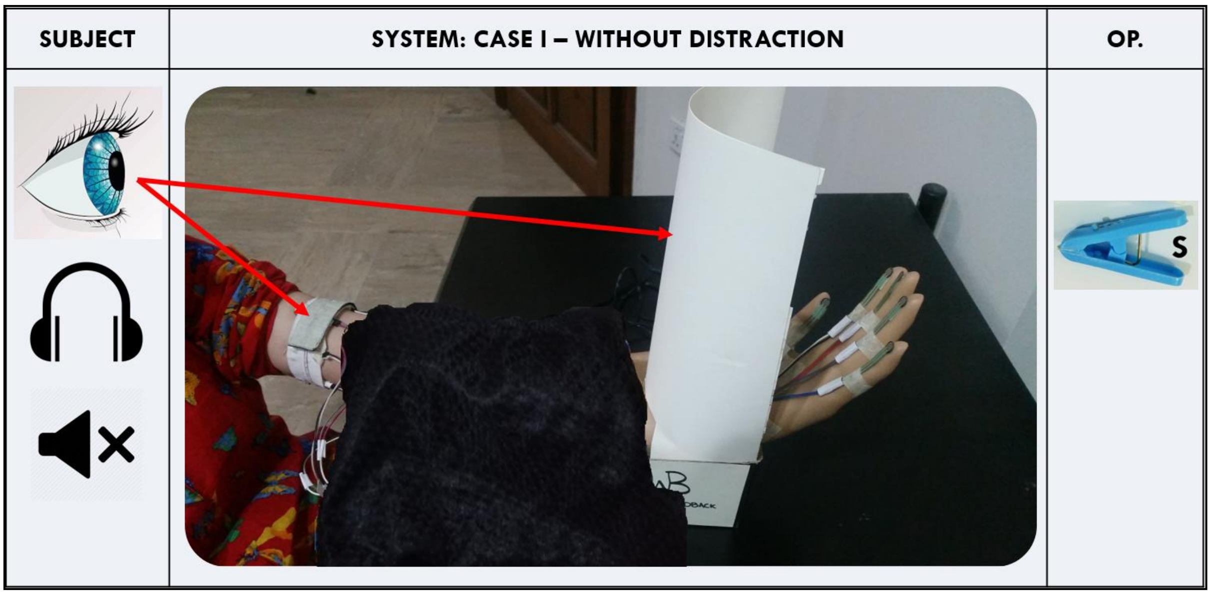

Figure 11: Activity I - Case 1 Testing

The whole table of 30 stimuli was presented to each subject without any cue in a distraction free environment. Each stimulus was held for 1 second and then subject's verbal response was anticipated in the next 5 seconds. The subject was to verbally announce which finger was pressed. In case of no response, the same stimulus was repeated once. For every correct or wrong response, a tick or cross was marked on the respective stimuli in the table and the next stimuli was presented.

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Table III (a)
Individual Finger Detection Activity

(a) Case I: Without Distraction					
Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Th	1	3	4	Th	2
3	2	2	Th	1	4
1	Th	4	2	3	1
2	3	1	3	4	Th
4	4	Th	1	2	3

3.2.2.2.2 Case II: With Distraction

After the above, without distraction activity, the subject’s environment was introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio was supplied through the headphones. The subject was now asked to only concentrate on the video and not look elsewhere. The hand was still kept hidden from view using the same opaque sheet.

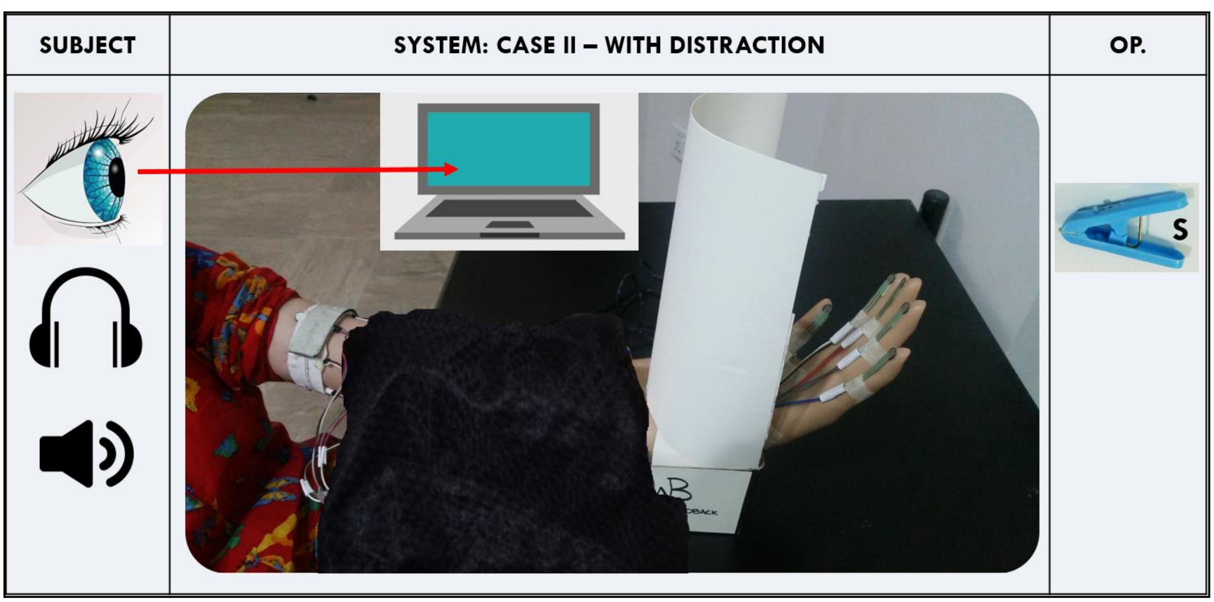

Figure 12: Activity I - Case II Testing

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Same activity as above, Case I, was conducted again. 30 stimuli were presented to the subject again but with audiovisual distraction this time. The orders of stimuli within each group were shuffled as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table II(b). The subject's verbal responses were anticipated and recorded in the same way as was done in the previous case.

Table IV (b)
INDIVIDUAL FINGER DETECTION ACTIVITY

(b) Case II: With Distraction					
GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
3	TH	TH	2	1	4
2	1	3	4	2	TH
4	3	1	1	TH	2
1	4	2	TH	3	3
TH	2	4	3	4	1

3.2.2.3 Activity Scoring

Each correct response in the activity was given a weight of 1. Number of correct responses were marked out of a total score of 30 for each case.

3.2.3 Activity II: Individual Force Level Detection

3.2.3.1 System Training

After completing Activity - I, the noise cancellation headphones were removed so that the subject could listen to the experimenter's explanation. The subjects were given a training on Vi-HaB for detection of forces applied on each fingertip of the dummy hand. A duration of 10 minutes was set as maximum for the training activity. The force training activity was conducted by applying three levels of force on individual fingers, sequentially, while the subject developed

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a feel of the difference in force levels based on vibrational intensities. These forces were presented using the three tactile evaluator clips. The subjects were to distinguish between three levels of force

- Low (L)
- Medium (M)
- Strong (S)

Before placing each evaluator clip, a verbal cue was given by announcing it i.e. Low, Medium, Strong and was held for 1 second. Each successive stimulus was presented with a gap of 5 seconds in between. Subjects were first presented with 3 training cycles, where one training cycle is equal to a complete circuit of force stimuli (from low to strong) on each finger.

