A Hybrid Haptic Feedback Stimulation Device to Recover the Missing Sensation of the Upper Limb Amputees

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Abstract. Providing sensory feedback for prostheses users increases the manipulation ability, as well as introduces a feeling of the embodiment. A novel hybrid haptic feedback stimulation system of the amputees of upper limb mutilation was designed, developed, and evaluated in this study. The haptic wearable device was built by mean of single servomotor as a pressure feedback display and a pair of vibration motors as a vibration feedback display. Accordingly, the pressure display is responsible for conveying the missing sensing of the contact pressure and its force level. While the vibration display has utilized to provide an indication about the continued contact pressure. Able-body participants are engaged to evaluate the performance of the proposed feedback stimulation system. The results show that the participants are able to distinguish the touch, the start of touch, the end of touch, and the range of force with 100 % accuracy. While 96 % and 88 % of the able-body participants are capable to identify the grasp and the slipping objects, respectively. Furthermore, the ability of the proposed haptic wearable device to convey the tactile sensory information to the user’s brain without confusing or pre-training was improved.

Keywords: Feeling recover; Contact pressure detection; sensory system; Tactile glove; Upper limb prostheses.

1. Introduction
In the US alone there are more than 1.6 million people living with the loss of a limb with upper-limb loss accounting for 68.6% of trauma related amputations and 58.5% of congenital birth defects [1]. The upper limb prostheses have been used to help the amputees who are unfortunately missing there healthy hands. The prosthetic hands were designed to assist the amputees to touch and grasp objects, however, the lack of feeling through the use of prosthetic hand still the main design’s issue, in order to make the amputees in continues interacting with their surroundings.
Several previous works developed the technologies of the tactile displays that used to stimulate the residual skin and nerves system of the amputees [2]. These technologies have ranged from non-invasive approaches using vibrators [3] or pressure [4] to more complex approaches providing spatially-mapped tactile displays of pressure, vibration, shear force, and temperature [5] in subjects who have undergone targeted re-innervation surgery [6]. Furthermore, the previous researchers are going to gathering two or more types of the haptic feedback system named the hybrid feedback stimulation system [7-11]. In general, a common requirement from amputees is to be able to operate prostheses without constant visual attention [12, 13], and proprioceptive feedback has been shown to improve targeting accuracy under non-sighted conditions [14].

The main purpose of this study is to present the first steps towards design a hybrid haptic feedback stimulation system (HHFSS), which has the ability to help the patients of the upper limb amputation to recognize multi-information about their surroundings without brain confusing or a pre-training requiring. The haptic device was designed to deliver the sensation of the contact pressure to the amputees’ brain by a multi-site pressure and vibration displays applied on specific spots on their residual limb. The pressure display used a single servomotor where the contact pressures on the fingertips of the prostheses were delivered as pressure on the skin. Meanwhile, the vibration display translated the pressures on the fingertips into vibration sensation by mean of two vibration motors. To the best of our knowledge, this is the first study to combine the haptic pressure and vibration feedback displays for upper limb prostheses, in the way that allows the stimulators to operate in different directions and various excitations signals but performing the same purpose, i.e. delivering of the tactile sensory information to the users in a quick manner.

2. Design conception of haptic feedback stimulation system

In general, a HHFSS of the prosthetic hand can be sorted into three principal parts: collect the data of the amputees' environment by using different kinds of sensors in the haptic system, process the sensitive data, and control the feedback stimulators to stimulate the amputee's understanding using a computer system, as shown in Figure 1. Indeed, the HHFSS excites the amputees’ nervous system by stimulating the skin of their remaining parts such as the forearm, upper limb, or any additional parts of the body.

![Figure 1. The design concept of HHFSS.](image)

Accordingly, six Quantum Tunnelling Composites (QTC) force sensors were utilized to detect the contact pressure, five sensors were attached to fingertips and one force sensor was fixed on the hand’s palm. The device was designed to excite the amputees’ nervous system with a hybrid sensation of
pressure and vibration stimulations at the same time by a mean of two circular vibration motors and one mini servomotor.

The obtained signals from the haptic glove system were conveyed to the control process system by utilizing an Arduino Mega microcontroller. Subsequently, those six force signals received from the QTC force sensors were compared to produce the highest instant output signal. The highest instant signal of entire sensory signals was passed through the control system as the input actuators signal of the haptic system. Depending on the input actuators signal, the control processor system manages the actuators of the HHFSS by exciting both the pressure feedback display and the vibration feedback display. The PID controller was used to control the excitation actuators at the high response and acceptable accuracy [15].

The purpose of the hybrid haptic feedback stimulation system is to excite the residual upper limb of amputees and convey the feeling of the touch, the start of touch, end of touch, grasp, slippage, and force range to the patient’s brain. Therefore, the hybrid haptic feedback system has been designed to increase the ability of the amputees’ brain to understand the huge quantity of data produced by the tactile glove system.

