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

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Abstract

Anon-invasive hybrid haptic feedback stimulation system that can sense the contact pressure was designed for a prosthetic hand, in order to recover the missing sensation of the amputation patients. The main objective of this work is to develop and evaluate the first step of a novel approach for a lightweight, 7 Degrees-Of-Freedom (DOF) prosthetic arm to perform an effective object manipulation and grasping. Furthermore, to convey the tactile information about the contact pressure with high identification accuracy. However, a novel wearable hybrid pressure-vibration haptic feedback stimulation device for providing the tactile information about the contact pressure between the prosthetic hand and the grasped objects to the user's brain is designed to achieve the main objective of this study. An evaluation of sensation and response has been conducted with forty healthy subjects to evaluate the ability of the haptic system to stimulate the human nervous system. The results in term of Stimulus Identification Rate (SIR) presented that the whole participants were correctly able to discriminate the sensation of touch, stare of touch, end of touch, and grasping objects. While 94%, and 96% of the entire stimuli were successfully identified by the volunteers during the experiments of slippage, pressure level, respectively.

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1. Introduction

According to the statistics study made by the Federal Statistical Office in Germany, 22,608 patients with upper limb insufficiency are recorded [1]. In the previous three decades, the number of amputees with upper limb mutilation has been increased, especially in industrialized countries. However, the Myoelectrical prosthetic hand is the best solution for amputees to help them to recover their live activities. While many problems were rice after wear the prosthetic hand more than eight hours like the lightweight and sensory feedback requirement[2]. Thus, numerous research on haptic feedback system is trying to develop prosthetic hand with a sensation system as close as possible to the real hand, in addition, it can perform the identical activity with the equal number of degrees of freedom comparing with the real hand.

The importance of conveying the missing sensation from the tactile prosthetic hand to the patient's nervous system is not only limited to transfer the feeling of the handgrip, but it also works on helping the user to control the applied contact gripping force to prevent sliding object. Moreover, the main important function of the haptic system is to enable the user to detect the surface type, roughness, temperature, humidity, and rigidity, depending on the types of sensors that included in the tactile system.

On the other hand, the creation of an accurate connection between the sensory system signals of the artificial hand and the physiological nerve channels of patients residual limbs still the main challenge faced by the industry of tactile prosthetic hand. Indeed, there are only two different methods to recreate the touch sense and provide it to the artificial hands' users. The first one called invasively method; it depends on the direct contact with the neural structures by the surgical access to the nerves of the amputees [3, 4]. The non-invasively stimulation method is the second type of recovering the missing sensation; it depends on the output stimulation devices erected on the residual limbs to motivate the neural that serves out the last hand [5, 6]. Nevertheless, recognizing the feedback stimulation signals of the artificial hand in a high-performance way is the main issue faced by amputees. However, several training hours with the tactile prosthetic hand are highly recommended [7].

The non-invasively tactile system consists of three main parts; the tactile sensory system, the haptic feedback stimulation system, and the computer interfacing system. Measuring different parameters signals from the surrounding and transferring itto the electrical signals are the main function of the tactile sensory system. In general, the voltage that passed through the sensor effected directly with any change at the environment parameters. Several previous works investigated how to measure the contact force or pressure between the prosthetic hand and the grasping object using a multi-type of sensors like quantum tunnelling composite sensor (QTC)[8], force sensitive resistor sensor (FSR)[9], piezoelectric sensor[10], and Bio Tac sensor[11].

The processed measured signals at the interfacing system, serve as the input signal to the feedback stimulation system. Broadly, the feedback actuator is a mechanical, vibrational, or electro device which has the ability to stimulate a patient's residual part [12]. The feedback actuator consists of three main types, depending on how to excite the amputees' body. These three types are the pressure actuator [13],the vibration actuator[14], and the skin stretch actuator [7]. It is worth mentioning that some of the previous works compared the performance of using more than one type actuator at the same time, in order to evaluate which actuator has better performance, like the comparison between the pressure and vibration feedback stimulation [6,15], also between vibration and skin stretch [16].

Amputees highly require to recover a sense of touch from their prostheses in carrying out their daily activities. Thus, a haptic feedback stimulation system providing a sense of touch is an essential functionality for upper extremity prostheses. The main purpose of this study is to enable the patients of the upper limb amputation to recognize a multi-information about the environment in an easy way without any issues related to brain confusing, by designing and developing a hybrid haptic feedback stimulation system. The hybrid system includes a hybrid tactile sensory system, which is responsible for gathering the perceptual information about the touch, start of touch, end of touch, slippage, and pressure level at the same time. Furthermore, the hybrid system has a hybrid haptic feedback wearable device, which is responsible for the human-machine interface, by transmitting the perceptional information to the user by mean of stimulating the skin of the user's residual parts.

On the other hand, the second purpose of this work is to design a prosthetic arm capable to help the patients, which have unfortunately lost their upper limbs and compensated it by haptic artificial prostheses, become able to perform multiple tasks similar to the real biological arm. This development necessary to improve their daily activities and increase the proportion of their acceptance to their prostheses.

2. Design conception of the tactile feedback prosthetic arm

In general study, the proposed prosthetic arm consists of motors, artificial tendons, and moveable fingers are bent by winding the tendons. A pressure, vibration, temperature sensors are attached to the fingertips and the palm of the prosthetic hand to be in contact with the grasped objects. The pressure sensors are in charge of measuring the contact pressure during touching or grasping objects. While the responsibility of the vibration sensor is recording the surface information when the prosthetic hand is going to slip over the surfaces. Lastly, determining the object's temperature and transfer it to measurable data is the accountability of the temperature sensors.

