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Vibrotactile Stimulation for 3D Printed Prosthetic Hand

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***Abstract*— Lack of haptic feedback in prostheses is proving to be the bottleneck in the field. Closed loop prostheses should fill the gap for amputees to experience exteroceptive (environmental pressure) or proprioceptive (proper state or joint angles) by means of different sensory feedback. Detailed work is being done on the development of electrotactile and vibrotactile stimulation system. The objective of this research is to generate vibrotactile feedback on a residual arm of an amputee. With this research, it is an endeavor for amputees to possess cognitive response while holding something amid environmental interactions with the help of convenient methodology and with suitable components in hand. To make this design pertinent to the objective, we have used coin shaped vibration motors, 0.5-inch diameter circular FSR provide haptic feedback from the tip of the finger. 3D printed prosthetic hand proved to be the best remedy for lowering the cost. The research was conducted on 6 healthy subjects and one amputee. Experimental results showed the effectiveness of proposed approach.**

I. INTRODUCTION

Several children are born with symbrachydactyly of hand, annually. They do not lead their lives as normal people do. On the contrary, losing a limb or upper part of limb accidentally is no less than a devastating event for a person. Numerous works are being done to overcome this impairment in decades. The development of prosthetic hand was not an overnight achievement, it has almost taken half of century but incorporating somatosensory sensation in a prosthetic limb is still a dream. The most advanced prosthetic hand manufactured by iLimb or bebionic, lack the functionality of tactile sensation which is by far the most needed objective to be achieved in the field of prostheses. According to the statistics, 1.7 million of amputees were observed in the United States alone in 2007 [1]. 1,621 amputees increase every year in the United States among injured military personnel in different military operations [2]. 65,000 amputations are caused by the loss of 1 or more fingers each year in US [3]. The solution for the amputation in this era can be a prosthetic upper limb. It may be an open loop prostheses which do not provide haptic feedback as a normal human skin does for somatosensory sensation.

Human skin is capable of detecting changes in temperature, pressure, vibration, electric stimulation. The human skin contains seven types of mechanoreceptors [13]. Four mechanoreceptor, out of seven lay on the skin tissue, each placed at the specific depth of the skin [14]. The deepest of which is Pacini Corpuscle under the class of RAII, lays 2mm beneath the surface of the skin. Pacini Corpuscle senses vibration in the bandwidth of 40 Hz-800 Hz and most sensitive at 200 Hz-300 Hz. Merkel cells are the one responsible for sensing pressure, and mostly they are exploited for tactile display applications [15]. Different modality indicates the different appropriateness of each receptor in order to replicate the particular sensation to feel on the skin. Pacini Corpuscle is under special consideration in this research, for vibration sensing. Recreation of the Merkel cells functionality through different means for pressure sensing also require special attention. Open loop prosthesis does somehow provide amputees to perform the basic function with their limb but prevents them from experiencing the environment due to the lack of haptic feedback.

Advance myoelectrically controlled hands capture the EMG signals from the residual arm through attached surface electrodes on the muscles and process them to provide specific signals to perform the required action (e.g. opening and closing) [12]. The non-availability of haptic feedback in those advance myoelectrically controlled hands is still a research question. The rejection rate of the prosthetic hand is very high, especially for electrically controlled due to the difficulties in adaptation [16]. On the other hand, body-powered prostheses offer kinesthetic feedback transmitting from Bowden cable. According to the psycho-physiological assessment, that a user gets stressed when relying solely on visual feedback [18].

Closed loop prosthesis is an actual need in the advancement of technology we are witnessing today. Users get accustomed to the auditory feedback produced from running motor and vibration through close fitting sockets in the electric controlled prosthetic upper limb [17]. Auditory feedback does help users to determine the movements without visual dependency. Miliou et al. [14] described the applications of prostheses with haptic feedback in the military and from medical to entertainment. Antfolk et al. [8] proposed the development of prosthetic limb with tactile feedback. Furthermore, Mulvey et al. [9] tested the feasibility of sensing feedback from the transcutaneous electrical nerve system (TENS). The real task of gripping is achieved through visual feedback of a person and his memory of grip for that particular object and without visual feedback, the person is left to rely on previously acquired information regarding that grip [10]. Therefore haptic feedback is the only way to remind him about the amount of force he had applied in the previous attempt. Researchers have demonstrated different methods of integrating tactile sensations in the past [5], [6].

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Shannon G.F. [7] has done a detailed study on the advantages of an electrotactile display through a prosthetic finger for texture discrimination.