Regarding the haptic wearable device, three actuators have been fixed on 70 cm diameter and 8mm depth curve case, as displayed in Figure 2. The curve case was designed using Solidwork 2018 and fabricated by a 3D printer using ABS material [16]. The feedback stimulator device includes one servomotor [17] for the pressure excitation and two Linear Resonant Actuator (LRA) vibration motors [18] for the vibration excitation. An auxiliary of piston of 15 mm diameter and a piston’s arm of 33 mm length were used with the servomotor to produce the pressing force.

![Figure 2. The design conception of the haptic wearable device.](image)

3. Fabrication of the tactile pressure glove
A plastic glove with QTC pressure sensors was created as the tactile glove system of the HHFSS. The tactile glove’s design, fabrication, and evaluation examinations were considered in our previous work [19]. In general, the haptic glove was fabricated from a plastic material. While each finger covered with hard support material under the pressure sensors, in order to limit the elasticity of volunteer’s skin from changing the recording of the pressure sensors. Three significant advantages based on this kind of fabrication of the tactile system are: (i) the volunteers can wear the haptic glove system easily and push their fingers’ links evenly because the glove is manufactured from the flexible material, (ii) the hard material which covered of fingertips and the ball hand form the basis of the pressure sensors satisfying to work with great efficiency, and (iii) the glove is suitable for different hand sizes because of its expandability performance.

The solid shield was designed using the Solidwork 2018 software and printed by a 3D printer. The QTC force sensors with 10 mm diameter and 0.1 N to 20N acting force limit from Peratech [20]; were attached on critical points of the hand. However, five sensors have been fixed on each fingertip, and another sensor was placed on the hand’s palm, as described in Figure 3. Such arrangement is used to ensure that all critical areas of the hand are successfully covered, that’s lead to enhance the possibility to detect the contact pressure.
4. The experiment setup and functionality test

The pressure level experiment has been accomplished to evaluate the functionality of the HHFSS. The evaluation of pressure level experiment has been performed by covering the finger of the haptic glove to a column cantilever. After that, a hanging mass was attached vertically to the force sensor, which was fixed on the finger. The hanging mass was increased from 0 to 2 kg (i.e. from 0 to 20N) by adding 200g for each increasing step. The main goal of this experiment is to check the responses of the servomotor and the two vibration motors due to the rising in the force sensor signal.

For the stimuli identification experiment, twenty-five healthful participants have been volunteered in this project, mean age (25-34 years). The volunteers wore the haptic glove and HHFSS on their right arm, as shown in Figure 4. The eyes cover was utilized to avoid any visual vision during the test, in order to impact the brain for completely depending on the haptic stimulation.

The main goal of the experiments is to examine the volunteers’ stimuli identification rate (SIR), which is the rate that the participants could rightly recognize the haptic information through simply using the hybrid haptic feedback stimulation system. Three different tests were performed to rightly check the effectiveness of the proposed design and its ability to convey multi tactile information to the user’s brain at the same operation time.

At the first test, irregular forces were applied to the force sensors of the tactile glove. The volunteers were asked to press their fingers on the table and touch several objects. The volunteers have to answer
whether they can distinguish the touch, start of touch, and end of touch. This is to evaluate the efficiency of the wearable device in transferring information to the volunteer's brain by means of the haptic wearable device.

At the second test, evaluating the ability of the participants to identify the grasping objects was verified. The examiner asked the participants to grasp objects in different sizes and make a handshake with him. This is to test the functionality of a HHFSS to identify the contact pressure during grasping objects.

At the third test: the slipping object experiment was performed by using a columnar pipe equipped with a steel hook from its bottom side, as described in Figure 5. The columnar pipe was carried up by the volunteer. Then, variable masses were attached to the hook of the cylindrical pipe. The hanging load was increased gradually from 0 to 5.5 kg, 0.5 kg for each time. The main purpose of this test is to verify the functionality of the HHFSS to recognize the slipping objects. The slip detection test was conducted by asking the volunteers to grasp and handle the columnar pipe, while the suspended weight was raised slowly till the pipe slid down from hand. On the other hand, the second purpose of this test is to measure the ability of the volunteer to distinguish the sense of the increase in the contact pressure.

The experimenter evaluated the experimental observations as follows: yes, if the participants were able to identify the kind and the level of the excitation through the test, no, if the participants were unclear or inefficient to separate the haptic information.

5. Results
For the pressure feedback display of a hybrid haptic feedback stimulation system, Figure 6 presents the linear association between the servomotor rotational position and the highest haptic glove signal during the pressure level experiment. The rotational action of the servomotor was varied from 0-35 degree when the force signal of the tactile sensory system raised from 0-5 V, i.e. the load was increased from
0-20N. Based on the servomotor’s maximum rotational movement, which is 35 degree, and the length of servomotor’s piston arm, the perpendicular displacement of the servomotor’s piston was calculated, which is equal to 15.6 mm. This indicated that the pressure feedback display of a HHFSS is able to deform the skin of the user’s upper arm within 15.6 mm perpendicular displacement. This amount of displacement has the ability to stimulate the patient’s nervous system and notify the patient’s brain about the changing weight. This also means that this is the highest value to overcome the dead layer of the patient’s skin.