To enable the users of the upper limb prostheses to recognize the sensation more intuitively, the sense of contact pressure was given to the prosthetic hand users when they grasp an object by mean of the hybrid pressure-vibration feedback stimulation system (FSS). The surface texture sensation was regenerated by using vibration FSS. While the tactile temperature sensory information is conveying to the user's brain by utilizing the thermal FSS. The recover sensation of pressure, surface texture, and temperature were presented by exiting the upper arm's skin of the users. The structure of the proposed haptic feedback stimulation system is presented in Figure 1, in order to clarify the main goal and the development progress of the general study. While this study will focus on measure the contact pressure and convey the tactile contact information to the user brain. The tactile information of the surface texture and the object temperature will be discuss in another works.

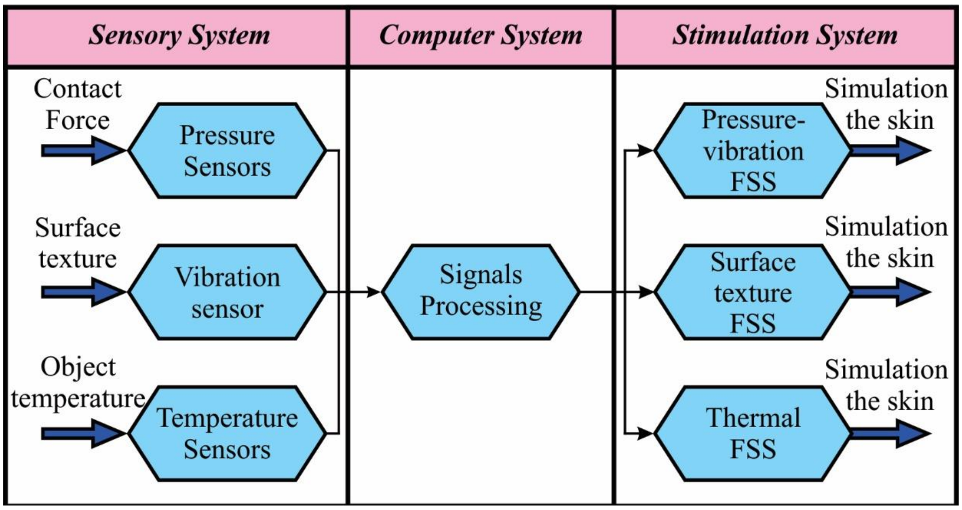

Figure 1. The structure of the proposed haptic feedback stimulation system.

2.1. Design conception of the tactile prosthetic arm

To create useful upper limb prostheses, it is necessary to have a well-designed mechanical system which mimics the functionality of the human arm as best as possible. The mechanical design involves how joints are actuated and the types of forces present in the system. The

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bionic arm design that presented in this study can be entirely manufactured with a 3D printer and basic tools. Figure 2 shows the assembly of the mechanical components of the proposed prosthetic arm.

After researching several actuation methods for prosthetic arms, an artificial tendon design was chosen as a viable way of actuating bionic hands. The tendons can be any high strength line which does not stretch when tensioned. These lines connect to the fingers and are tensioned by motors in the forearm. Pulling on the tendons cause the fingers to open and close. The electric motors driving these tendons must be completely housed inside the device in order to make it portable and attachable to an amputee. Ideally, the motors should be placed as closely as possible to the prosthetic fingers, however, due to their relatively large size, the motors housed within the forearm. Amputation can occur anywhere along the arm and is unique in every case. An ideal design facilitates connection to a stump located anywhere along the arm.

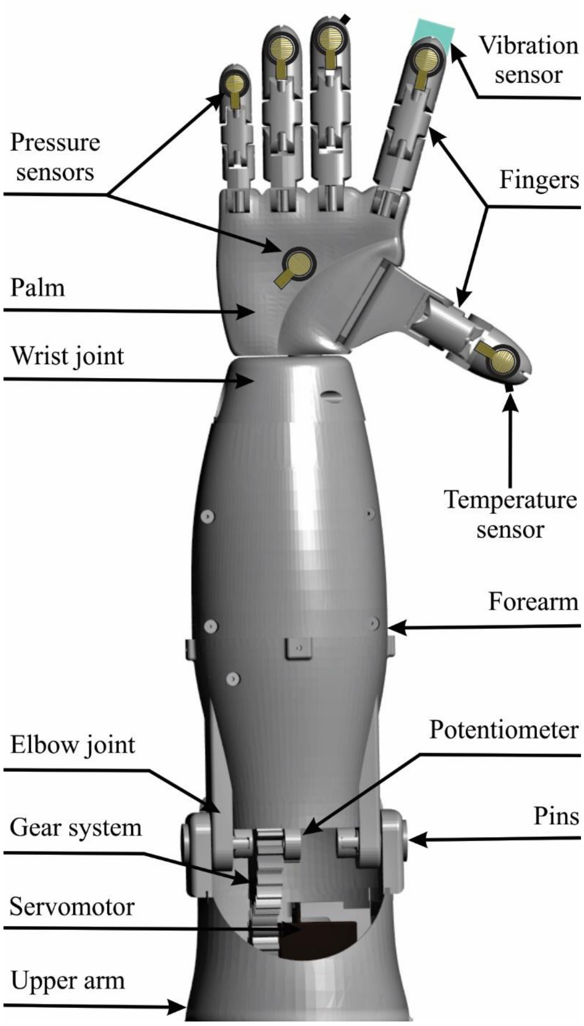

Figure 2. Design conception of the tactile prosthetic arm.