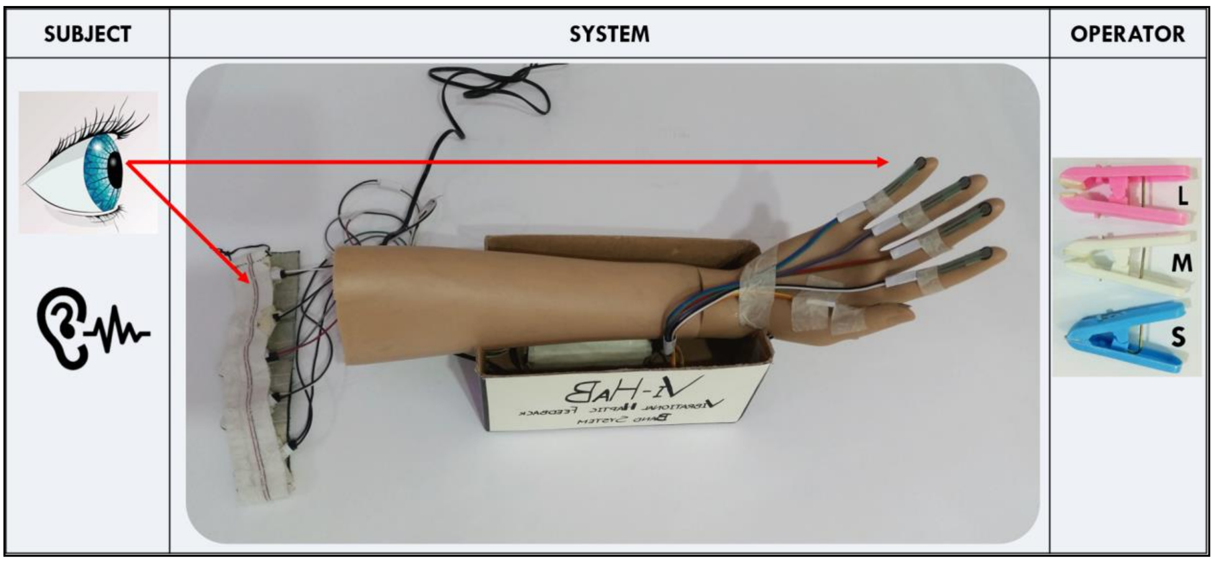

Figure 13: Activity II Training

After this, random orders were presented on subject's request. The activity was conducted after the subject gave a go ahead, within the specified time of 10 mins.

3.2.3.2 System Testing

3.2.3.2.1 Case I: Without Distraction

After the training session, the noise cancellation headphone was placed on the subject for distraction free environment. The dummy hand was kept hidden using the opaque sheet. Using all three evaluator clips a total of 20 stimuli were presented to each subject.

These 20 stimuli were divided into 5 groups where each group represented one finger. Within

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each group, three force stimuli were presented randomly on a finger. As shown in Table III(a), 'L' represents low, 'M' represents medium and 'S' represents strong and for presenting each of these stimuli, the respective evaluator clips, low-level, medium-level or strong-level were used.

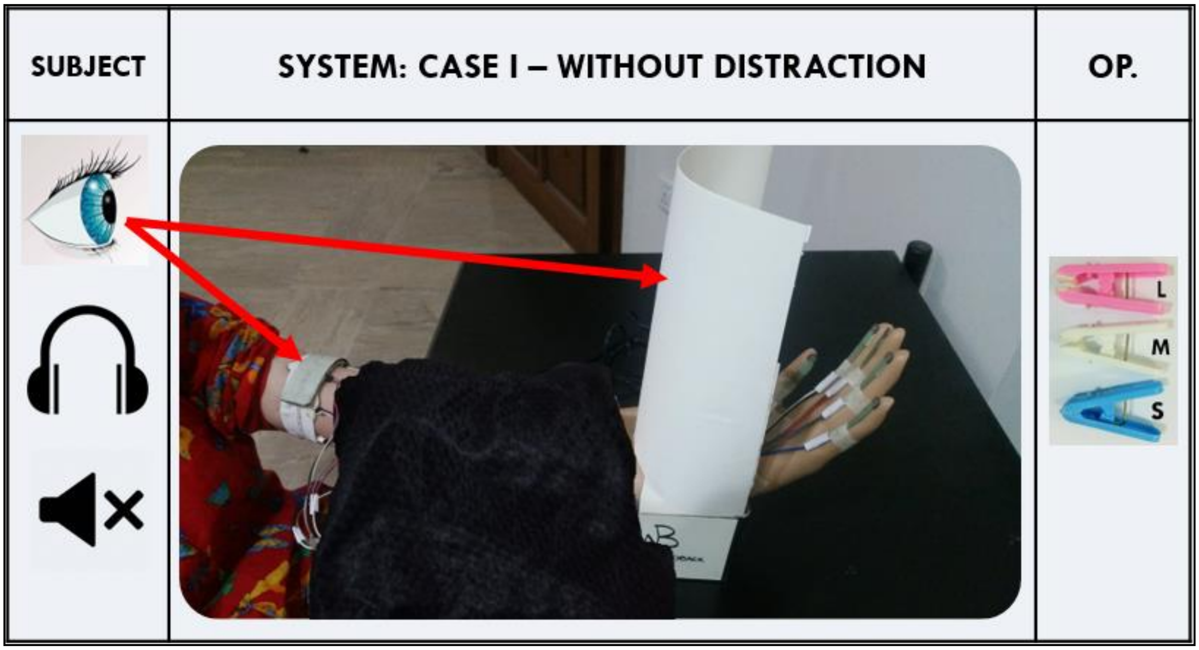

Figure 14: Activity II - Case I Testing

First a pulse was given on the finger mentioned in the table and the subject was to determine and announce the finger being pressed. The response was marked with either a tick or cross mark in the table. After that, force levels were presented without any verbal cue with a gap of 2 second between each stimulus on the same finger. Subjects were asked to wait for all three force stimuli and then subject's verbal response was anticipated in the next 5 seconds. The subject was to verbally announce the sequence of stimuli that were presented from first to last. In case of no response, the same sequence was repeated once. For every correct or wrong response, a tick or cross was marked on the respective stimulus in the table and the next sequence was presented.

The whole table of 20 stimuli was presented to each subject without any cue in a distraction free environment.

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Table V (a)
FORCE LEVEL DETECTION ACTIVITY

(a) Case I: Without Distraction				
FINGER 1	FINGER 3	FINGER 2	THUMB	FINGER 4
S	M	L	M	S
L	L	M	S	M
M	S	L	L	M

3.2.3.2.2 Case II: With Distraction

After the above, without distraction activity, the subject's environment was introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio was supplied through the headphones. The subject was now asked to only concentrate on the video and not look elsewhere. The hand was still kept hidden from view using the same opaque sheet.