![Graph of increasing servomotor angle against contact pressure](image)

**Figure 6.** The increasing of the servomotor angle against contact pressure racing.

For the vibration feedback display, a repeatable pulses signal with 3V maximum amplitude, 0.2 sec period time, and a pulse width equal to 50% of the period time was designed to drive the two vibration motors, as shown in Figure 7. The special pulses vibration motor signal was designed based on several stimulation trials, in order to obtain the best feedback stimulation from the vibration feedback display without any interference with the noise frequency of the servomotor.

![Graph of vibration motor excitation signal](image)

**Figure 7.** The excitation signal of the vibration motors during 1 sec.
The excitation signal of the vibration motors was designed to work with constant frequency when the largest instant pressure signal varying from 0-5V. In other words, the excitation frequency of the vibration motors works undependably on applied contact pressure. The main reason behind this type of the excitation is to inform the user that the touch or grasp action is started and the still continues. The excitation signal was programmed to start working when the sensory signal exceeds 0.5V, in order to avoid activating the vibration feedback display when the phantom signals generated by the pressure sensors. The behaviour of the excitation pulsing signal and the vibration motors’ excitation signals among the large instant pressure signal of the tactile sensory system were described in Figure 8.

The stimuli identification rate (SIR) was measured for all experimental tests, which evaluated the performance of a hybrid haptic feedback stimulation system for conveying the tactile data to the volunteers’ brain, as illustrated in Figure 9. The results showed that all volunteers were able to realize the touch, start of touch, end of touch, and the force range with 100% accuracy. Furthermore, the lowest recognition accuracies of 88% and 96% were attained for the test cases of grasping objects and the slippage, respectively. The low identification percentage of the slippage test was related to the design of the sensory glove itself. A stable sliding sensor is not available in the sensory glove in order to notice the slippage. It simply depends on the organization among the pressure sensors and the replies of the participant’s nervous system.

The contributions of this work can be proved by performing a comparison study between the SIR results of the current study and previous studies, as summarized in table 1. The selected previous studies were selected as similar as possible to this work, in which spot pressure sensors were utilized in the respective works. On the other hand, previous studies used different types of feedback stimulation system, such as pressure, vibration, electro, squeeze, and skin stretch to compare the functionality of the designed wearable device with all types of the existing feedback stimulation systems. In addition, table 1 also summarizes the information about the installation position of the previous haptic feedback displays and type of subjects. The SIR results indicated that the current work present the best results in all the experiment examinations.
Figure 8. The excitation signal of the vibration motors: A) the vibration motor input signal, and B) the vibration motor output signal.

Figure 9. The volunteers' stimuli identification rate during the entire experiments.

Table 1. Comparison between the stimuli identification rate of the current study with the previous works.

| References | Type of sensory system | Type of Feedback display | Setup of Feedback display | Stimuli identification rate (SIR) |
|------------|------------------------|--------------------------|---------------------------|----------------------------------|
|            |                        | Hybrid pressure & vibration | Upper limb               | Touch  | Grasp  | Force range | Slippage |
| Current Study | Pressure               | Hybrid pressure & vibration | Upper limb               | 100 %  | 96 %   | 100 %       | 88 %     |
| [21]        | Pressure               | Vibration                | Forearm                  | 99.3 % |         | 94.7 %      |          |
| [22]        | Pressure               | Vibration                | Upper limb               | 94 %   |         | 75 %        |          |
| [23]        | Pressure               | Vibration                | Upper limb               | 93.9 % |         | 85 %        |          |
| [24]        | Pressure               | Pressure and Vibration   | Upper limb               | 93 %   |         | 90 %        |          |
| [25]        | Pressure               | Electro                  | Forearm                  | 90 %   |         |             |          |
| [26]        | Pressure               | Squeeze                  | Forearm                  | 70.3 % |         |             | 62.2 %   |

6. Conclusion
This paper presents a new hybrid haptic feedback stimulation system of the upper limb prostheses to assist the amputees of upper limb mutilation to recover the missing feeling through their prostheses. The hybrid haptic device was created to excite the user’s skin using two types of stimulators: pressure and vibration stimulators. The sensory glove created from a plastic element. Five QTC pressure sensors were
installed on each fingertip and another sensor was placed on the palm. The structure of a hybrid haptic feedback stimulation system device consists of a servomotor and a pair of vibrators, which operate concurrently to excite the patients’ nervous system.

The evaluation experiment tests indicated that the hybrid haptic feedback stimulation system works with a high level of precision. In overall, the SIR of the evaluation experiments confirmed the functionality and effectiveness of the hybrid haptic feedback stimulation system to convey multi tactile information to the volunteer’s brain without pre-training. The SIR rate of 100% were achieved for most of the experimental tests, i.e. start of touch, end of touch, touch and the force range. However, only 88% and 96% of the volunteers passed the slippage test and were able to recognize the grasping targets, respectively. In addition, the SIR of current work was compared to the results of the previous studies, in order to highlight the work contribution. The comparison results showed that the results of the current work are better than of the previous works, in spite of the current experiment was performed without any kind of a pre-training to improve the perception precision.

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