Chai et al. [11] designed a close loop sensory feedback system which generates signals of a specific pattern according to the pressure exerted on the finger tip of the prosthetic hand. On the contrary, prosthetic upper limb without haptic feedback does not provide leverage to feel the grip and force exerted by the users. Researchers have studied different ways to implement haptic feedback on prostheses, they have specifically experimented vibrotactile feedback by using different types of sensors and actuators. Hanif et al. [16] conducted the research to discriminate texture with the help of vibrotactile actuators, texture discrimination was possible with the vibration felt at the tip of the finger by sliding it along the surface. The vibrotactile feedback is highly compatible with every type of prostheses and more preferred than electrotactile stimulation [19]. According to our hypothesis haptic stimulation from prosthetic limb would make grasping and manipulating easier for amputees. It must be in their intuition of how much force they should apply to grasp a particular object. One of the main purposes of this research was to develop a compact, robust and most importantly lightweight haptic feedback system.

Our main contribution in this research is that, we have enabled amputees to apply calculated force through their conscious to hold an object, we have combined the artificial upper limb with force sensor to measure the applied force and vibrotactile feedback to make him feel the amount of force he applies in an instance for users to grasp anything and apply force intuitively to grip it. The vibrotactile feedback system appeared to be cheap and non-invasive [12]. Witteveen et al. [6] studied that vibrotactile feedback can be acquired from vibration motors and tactors. One of the main advantages of proposed haptic feedback system is that it can be implemented on any type of commercially available prostheses. On the basis of the response from the users which says that although body-powered prostheses provide kinesthetic feedback from a push or pull, but grasping and manipulating objects largely relies on the tactile sensation, which can be easily acquired from a pressure sensor. Therefore, a pressure sensor is placed on the fingertip of the prosthetic hand and usage of the miniature vibrotactile actuator at the stump for exteroceptive stimulation is appropriate for haptic feedback. Prosthetic upper limbs with haptic feedback may fulfill an amputee's inability to feel through his prosthetic upper limb. It provides an artificial sense of touch to improve the performance of daily home chores. Test subjects in this research endorsed the effectiveness of our proposed design.

II. System Design

Previous haptic feedback prosthetic system used to be obtrusive and bulky [8].The issue of portability was resolved by the usage of miniature force sensor and coin type vibration motor. A unique combination of components is used including Arduino Uno, an FSR (Force Sensing Resistor) and a couple of coin type vibration motors. A complete signal processing units were used previously for pulse generation, for that purpose Arduino Uno is being used instead. FSR was placed on the index finger with the help of double-sided adhesive tape and cover it for better grip and to prevent from damages as shown in Fig. 1. Proper circuitry along with Arduino Uno was placed on opisthenar of a prosthesis as shown in Fig. 2. A pair of vibration motor was attached beneath the Velcro on forearm as shown in Fig. 3. The force measured by Force Sensor was sent to Arduino Uno through its ADC module and after performing required processing, Arduino Uno generates proportional output to operate actuators. Although we have tested and experimented it with 3D printed prosthetic hand but the biggest advantage of proposed design is that it can be integrated with any kind of prosthetic hand whether it be electric controlled or body-powered with certain modification in design.