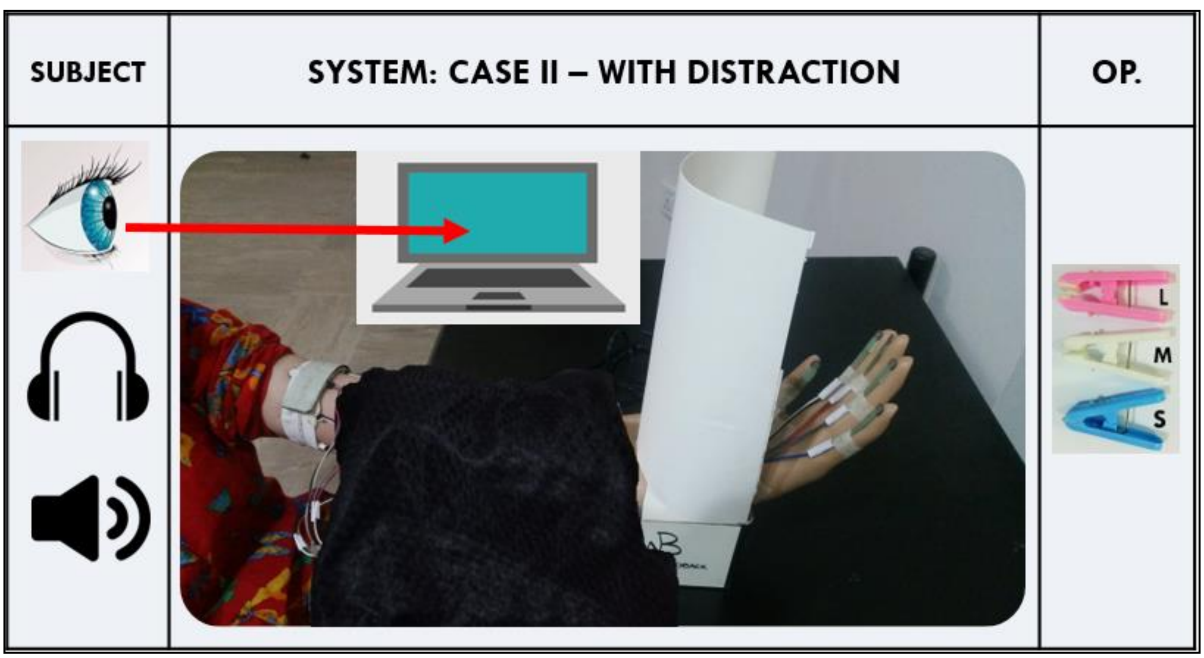

Figure 15: Activity II - Case II Testing

Same activity as above, Case I, was conducted again. 20 stimuli were presented to the subject but with audiovisual distraction this time. The orders of stimuli within each group were shuffled

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as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table III(b). The subject's verbal responses were anticipated and recorded in the same way as was done in the previous case.

Table VI (b)
FORCE LEVEL DETECTION ACTIVITY

(b) Case II: With Distraction				
FINGER 4	THUMB	FINGER 3	FINGER 1	FINGER 2
L	S	S	M	M
M	M	L	S	L
L	M	M	L	S

3.2.3.3 Activity Scoring

Each correct response in the activity was given a weight of 1. Number of correct responses were marked out from a total score of 20 for each case.

3.2.4 Activity III: Simultaneous Force Level Detection

3.2.4.1 System Training

After completing Activity - II, the noise cancellation headphones were removed so that the subject could listen to the experimenter's explanation. The subjects were given a training on Vi-HaB for identifying two spatially displaced force stimuli presented together. A duration of 10 minutes was set as maximum for the training activity.

The training activity was conducted by applying two different stimuli simultaneously on two random fingers, while the subject was to identify the just the two different force levels being applied. Subjects were presented with 4 stimuli pairs in random order on random fingers. These stimuli were presented using any two of the three tactile evaluator clips at a time.

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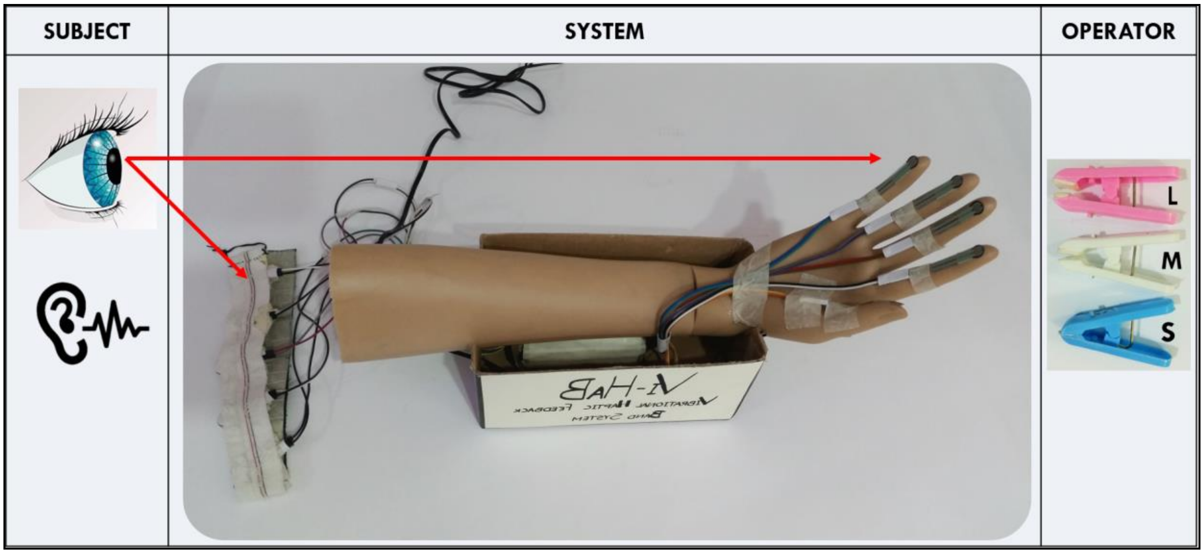

Figure 16: Activity III Training

Before presenting the stimuli, the two force levels were verbally announced. Each successive stimulus pair were presented with a gap of 5 seconds in between The activity was conducted after the subject gave a go ahead, within the specified time of 10 mins.

3.2.4.2 System Testing

3.2.4.2.1 Case I: Without Distraction

After the training session, the noise cancellation headphone was placed on the subject for distraction free environment. The dummy hand was kept hidden using the opaque sheet. Using all three evaluator clips a total of 10 stimuli were presented to each subject.

These 10 stimuli were divided in 5 groups where each group has one set of stimuli as shown in Table IV(a). In each group, the stimuli are marked as 'X - Y' where X represents the finger on which the stimuli is being presented and Y represents the evaluator clip/force level that is being presented on the respective finger. The subject was only to identify the two level of two simultaneous stimuli being presented i.e. a combination of any two out of the three force levels (low, medium, strong).

The two stimuli within each group were simultaneously presented to the subject. They were asked to announce just the force levels of simultaneous stimuli they felt and the verbal response was anticipated in the next 5 seconds. The subject was to verbally announce the level of two stimuli that were presented. In case of no response, the same sequence was repeated once. For

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every correct or wrong response, a tick or cross was marked on the respective stimulus in the table and the next sequence was presented with a gap of 5 seconds.