2.2. Design conception of the hybrid tactile sensing system

Pressure sensing plays an important function in the human hand for holding, grasping, pushing or pulling objects. It allows us to adjust the pressure applied to objects for better maneuverings. For optimal covering of the fingers and palm of a prosthetic hand and to enable the use of all sensing functionalities. In addition to the priority of using low price tools, in order to reduce the overall prosthetic arm's cost. Six of spot piezoresistive pressure sensors are used to cover the prosthetic hand instead of using tactile artificial skin to cover the entire hand. Accordingly, five pressure sensors were attached at each fingertip and one sensor fixed on the hand's palm[8], as shown in Figure 3. The main reason for this type of distribution is to increase the probability of detecting the contact pressure during touching or grasping objects.

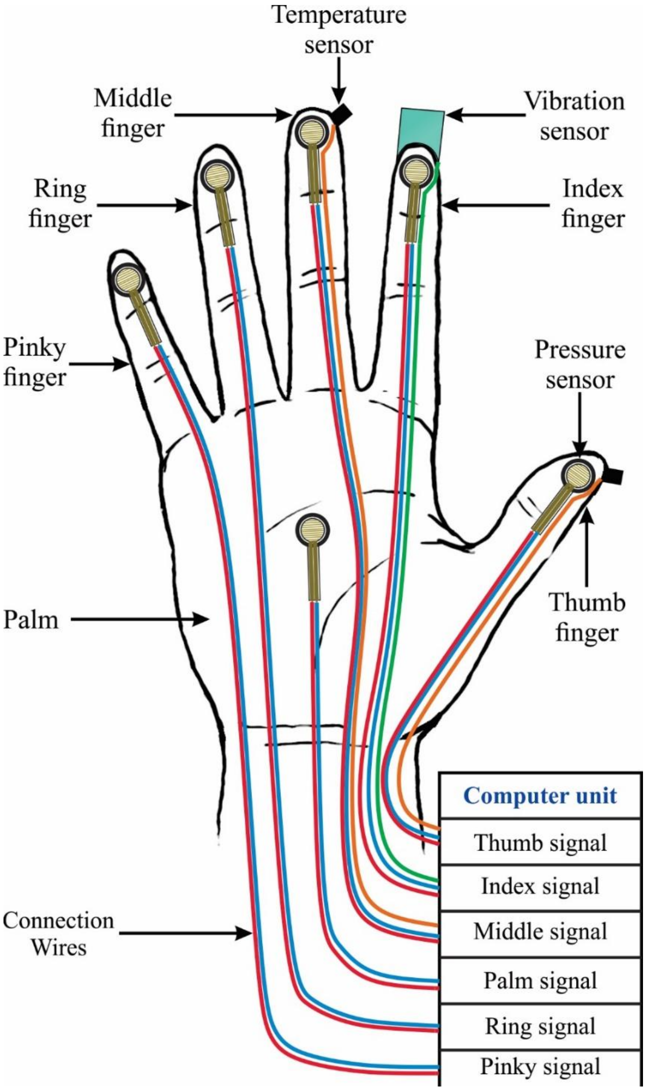

Figure 3. Design concept of the hybrid tactile sensory system.

2.3. Design conception of the hybrid haptic wearable device

A hybrid haptic pressure-vibration feedback stimulation system (HHPVFSS) for both pressure and vibration has been designed to increase the haptic response and ability of the amputees' brain to understand the huge quantity of data produced by the haptic glove system. 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. Since the two vibration motors can work independently and provide the vibration stimulation directly to the arm, therefore, it was fixed at inner side of the curvature wearable case in direct contact with the patient's skin. On the other hand, a circular piston of 15 mm diameter and piston's arm of 33 mm length have been added to the servomotor to deliver the pressure stimulation.

The diameter of the piston and length of the piston's arm were increased to increase the excitation activity and enhance the haptic stimulation. Moreover, both of the position of the piston arm of the pressure FSS and the frequency strength of the vibration FSS become proportional to the larges instant pressure signal, which generated from the tactile sensory system.

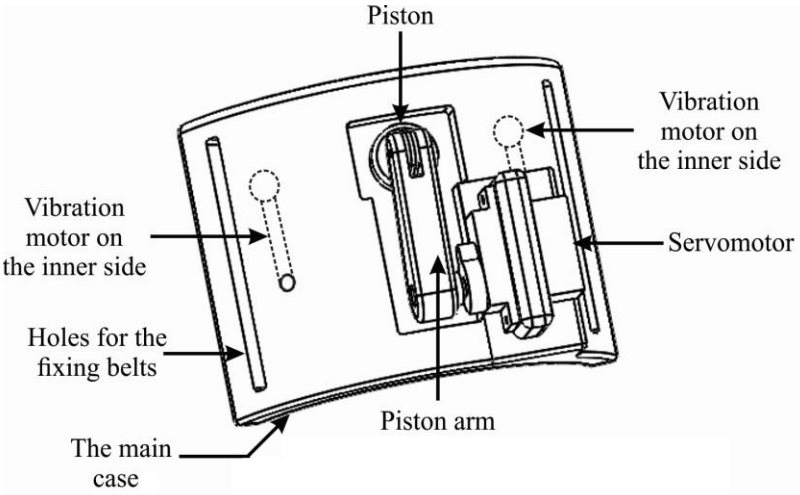

Figure 4. Design conception of the hybrid haptic wearable device.