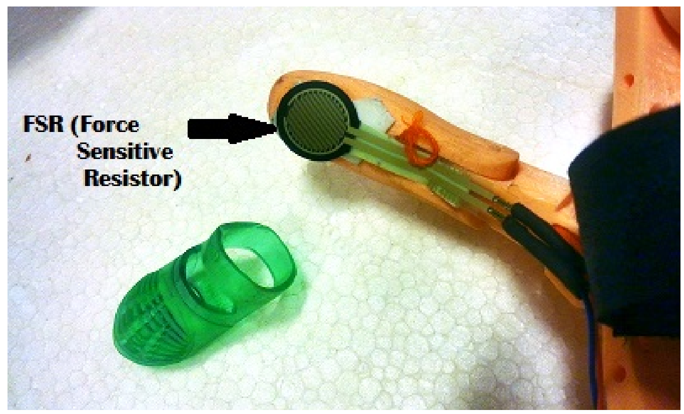

Fig. 1. Force Sensing Resistor placed on thumb of 3D printed prosthetic hand

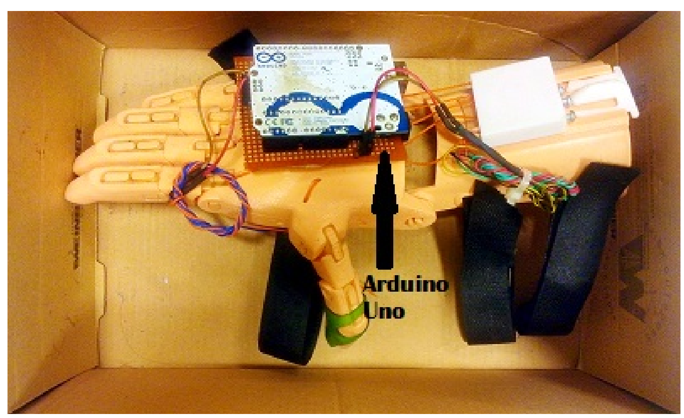

Fig. 2. Arduino uno screwed on the back of palm

Each of the components are discussed in detail below.

A. Prosthetic upper limb.

We have used open source 3D printed prosthetic hand as shown in Fig. 4. It is a body powered passive prosthetic hand. Countless amputees use body-powered prosthesis upper limb because of its kinesthetic feedback and low cost. Due to the provision of 3D printing facility, its total cost

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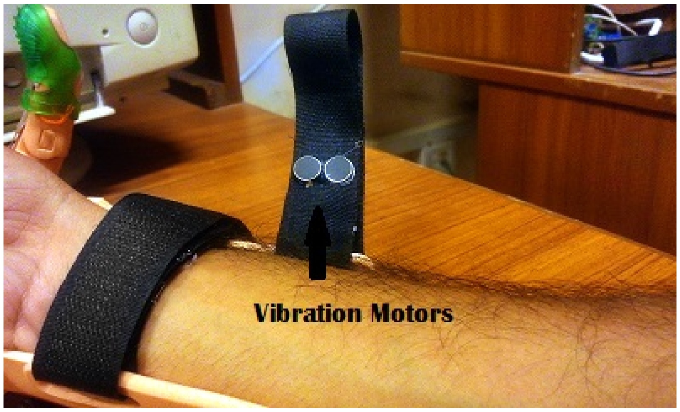

Fig. 3. Vibration motors on the forearm

has significantly decreased [20] and its lightweight provided us enough margin to attach components without making it uncomfortable for the users.

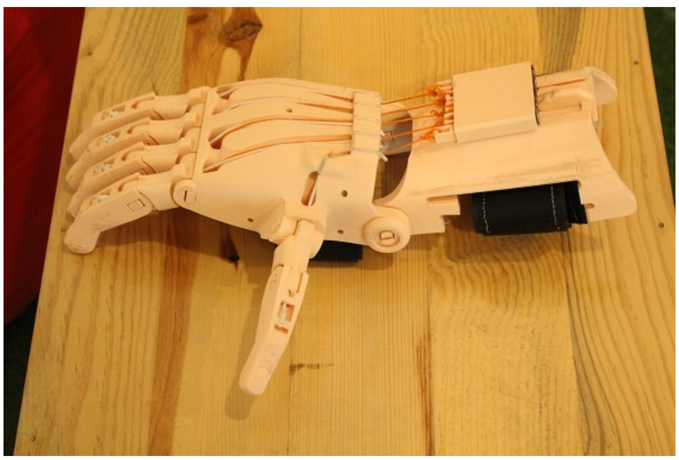

Fig. 4. Open Source 3D printed prosthetic hand

B. Force Sensing Resistor

FSR is a polymer thick film as shown in Fig. 5, its resistance decreases with the increase in force applied by the user. Although FSR is not suitable for precise measurement but it is optimized for human's sense of touch. The main purpose of using FSR is to measure the force while amputee is interacting with the environment using a prosthetic hand. FSR comes in the range of different shapes and sizes [21]. We have used 0.5-inch diameter circular FSR because it covers comparatively the larger area and the probability of coming into contact while interacting with the environment are high.

C. Vibration Motor

Coin type vibration motors are shaft-less and their compactness makes them easy to mount on any surface with a self-adhesive mounting system as shown in Fig. 6. It comes in the range of 8 mm to 12 mm of diameters [22]. We have used 10 mm diameter because it is suitable for our haptic feedback system. The purpose of using this type of actuator is low power consumption, which allowed us to use relatively compact power source.