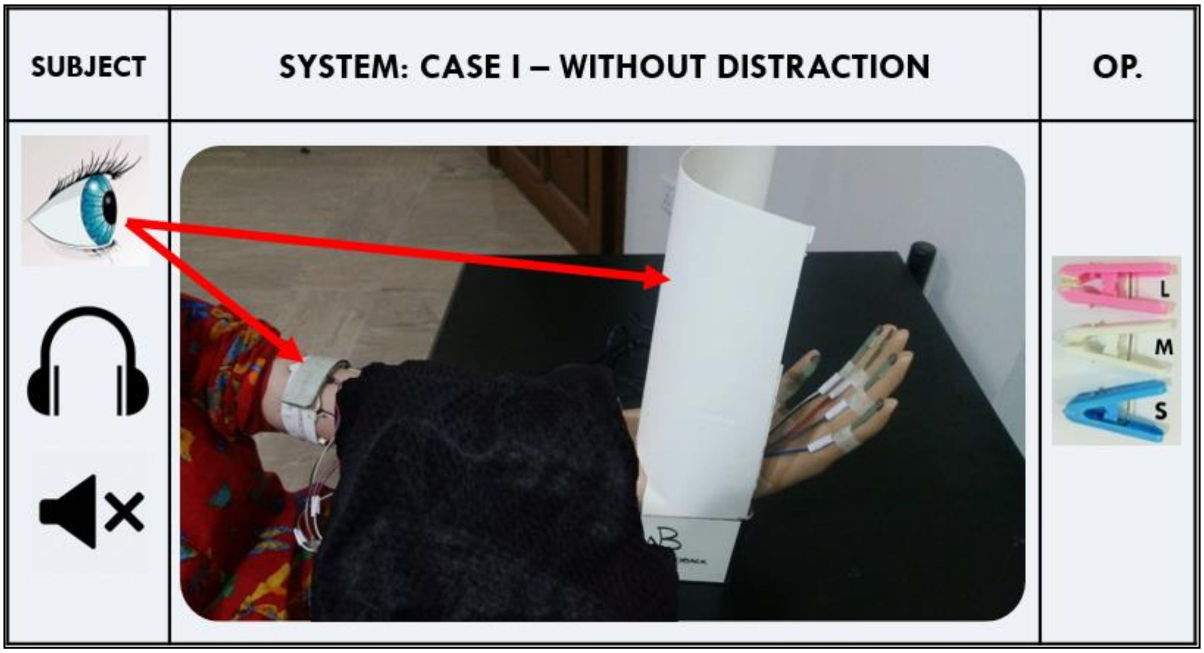

Figure 17: Activity III - Case I Testing

Table VII (a)
SIMULTANEOUS MULTIPLE FORCE LEVEL DETECTION ACTIVITY

(a) Case I: Without Distraction

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
TH - S	1 - M	2- M	1 - L	2 - S
4 - L	3 - L	3 - S	4 - M	4 - M

3.2.4.2.2 Case II: With Distraction

After the above, without distraction activity, the subject's environment was introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio was supplied through the headphones. The subject was now asked to only concentrate on the video

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and not look elsewhere. The hand was still kept hidden from view using the same opaque sheet.

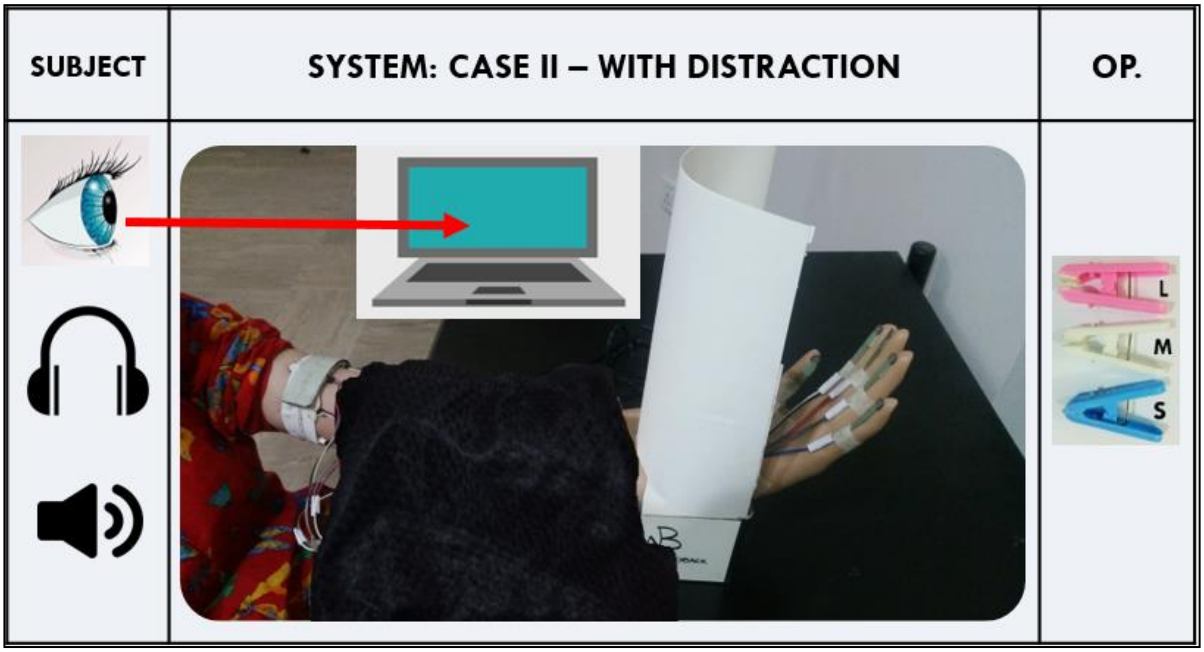

Figure 18: Activity III - Case II Testing

Same activity as above, Case I, was conducted again. 10 stimuli were presented to the subject again but with audiovisual distraction this time. The orders of stimuli within each group were shuffled as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table IV(b). The subject's verbal responses were anticipated and recorded in the same way as was done in the previous case.

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Table VIII (b)
SIMULTANEOUS MULTIPLE FORCE LEVEL DETECTION ACTIVITY

(b) Case II: With Distraction				
GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
2- M	2 - S	TH - S	1 - L	1 - M
3 - S	4 - M	4 - L	TH - M	3 - L

3.2.4.3 Activity Scoring

Each correct response in the activity was given a weight of 1. Number of correct responses were marked out from a total score of 10 for each case.

3.3 System Accuracy

Subject's score in activities were individually calculated by finding out the percentage of correct responses in both cases.

$$Subject's\ Score = \%\ of\ correct\ responses = \frac{No.of\ correct\ responses}{Total\ Activity\ Score}\, x\ 100 \qquad (2)$$

Accuracy of individual test case (without distraction, with distraction) was calculated by averaging all the Subject's Scores.

$$accuracy\ of\ test\ case = \frac{\sum of\ Subjects\ score}{No.of\ subjects} \qquad (3)$$

A comparison was drawn between the systems performance in without and with distraction cases.

The accuracy of system in individual activities were calculated by averaging the percentage accuracies of both cases.

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$$Accuracy\ of\ activity = \frac{\sum of\ \ accuracy\ of\ test\ cases}{2} \qquad (4)$$

Overall system accuracy was calculated by averaging the accuracy of all activities

$$System\ Accuracy\ = \frac{\sum of\ \ accuracy\ of\ activities}{3} \qquad (5)$$

3.4 Performance Measure of The System

According to the performance measure set for the developed system, the accuracies of Activity I and II should be above 50%.

This benchmark percentage has been selected from the performed "Method of constant stimuli (RL)" according to which, the intensity where the proportion of correct responses is 0.5 is taken as the "Absolute Threshold (RL)".