3. Fabrication of the tactile feedback prosthetic arm

3.1. Fabrication of the tactile prosthetic arm

The fabrication of the designed prosthetic arm is presented in Figure 5. Each finger consists of three individual printed components linked together with plastic pins. The artificial tendon loops around the inside tip of the finger to create a tendon locking point. This tendon runs through channels inside the finger to form an enclosed loop. Then, the tendon fixes to rotational pulleys from the free end side. When the pulleys are driven, forces are applied to all the joints and the finger curls up.

High quality braided fishing line has been used as it offers minimal stretch when tensioned. Tendons in the biological human handwork in a similar way, however, there are far more biological tendons attached to different bones allowing for more precise control of the fingers.

The thumb has also been designed in a similar fashion. Most commercial and research prosthetic hands aim to provide at least two degrees of freedom in the thumb. This thumb however only provides a single degree of freedom, Thus it can only open/close in a single way. Lastly, each finger of the prosthetic hand connects to the hand's palm by utilizing plastic pins.

For the wrist joint, the palm section was directly connected to the shaft of the servomotor in the forearm. A passage through the pivot point of this joint allows the tendons to pass from the fingers through to the forearm. This allows for ± 90 degrees of rotation about the wrist and eliminates the problem of angular position control.

3*.2. Fabrication of the hybrid tactile sensory system*

The hybrid tactile sensory system of the tactile prosthetic arm was developed to convey a multi-modal tactile feedback to the human operator's hand that would assist the user while performing dexterous object manipulation and recognition tasks. The main design goal behind the development of the hybrid tactile sensing system is the construction of a robust, safe, low cost and, above all, have high measuring responses with acceptable accuracy.

The hybrid tactile sensory system, as presented in Figure 5.a, consists of a rigid platform supporting four six pressure sensors, one vibration sensor, and two temperature sensors. For pressure sensory system, six QTC pressure sensors of SP200-10 series with 10 mm diameter and 0.1 N to 20 N operating force range from Peratech [19] were distributed over the hand. One of the six pressure sensors attached to the prosthetic hand's palm and the rest of sensors covered the fingertips. The six pressure sensors were programmed in a special way. Accordingly, the largest instant pressure signal is the only output signal from the pressure sensory system, as presented in the own previous study [8].

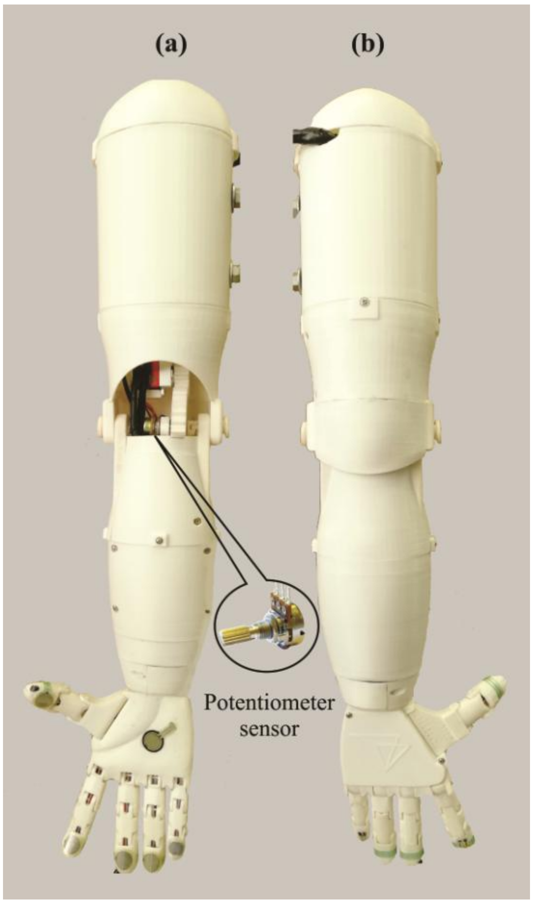

Figure 5. Fabrication of the tactile prosthetic arm: a) front view, and b) rear view.

For tactile sensory applications requiring the highest obtainable pressure accuracy, part calibration will be necessary. Curve fitting method was utilized to calibrate the six QTC pressure sensors. Curve fitting is the most complete calibration method. A parametric curve fit is done for the nominal curve of a set of QTC pressure devices, and the resultant equation is stored for future use. Fit parameters are then established for each individual sensor [19]. The calibration method was performed by measuring the pressure sensor outputs voltage when the sensor inserts under increasing load with a known stander of mass. Therefore, a supporting load stand with a load's bar was designed and fabricated, as shown in Figure 6, in order to be sure that the increasing loads are applying directly and vertically on the sensor under the test. A number of constant masses of 0.5 kg were used. Thus, it became able to increase the mass individually and record the sensor's output voltage at each increasing step.