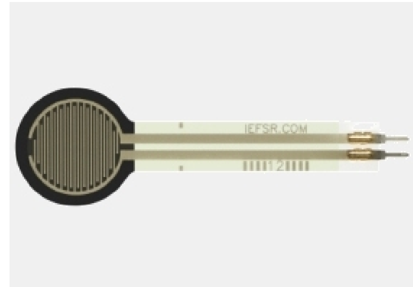

Fig. 5. (Http://www.interlinkelectronics.com/FSR402.php) Force Sensing Resistor

Fig. 6. (Https://www.precisionmicrodrives.com/vibration-motors/coin-vibration-motors) Coin shaped vibration motors

D. Power Consumption

Power consumption should be low enough to give optimum running time. We have achieved our objective by limiting the entire system to consume 1.5 W. Total power consumption depends on the current consumed by the actuators which can go up to 60 mA. The maximum output current of I/O pin is 20mA and 50mA in Arduino Uno for 5V and 3.3V I/O pins respectively. So, the power supply of 445 mW-1.5 W can be optimum for this device to run.

III. CONTROL ALGORITHM / IMPLEMENTATION

We have adopted a simple yet different approach for generating vibration patterns i.e the amplitude is proportional to force and frequency decreases with passing time. Moreover, in accordance with our approach as shown in Fig. 7, when a subject first touches something he feels a pulse of high amplitude for 0.5 sec, this burst makes him feel that some object has come into contact with his prosthetic hand, after this constant vibration; a predefined pattern of vibration of 45Hz will be produced. Further, frequencies of repeating vibration pattern will also decrease with time until it reaches 0.4 Hz. The Purpose of decreasing frequency is to make subject feels that he has held an object for a long time. Another burst of vibration (a constant pulse of 0.5 seconds) user feels when he leaves the object, this is to inform him that he has left the object or object has slipped through his hand.

The force is sensed through force sensor using analog read pin of the controller, then the analog value is mapped to the range of (0 - 255). 0 to 255 is the PWM range that causes the average digital output to vary from 0V to 5V. This average voltage is responsible for varying the amplitude of vibration. The time period of vibration was set to 220 mS initially and then there is an increment of 70 mS after each vibration which is decreasing the pulse repetition frequency. Analog value increases along the force applied on FSR, duty cycle of vibration motor increases accordingly. Hence, the intensity of vibration is proportional to the analog value of FSR. When the maximum force is applied , the duty cycle becomes approximately equals to 100%, then actuators will produce maximum vibration.

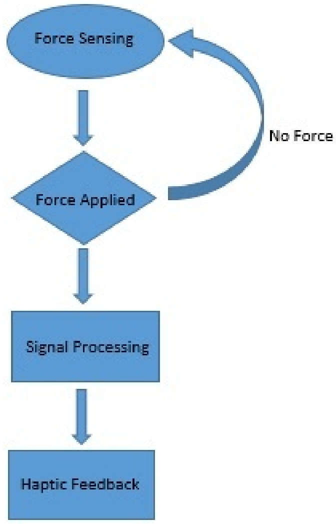

Fig. 7. Process flowchart

IV. Experimental Procedure and Results

On healthy Subjects

A. Procedure

The first phase of the experiment was conducted on healthy subjects. The purpose of conducting such experiments was to identify real issues, which amputee faces from the prosthetic limb as a replacement of natural limb. Total number of participants in this experiment were 7, out which 5 of them were healthy females and 2 healthy males, between the age of 20-25 years old. Since a healthy person cannot use a prosthetic hand like amputee does, therefore this experiment consist of 2 persons at a time to imply amputee's condition. User-I would wear force sensor with the help of double-sided adhesive tape in order to grasp an object and User-II wore prosthetic hand to interpret the signals and differentiate the weight of object held by User-I. One of the participants became User-I, and rest of 6 participants became User-II, one by one. Each of User-II was given 5 attempts to recognize weights. To make this experiment more difficult, visual feedback for User-II was blocked by hiding objects held by User-I as shown in Fig. 8. User-II had to solely rely on haptic feedback.

Fig. 9 shows, three disposable plastic bottles were used. Each bottle was filled up to 3 different levels for participants to differentiate their weight.

Fig. 8 shows that User-I held each bottle in random sequence. User-II had to guess the sequence by interpreting the intensity of vibration on the basis of haptic feedback. The entire procedure was repeated 5 times with each participant. Each of the user-II was given 5 attempts to show the effectiveness of practice. The answers were categorized under the number of attempts and the correct guesses made by User-II in each attempt.