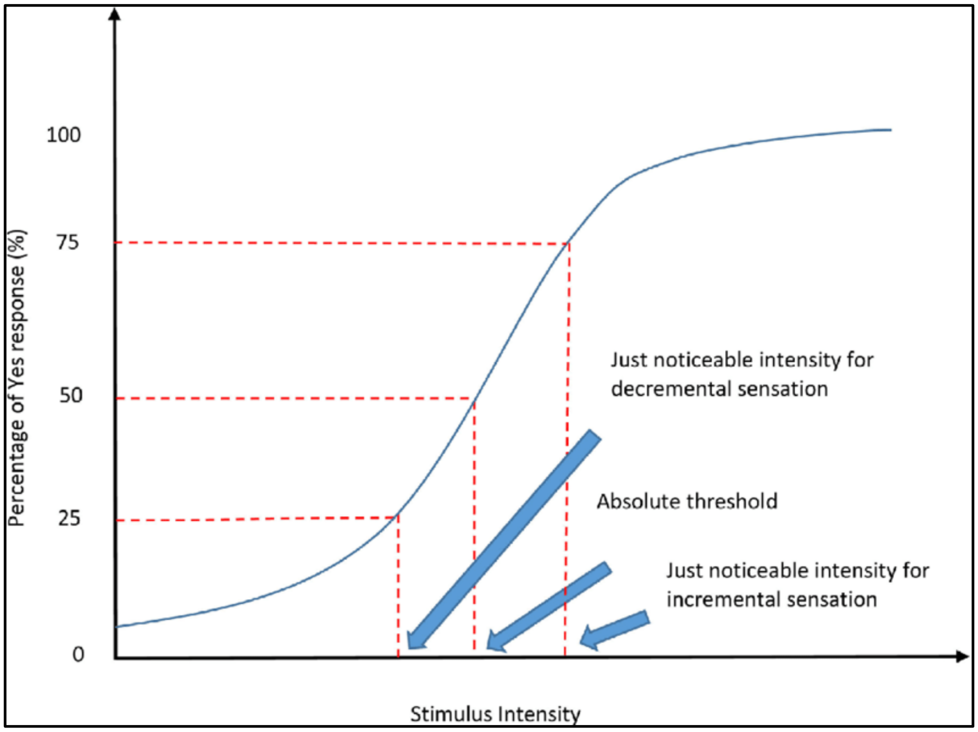

Figure 19: Performance Measure Thresholds

So, if a haptic system has an accuracy above this level i.e. 50%, then it points to the fact that it is operating above the absolute threshold and all the incoming stimuli will be easily detected. [66]

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For Activity III, the accuracy should be above 70% because the "Difference Threshold (DL)" is the intensity where the percentage of correct responses is ~70%. So, an accuracy value above this level shows that the incoming stimuli will be successfully distinguishable from each other. [60].

Since the performance measures for activities are not uniform thus the performance measure for overall system accuracy was defined as the average value of these two benchmarks, 50% and 70% i.e. 60%.

3.5 Wilcoxon Double-Sided Signed Rank Test

It is a famous test of statistics which is conducted on non-parametric data. This technique is utilized when different types of test are conducted on a set of consistent subjects and the difference between the resulting paired samples, before and after certain conditions, are to be found.

The paired sample in this data is the individual subject's activity result before and after the addition of distraction to the environment. [43]

The test starts with a hypothesis, called the "Null Hypothesis", which makes the assumption that there is no zero median between paired samples.

Then the test begins to calculate the probability of deviation from the null hypothesis. [44]

There are three important (one input and two output) factors in this test that are as follows.

3.5.1 Significance Level (α)

Significance level sets the probability of rejecting the null hypothesis when it is true. It is a variable input factor which is set at 0.05 (5%) as default.

A 0.05 significance level indicates that there is a 5% risk of conclusion that a difference exists when there is no actual difference. [45]

3.5.2 P- Value (p)

P- value is an output factor which indicates the probability of obtaining an effect at least as extreme as the one in the data sample. It has a continuous range from 0 to 1.

This number also tells how well the sample data supports the null hypothesis.

- High 'p' indicates that the data is likely with a true null

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- Low ‘p’ indicates that the data is unlikely with a true null.

The null hypothesis is rejected if the P- value is less than or equal to the significance level. [46]

3.5.3 H-Value (h)

H- value is an output factor which tells if the null hypothesis has been accepted or rejected by the test. It varies between discrete values of 0 and 1.

At a 5% significant level if ‘h’ gives a logical 0, it means that the test has failed to reject the null hypothesis. If ‘h’ gives a logical 1, it means that the test rejects the null hypothesis.

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CHAPTER 4: RESULTS AND DISCUSSIONS

In this study, results have been shown group wise as per conducted tests.

4.1 GROUP I

Subjects scores for activities I, II and III have been presented in a bar graph format in Fig. 6, Fig, 7 and Fig. 8 respectively. The x-axis represents the subject number, S1 – S14. Each bar set along the y-axis shows the subject's score out of 100%, in both without and with distraction cases. Two horizontal lines parallel to x-axis, Average 1 and Average 2, show the average of all the subjects scores in both, without and with distraction cases respectively.