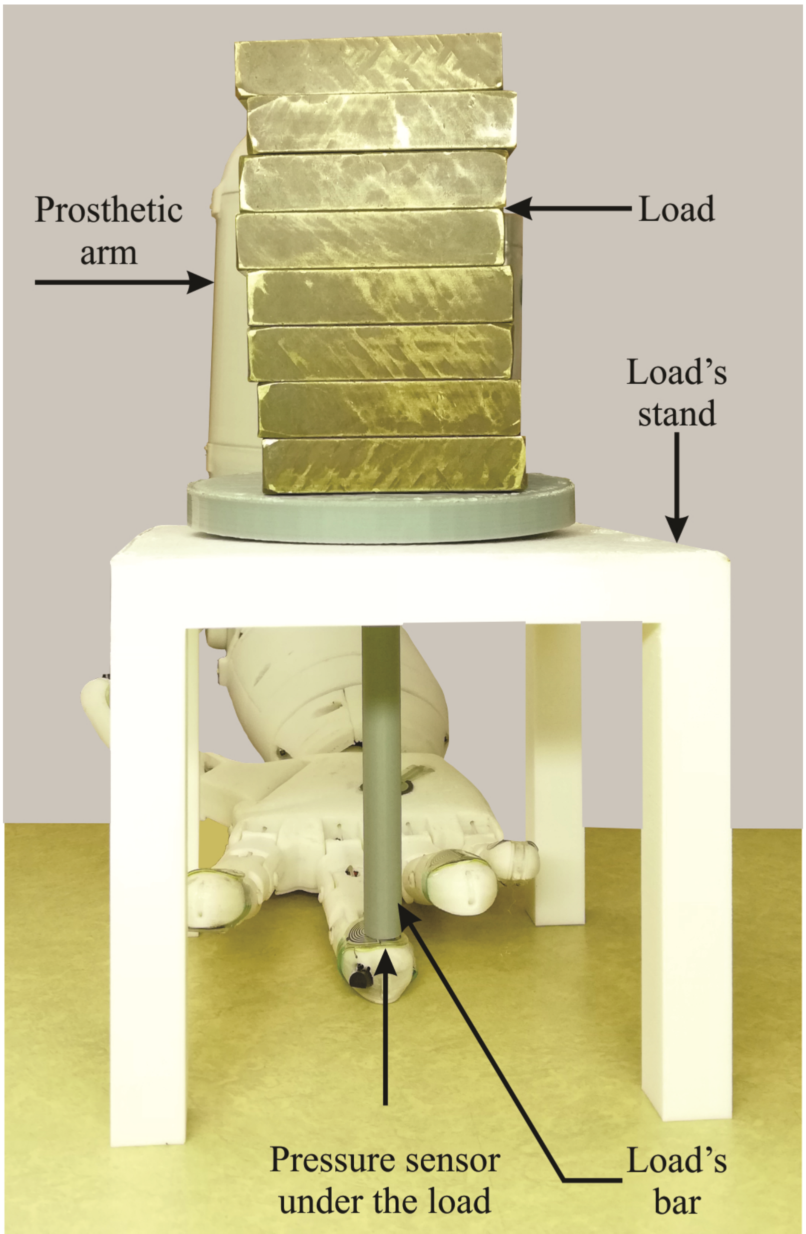

Figure 6. Calibrating setup of the tactile pressure sensors.

The mass vs. output voltage characteristic of the QTC pressure sensor is plotted in Figure 7, which present an overview of QTC typical response behaviour. Where the horizontal axes referring to the increasing applying load in kg and the vertical axes represents the pressure sensor's output in voltage. This format allows interpretation on a linear scale. A Polynomial curve fitting of fourth degree order with R-square equal to 0.9981 seems to be suitable for these set of data, as follow:

$$P_f = P_1 \times L^4 + P_2 \times L^3 + P_3 \times L^2 + P_1 \times L + P_5 \qquad (1)$$

Where: the variables P_f and L refer to the pressure fitting values and the applying stander load, respectively. While P_{1-5} are the fitting question constants, which are equal to$P_1 = -0.01002$,$P_2 = 0.1699$,$P_3 = -1.158$,$P_4 = 3.777$, and$P_5 = 0.05$.