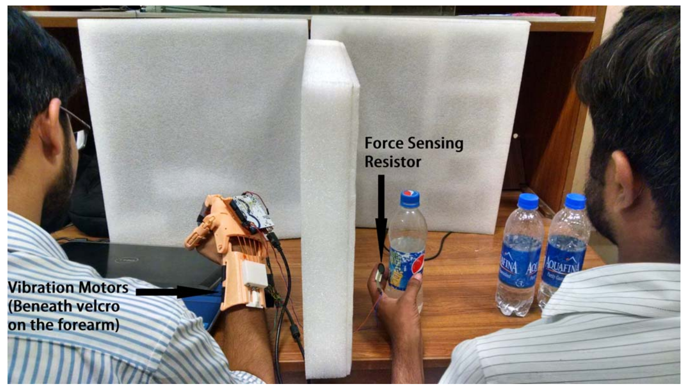

Fig. 8. Experimental setup

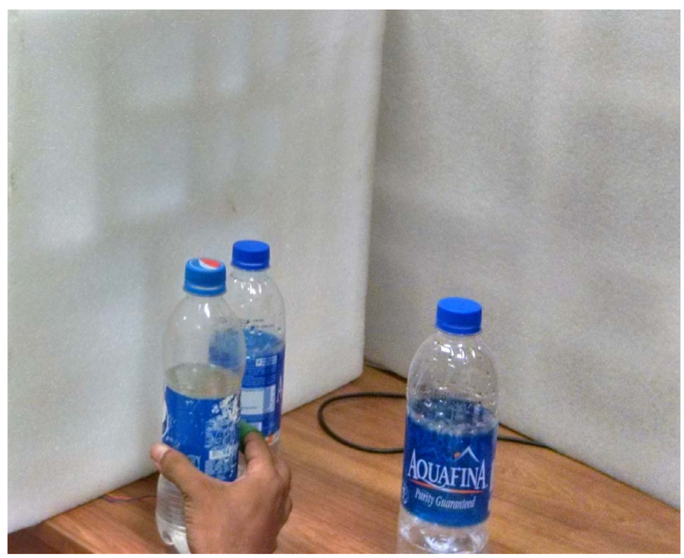

Fig. 9. Three bottles filled to different levels

B. Result

The output response from holding each bottle was significantly different. In Fig. 10, user held an empty bottle. The output is very low in amplitude, low amplitude signifies the low intensity of vibration and pulse repetition rate is gradually decreasing with time between the start and end spikes. In Fig. 11, the half-filled bottle was held, the amplitude is greater than that of an empty bottle but not maximum. Fig. 12 shows the response of holding a filled