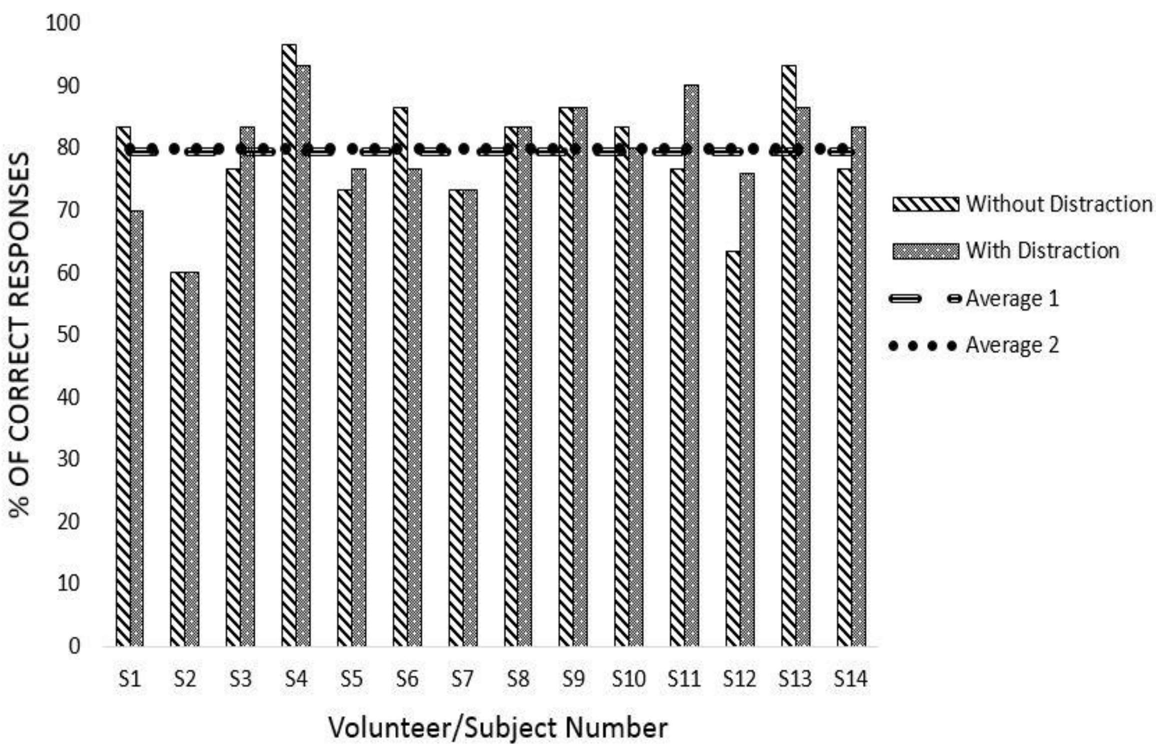

Figure 20: Individual finger detection activity

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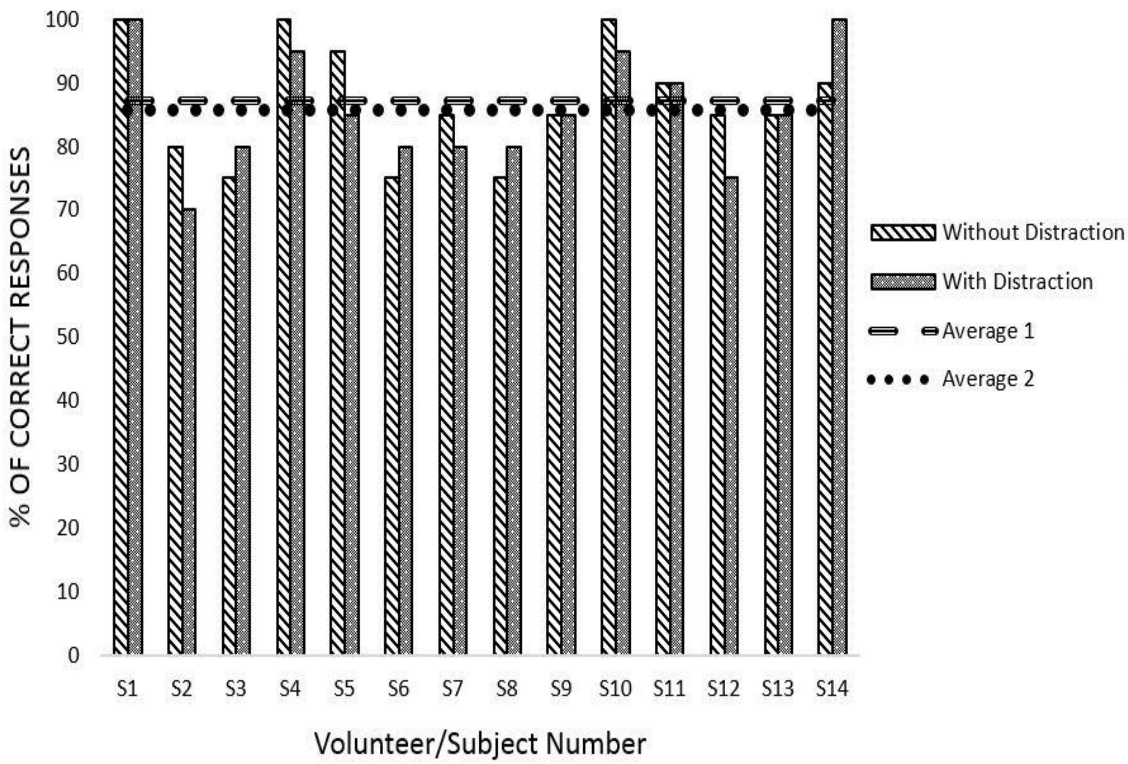

Figure 21: Force Detection Activity

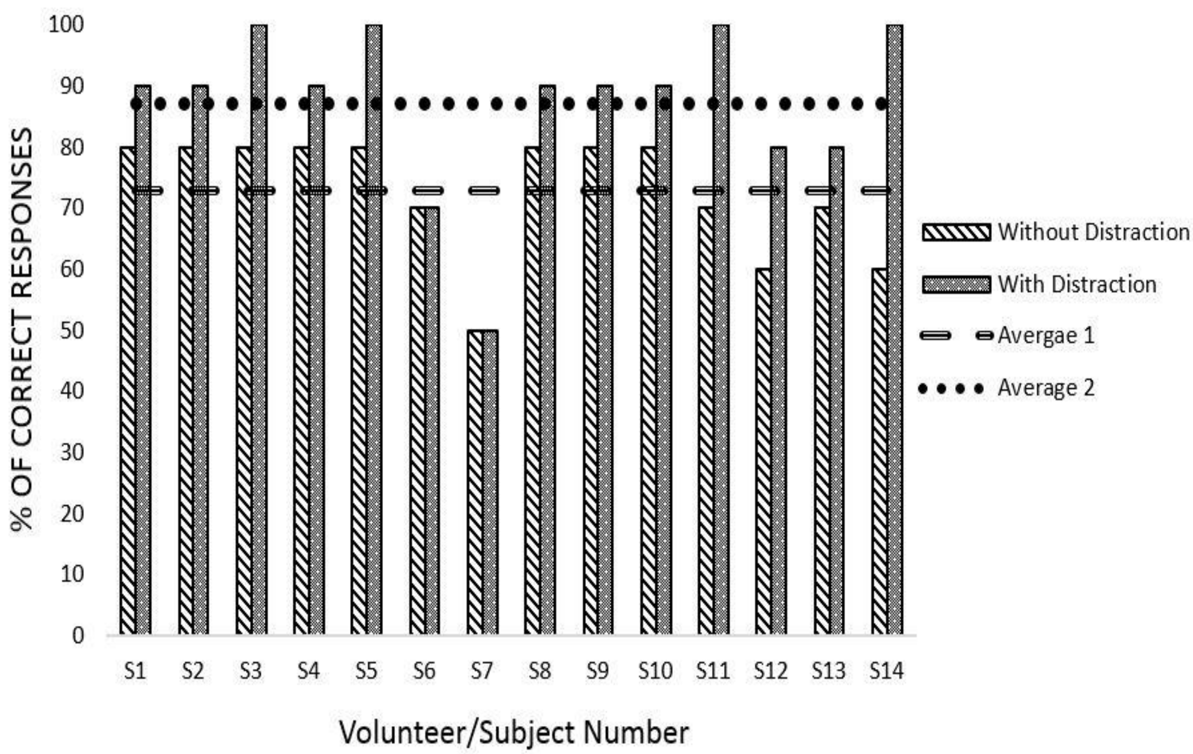

Figure 22: Simultaneous force detection Activity

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Accuracies of activities are also shown in Table V. For “Individual finger detection activity”, the system accuracy in case I (without distraction) came out to be 79.48% while in case II (with distraction), it was 79.92%. The Net accuracy of system in this activity came out to be 79.70%.

For “Force level detection activity”, the system accuracy in case I (without distraction) came out to be 87.14% while in case II (with distraction), it was 85.71%. The Net accuracy of system in this activity came out to be 86.43%.

The accuracy values in both these activities, I and II, were well above the set performance measure i.e. 50%.

Table IX
RESULTS

Activity	Accuracy in Cases: Without Distraction (%)	Accuracy in Cases: With Distraction (%)	Net Accuracy in activity (%)	Error (%)	Performance Measure
Individual Finger Detection	79.48	79.92	79.70	-0.44	50
Force Level Detection	87.14	85.71	86.43	1.43	50
Simultaneous Force Level Detection	72.86	87.14	80	-14.29	70
Overall System Accuracy (%)			82.04		60

In the above mentioned two activities, I and II, it was observed that the performance mildly improved and deteriorated by a percentage of -0.44 and 1.43 respectively, after the addition of distraction to the system; which is negligible. This negligibility claim was supported by the Wilcoxon test results. A significance analysis was conducted between data of with and without distraction cases for all subjects with a significance value of 0.05. The h-value gave a logical 0 for both activities I and II with p-values of 0.8613 and 0.4629 respectively, thus verifying the null hypothesis; meaning that there is essentially no difference in the system performance with or without distraction.

For Simultaneous force level detection activity, the system accuracy in case I (without distraction) came out to be 72.86% while in case II (with distraction), it was 87.14%. The Net

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accuracy of system in this activity came out to be 80% which was well above the set performance measure of 70%.