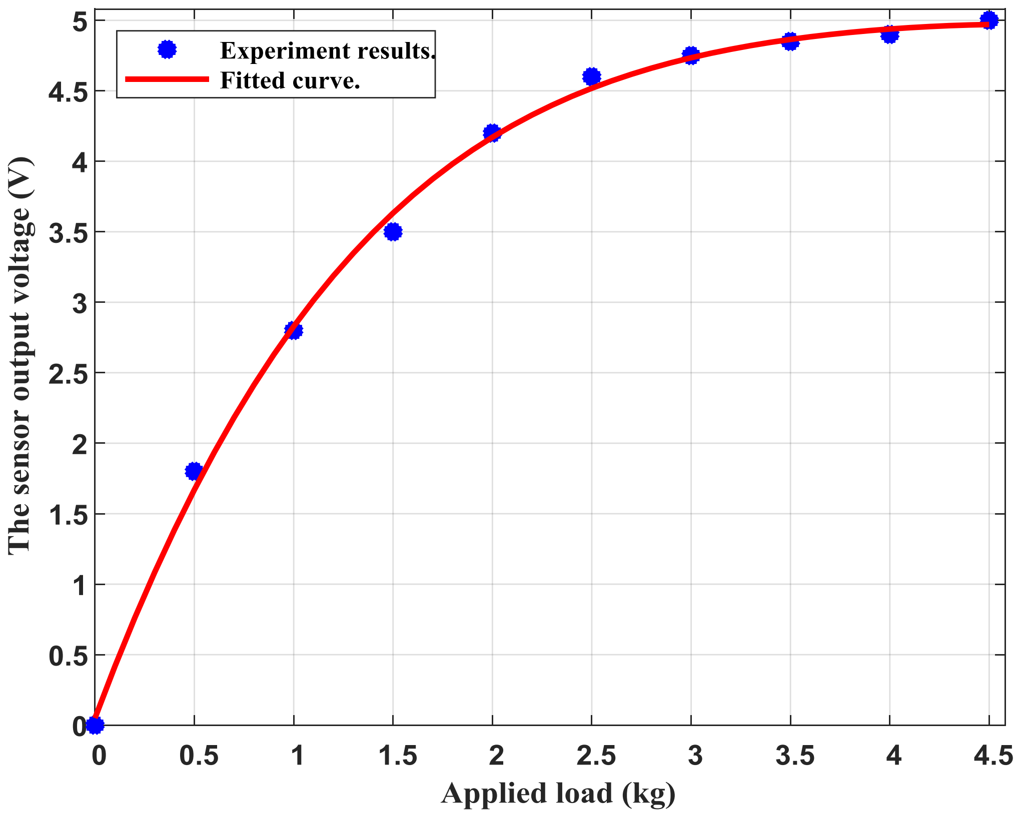

Figure 7. The relationship between the pressure sensor output voltage Vs. the applied load.

3.3. Fabrication of the hybrid haptic wearable device

To convey the sensation of the contact force measured in the pressure sensory system, a combined of pressing and vibration actuators were integrated into a curvature case, as shown in Figure 8. The fixing belts were used to fit loosely around the upper arm of the subject. A tiny and lightweight with high output power servomotor equipped with a piston arm of 40 mm length and circular piston of 15 mm diameter represent the pressure FSS. The SG-90 servomotor was chosen to be the driver of the pressure FSS because it has a miniature weight of 14.7 g, 2.5 kg.cm torque, and 4.8 - 6 operating voltage [20]. These features are very suitable for the haptic wearable device. On the other side, two Linear Resonant Actuator (LRA) vibration motors were attached to the inside wall of the main case to integrate the vibration FSS. The main characteristics of the using vibration motors in this field of study are lightweight, low noise, low power consumption, and high performance [21].

As the contact pressure between the prosthetic hand and the attached or grasped objects increased, the HHPVFSS will excite the user's upper arm as soon as possible by producing a mutual of pressure and vibration sensation. The pressure sensation increases by growing the angular position of the servomotor. Thus, the pressing of the piston on the user's skin will increase in turn. While the vibration sensation growths by increasing the supplying Pulse-Width Modulation (PWM). Therefore, the patient will be able to recognize the varying in the excitation vibration frequency. In general, the HHPVFSS will contribute to recovering the sensation of touch, start of touch, end of touch, grasp, slippage, and the contact pressure level. Furthermore, the HHPVFSS will play a major role to fastly excite the amputee's brain at a hot painful stimulus state.

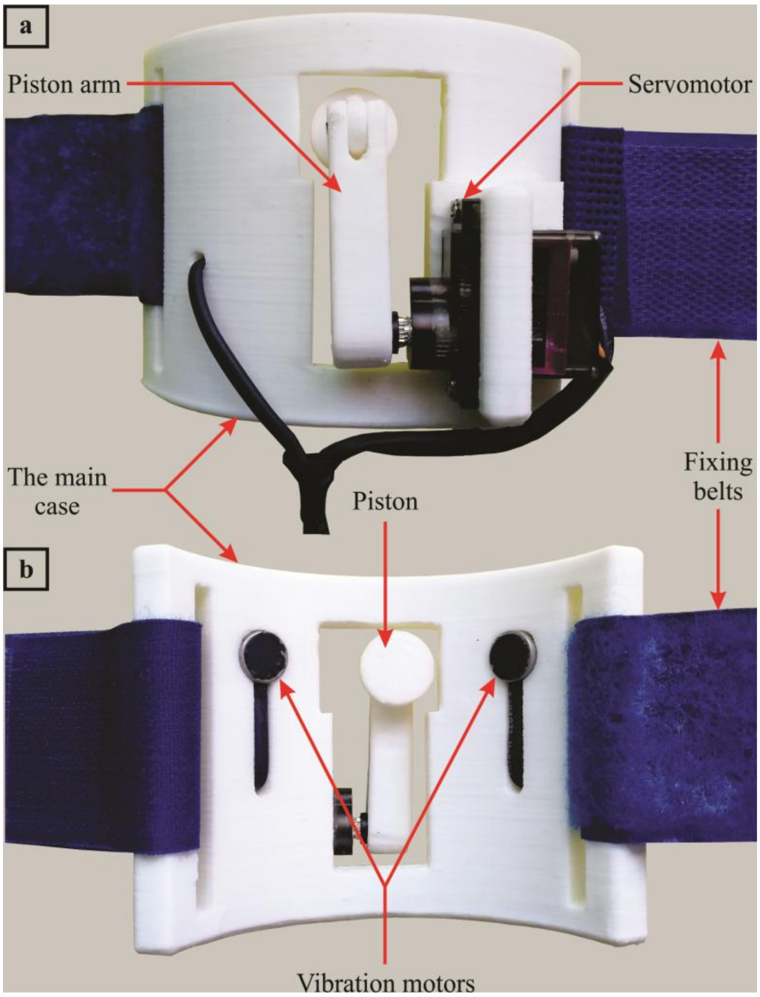

Figure 8. Fabrication of the HHPVFSS: a) front view, and b) inside view.