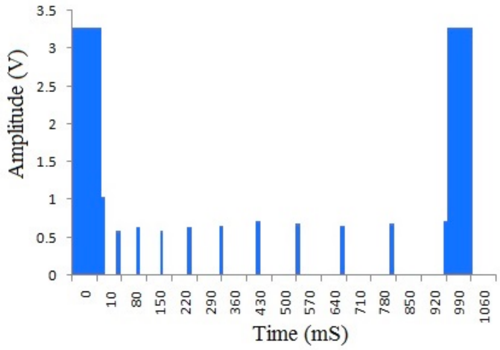

Fig. 10. Response from empty bottle

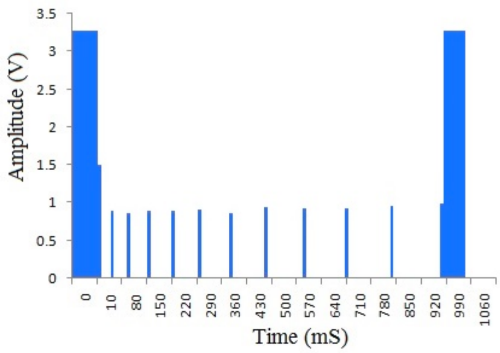

Fig. 11. Response from half filled bottle

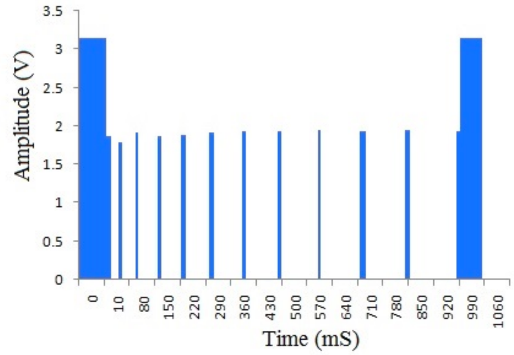

Fig. 12. Response from completely filled bottle

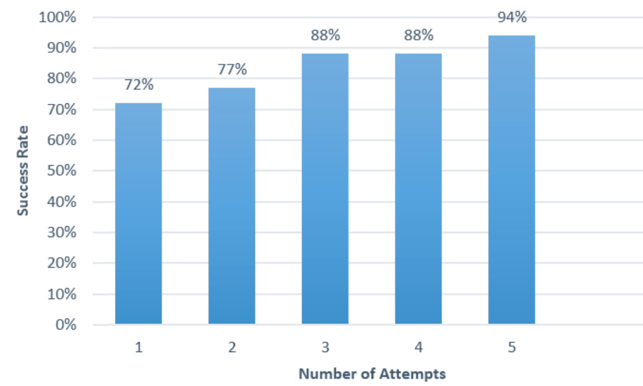

Fig. 13. Subject's response

bottle. Fig 10, 11 and 12 gives difference in the response of the output among different forces applied on different objects while grasping. These different responses were intended to make the participants observe and determine the bottles. Fig. 13 shows that percentage of correct guesses by User-II combined in the first attempt was 72% only. Success rate describes that each User-II was able to determine 72% correct bottles only. After few more attempts, success rate climbed up to 94%, which means that 94% of guesses were made correctly by the participants altogether. This improvement is evident that regular amount of practice is required to adapt haptic feedback.

On Amputees

C. Procedure

The second phase of our research was conducted on an amputee, whose right hand had no fingers including thumb as shown in Fig. 14. The Subject was given enough time for practice and to learn the basic operation of a prosthetic hand. He was asked to hold an empty 500 ml disposable plastic bottle without haptic feedback system on prosthetic hand and then he was asked to pick an empty bottle by a prosthetic hand incorporated with haptic feedback system as shown in Fig. 15. Subsequently, a completely filled bottle with the same. He was asked to hold bottle multiple time because it was difficult for him to adopt something he has never experienced before. Regardless of several practices and trials he got used to proposed design and performed the desired task intuitively.

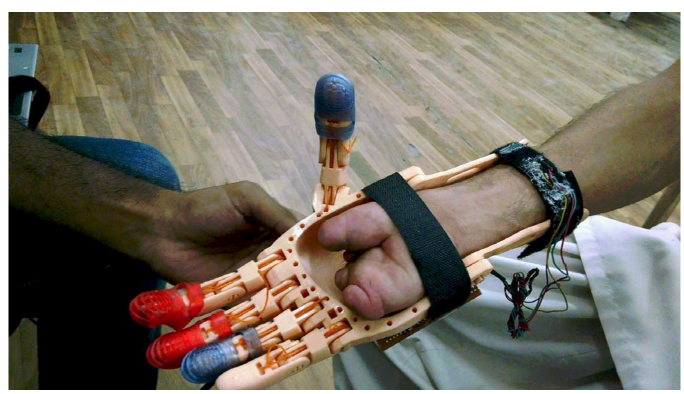

Fig. 14. Subjects hand

D. Result

After the experiment, we recognized that user requires practice to become accustomed to the vibrotactile sensation. The answer to the basic question asked from the patient that would he prefer prosthetic with vibrotactile sensation or he would go for a normal prosthetic hand. Our subject opted for prosthetic hand including haptic feedback system instantaneously.

The varying vibrotactile sensation according to the force applied and vibration signaling the contact occurred and

Fig. 15. Subject holding bottle with prosthetic hand consisting vibrotactile stimulation system

contact ends may prove significant for the comparative evaluation with normal vibrotactile stimulation.

V. CONCLUSIONS

In this research, we have developed a system which generates haptic feedback to feel the force applied by the subjects through his prosthetic hand. The proposed idea was tested on subjects through experiments and concluded that subjects would be able distinguish the effects of force through the intensity of vibration, which is proportional to the force applied and rate of pulse repetition decreases with time. The experiment was conducted on 6 healthy subjects and an amputee. Analysis were made that after some demonstration and practice, healthy subjects were able to determine the objects with the help of haptic feedback in the form of vibrotactile sensation on their forearm while keeping their visual feedback blocked at the same time. Great improvement was seen among 6 subjects from first to fifth attempts. The proposed idea was tested on a disabled person too. The purpose behind this test was to measure its virtue mainly, his comments on the idea and the system were taken into account and further improvements shall be made accordingly. In future, more experiments will be conducted with disabled persons to see the effectiveness of the proposed.

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