This activity exhibited a unique phenomenon of significantly large negative error of -14.29%. this shows that the system performance improved after the addition of distractions. The result of Wilcoxon test conducted between the data of all subjects for with and without distraction cases in this activity also verified the difference when the h-value gave out a logical 1 with a p-value of 4.8828e-04

Table X
WILCOXON'S SIGNED RANK TEST

Activity	Wilcoxon Test	
	p	h (Logical)
Individual Finger Detection	0.8613	0
Force Level Detection	0.4629	0
Simultaneous Force Level Detection	4.8828e-04	1

This is because the spatial acuity feedback of skin is better than vision in presence of a reference factor [57]. When there is no distraction, the subject unconsciously tries to judge by looking at the band. But when distraction is added, it severs the visual link and subjects inherently rely on feedback from the skin. Moreover, the simultaneous forces complement and serve as a reference to each other, as intended by the DL activity, which makes it easier for the subjects to distinguish the level thus, the accuracy improves.

The overall accuracy of Vi-HaB system came out to be 82.04%. This value is well above the performance measure for the overall system i.e. 60%.

4.2 **GROUP II**

Subjects scores for activities I, II and III have been presented in a bar graph format in Fig. 6, Fig, 7 and Fig. 8 respectively. The x-axis represents the subject number, S1 – S14. Each bar set along the y-axis shows the subject's score out of 100%, in both without and with distraction cases. Two horizontal lines parallel to x-axis, Average 1 and Average 2, show the average of all the subjects scores in both, without and with distraction cases respectively.