4. Experimental setup and procedure

The evaluation experiments were performed to verify the performance of the hybrid haptic wearable device. The main two goals of the experiments are: (i) to improve the operability of the designed prosthetic arm to perform the touching, grasping, and manipulating tasks; and (ii) to establish the ability of the hybrid feedback stimulation system to convey the tactile information about the contact pressure to the user's brain without confusion or long pre-training requiring.

To achieve these goals, the experiments were divided into four parts to cover all functional aspects of the system. The two parts are the contact pressure detection experiment, and pressure level detection experiment. The upper limb amputees were simulated by forty able-body volunteers (20 males and 20 females, mean age (SD) 25.478 ± 4.45 years). The subjects were right-hand dominant and did not suffer from any cognitive impairment that could affect their performance during the tests.

In all evaluation experiments, the prosthetic arm and the computer were put on the table and the healthy subjects were seated against the table with a full rest position, as shown in Figure 9. The HHPVFSS was installed on the subjects' right upper arm. In addition, the subjects' vision and hearing were obstructed using an eye mask and earmuffs to prevent this information from influencing the subject's perception.

Figure 9. Experimental set-up: evaluating the effectivity of the haptic wearable device to convey the tactile information.

4.1. Contact pressure detection experiment

The contact pressure detection experiment divided into three tests: a touch detection test, grasp detection test, and slippage detection test. The first test is just to detect the touch at any pressure sensor due to randomly applying force level. The examiner worked on touching the prosthetic fingertips to generate the randomly applying force, as shown in Figure 10.a. The subjects have to guess whether the touch, start of touch, and end of touch have happened or not.

While the second experiment test is to distinguish the grasping objects. The examiner handed a small ball to the tactile prosthetic hand or shake hand with it, as shown in Figure 10.b. The subjects were informed to indicate the grasping objects whenever they felt it.

Lastly, the third experiment test is performed to quantify the usefulness of the proposed hybrid haptic wearable device to detect the slipping objects. At which, the cylindrical bar with a steel hook fixed from the lower side was handed to the tactile prosthetic hand. Then, stander loads were hanging gradually to the steel hook, as displayed in Figure 11. The prosthetic hand was programmed to increase the power of a hand grip whenever the load increasing to stimulate real behaviour with a healthy hand. The volunteers have to feel this behaviour and detect the slippage when it happens after the hanging load exceeds the prosthetic hand's grip ability.

4.2. Pressure level detection experiment

The task of the third test case is to detect the pressure level of an occurred touch by exciting the patients' skin with a suitable hybrid excitation by mean of the HHPVFSS, which diverge according to the tactile signals of the pressure sensors. The aim of this experiment is to evaluate the ability of HHPVFSS to pass the tactile information about the pressure level to the participants' brain. The experiment sorted into two phases named a training phase and an evaluation phase.

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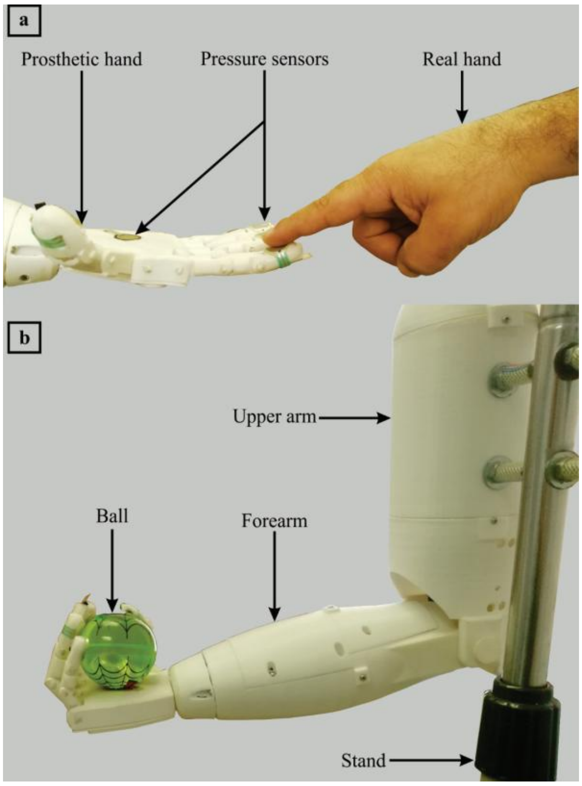

Figure 10. Contact pressure experiment : a) touch detection, and b) grasp detection.

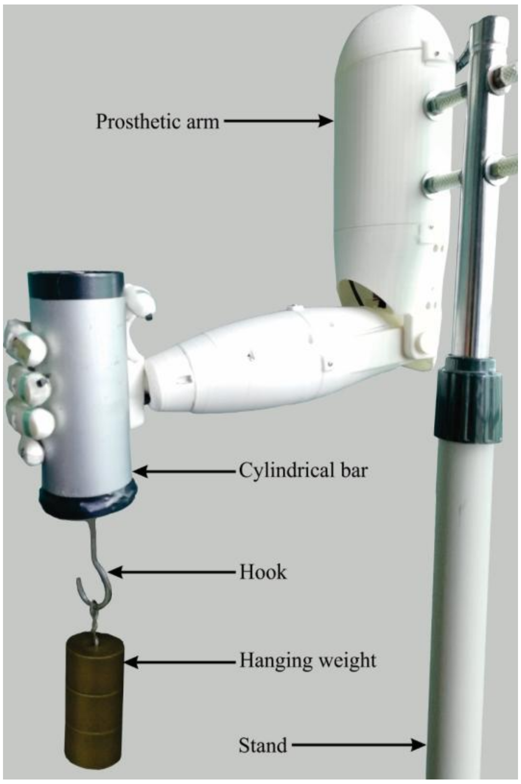

Figure 11. Contact pressure experiment: slippage detection.