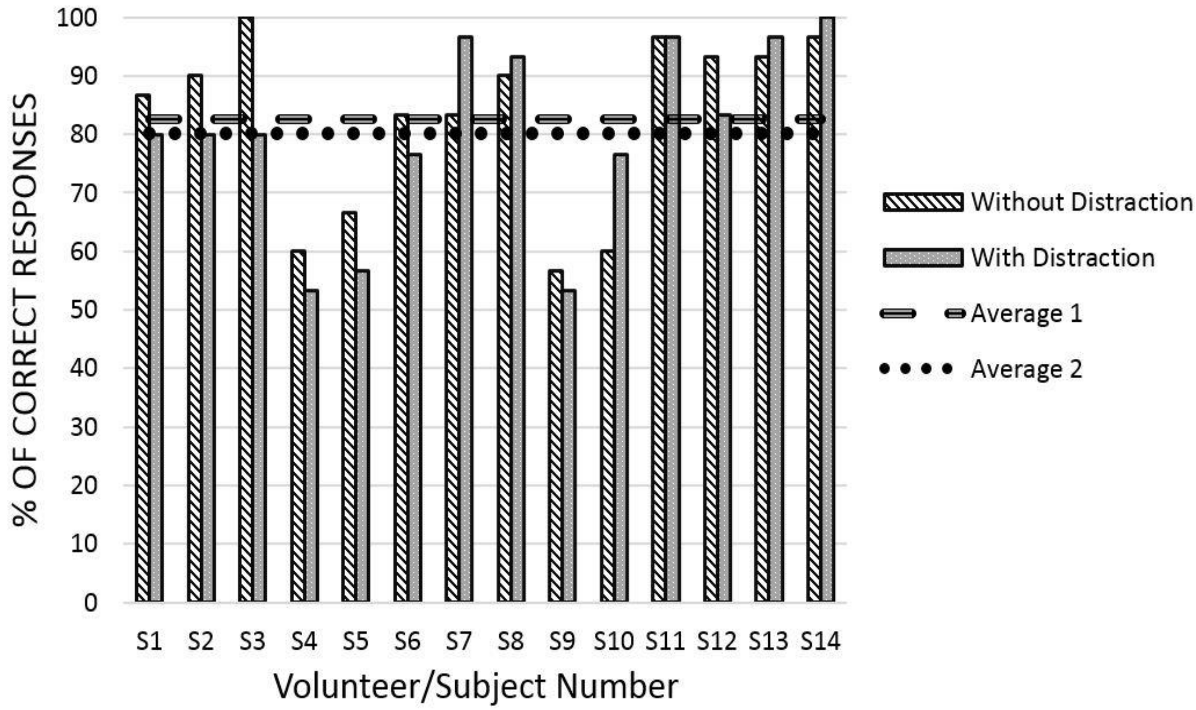

Figure 23: Individual Finger Detection Activity

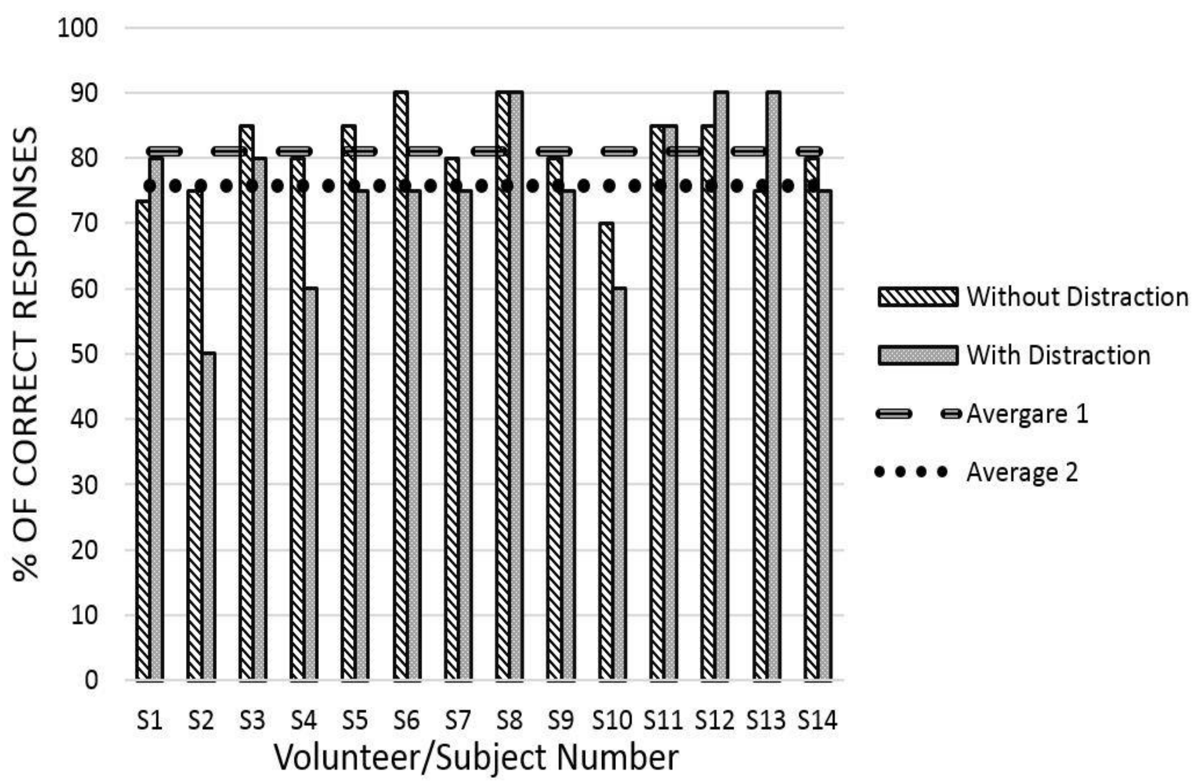

Figure 24: Force detection activity

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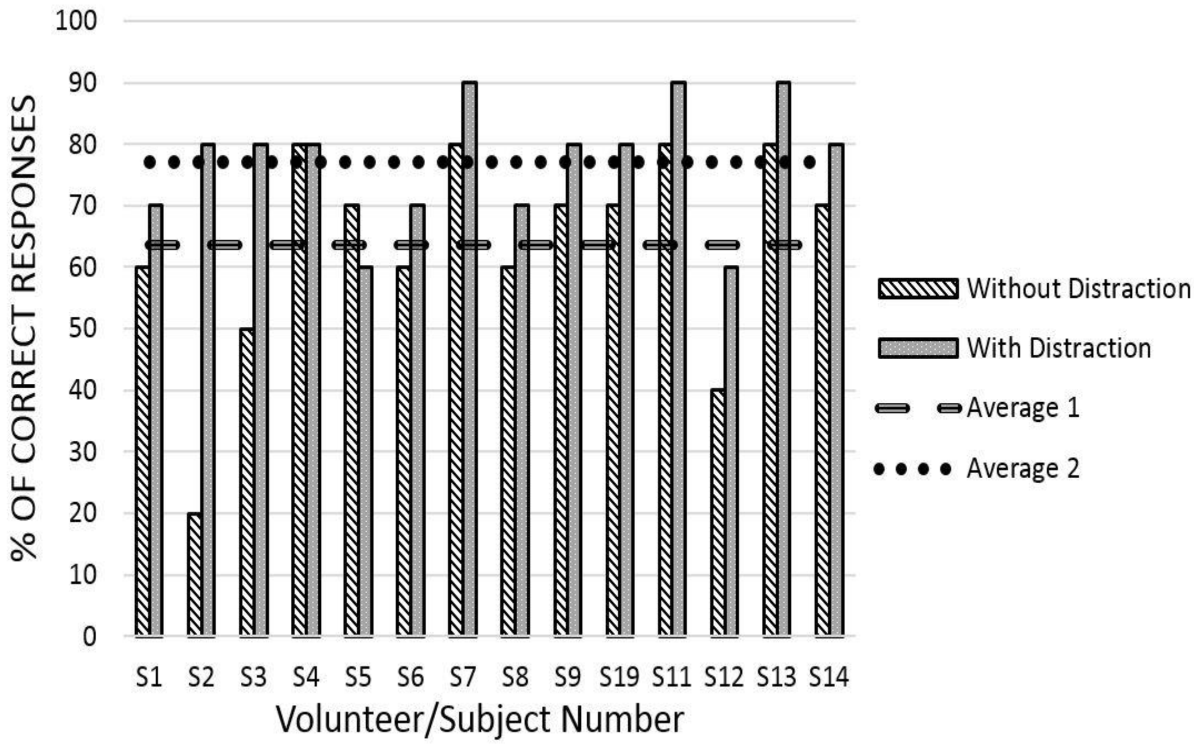

Figure 25: Simultaneous force detection Activity

Accuracies of activities are shown in Table V. For "Individual finger detection activity", the system accuracy in case I (without distraction) came out to be 82.69% while in case II (with distraction), it was 80.2%. The Net accuracy of system in this activity came out to be 81.44%.

For "Force level detection activity", the system accuracy in case I (without distraction) came out to be 80.95% while in case II (with distraction), it was 75.71%. The Net accuracy of system in this activity came out to be 78.33%.

The accuracy values in both these activities, I and II, are well above the set performance measure i.e. 50%

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Table XI
RESULTS

Activity	Accuracy in Cases: Without Distraction (%)	Accuracy in Cases: With Distraction (%)	Net Accuracy in activity (%)	Error (%)	Performance Measure
Individual Finger Detection	82.69	80.2	81.44	2.49	50
Force Level Detection	80.95	75.71	78.33	5.24	50
Simultaneous Force Level Detection	63.57	77.14	77.14	-13.57	70
	Overall System Accuracy (%)		78.97		

In the above two activities (1 and 2), it is observed that the performance deteriorates by 2.46% and 5.24% respectively, after the addition of distraction to the system, which is negligible. This claim is supported by the "Wilcoxon Test" conducted on the data. The "h" Value gives a "logical 0" for both activities, thus verifying the null hypothesis; meaning that there is essentially no difference between the data before and after the addition of distraction.

For "Simultaneous force level detection activity", the system accuracy in case I (without distraction) came out to be 63.57% while in case II (with distraction), it was 77.14%.

This activity exhibits a unique phenomenon of negative error; 13.57%. it shows that the system accuracy has increased in presence of distractions.

Table XII
WILCOXON'S SIGNED RANK TEST

Activity	Wilcoxon Test: p	Wilcoxon Test: h (Logical)
Individual Finger Detection	0.3335	0
Force Level Detection	0.1157	0
Simultaneous Force Level Detection	0.0027	1

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This is because the spatial acuity of skin is better than ears in presence of a reference factor. When there is no distraction, the Subject relies more on the auditory feedback i.e. the vibrational sound of the motor. But when distraction is added, it severs the auditory link and subjects inherently rely on feedback from the skin. The simultaneous forces complement and serve as a reference to each other, as intended by the DL activity, which makes it easier for the subjects to distinguish the level thus, the accuracy improves. [39, p. 1442]

The purpose was to see whether the system performs equally well with distractions. Since the system accuracy is improving in case II, which is a real-world scenario, results of case I can be ignored; thus, the net accuracy of system in this activity is the accuracy of case II i.e. 77.14%. This value is well above the set performance measure i.e. 70%

The overall accuracy of Vi-HaB system came out to be 78.97%. This value is well above the performance measure set for the overall system i.e. 60%.

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CONCLUSION

In this study, a wearable vibrotactile haptic feedback system was designed for upper-limb rehabilitation systems. The system combines three important types of haptic feedback information that are individual finger awareness, force feedback from every finger independently and using the same system, simultaneous force feedback i.e. the overall grasping force can also be made known to the user.

The accuracy of Vi-HaB was tested by conducting three sets of activities with a group of 14 disabled subjects. Each activity was to evaluate the accuracy of the system for generating a specific type of feedback information. Individual accuracies were calculated for each type of haptic information being presented. Moreover, the overall accuracy of the system was also calculated which came out to be 82.04%. This value was found to be well above the set minimum performance measure for the system i.e. 60%. A statistical analysis was also conducted between the data sets collected under two different conditions; one being the without distraction case and the other with distractions. The results showed that the system is fit to use in both lab and real-world conditions without any deterioration in performance.

This study also verifies the assumption made by Wijk et al. [30] that the training time for associating predefined points on arm with fingers in amputees as compared to able-bodies subjects should be less. In the study with able-bodies subjects [30], it took approx. 20 minutes to complete the training session for one activity as compared to this study with amputees where the maximum duration for training session of an activity was 10 minutes.

It is evident that this vibrotactile system can be used to associate predefined points on the upper arm with fingers. It can be integrated with rehabilitation systems i.e. in upper limb prosthesis, exoskeletons for force feedback from individual fingers. It is a wearable, low power consuming system which is free of mechanical noise, does not interfere with EMG and EEG signals and is independent of phantom hand map limitations.

In future this system’s response or usability in force control of rehabilitation systems can be studies by mounting it on an EMG controlled prosthesis. It can also be evaluated to be employed as a feedback system in teleoperation and virtual reality applications.

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FUTURE WORKS

The developed system has scope for following applications in future:

- For force control in upper limb prosthesis and exoskeletons
- For exploring other prospective feedback points on the human body e.g. neck
- For verification of vibrotactile thresholds
- For long range teleoperation
- In virtual reality applications

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