At the training phase, the participants are subject to brief training on how to discriminate between the four levels of applying pressures for 96 seconds. A virtual excitation signal was generated as an alternative to a real pressing experiment, in order to be sure that all the participants will get the same level of the training. The virtual signal changes between four levels of pressure, three times each level. Accordingly, the excitation level will be changed every 8 seconds during the experiment. The four levels of applying pressures are no touch (0 V), light level (1.5 V), middle level (3 V), and heavy level (5 V), as shown in Figure 12. Getting information by a vision was allowed to make the volunteers comparing between the visual information and the haptic information by watching the changing virtual signal on the computer screen.

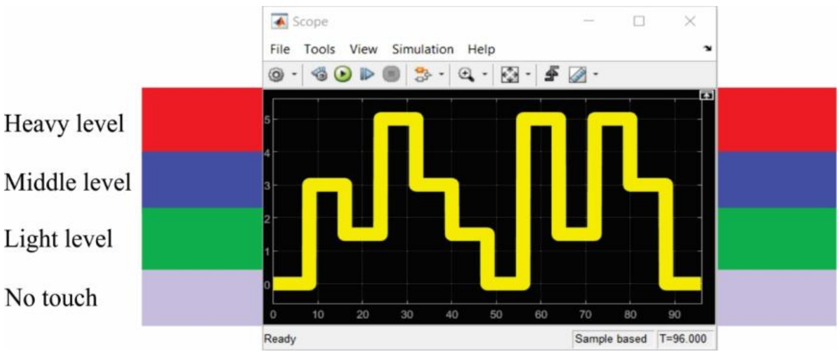

Figure 12. A virtual training phase pressure level excitation.

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At the evaluation phase, the participant should guess the level of the contact pressure by utilizing virtual and real excitations. For example, a pressure is applied at a light level and the participant should recognize that now a touch occurred at a light level. The virtual excitation is similar to the training phase excitation. While the load's stand and the standard loads, Figure 6, were used to generate a real excitation.

5. Results and discussion

5.1. Evaluation of pressure level detection experiment

The relationships between the excitations of the pressure and vibration FSS of the HHPVFSS due to the increasing in the pressure largest instant sensory signal are shown in Figure 13. The programmed excitations signals of the HHPVFSS wearable device's actuators are simulated against the simulation time (t) when the pressure largest instant sensory signal ($u(t)$) increases linearly from 0 to 5 V during 5 sec simulation time, as plotted in Figure 13.a. Then at Figure 13.b, the excitation signal of servomotor of the pressure FSS ($p(t)$) is going to proportionally increase from 0 to 25 degrees, as follow:

$$p(t) = u(t) \times \left({}^{25}/_{5} \right) \qquad (2)$$

At the other side, Figure 13.c displays the excitation signal of the two vibration motors of the vibration FSS ($v(t)$) due to the rising in the $u(t)$, it's programmed as follow:

$$v(t) = u(t) \times g(t) \times \left({}^{115}/_{5} \right) + 140 \qquad (3)$$

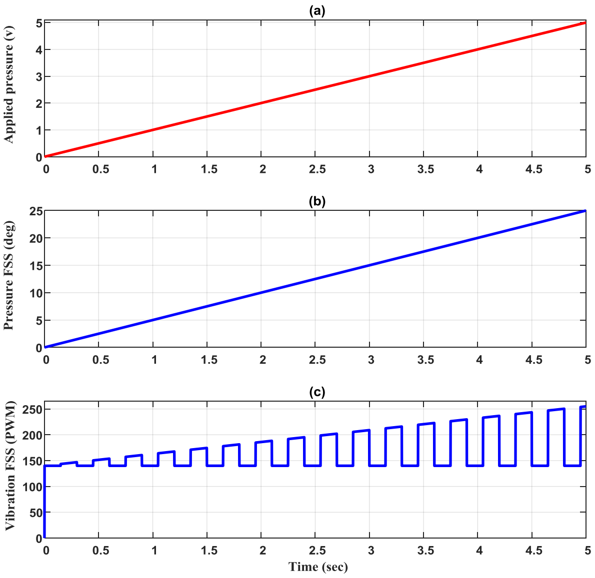

Figure 13. The relationship between the excitations of the pressure and vibration FSS and the largest instant sensory signal.

Where: $g(t)$ indicates the pulsing generator signal. Actually, it is a square-wave signal of a unity amplitude, 0.3 sec period time, and 50% pulse width. Thus, the vibration starts varying as a square-wave from 140 to 255 PWM because under 140 PWM the power of the vibration is very low, i.e. insensible and 255 PWM is the maximum allowed operation power for the LRA vibration motors.

In order to evaluate the actuators' behaviours of the pressure and vibration FSS during the evaluation of pressure level detection experiment, the actuators' excitation signals were validated relative to the virtual pressure sensory signal that described in Section 4.2. When the virtual pressure signal varies among four levels: 0 V (no touch), 1.5 V (light pressure), 3 V (middle pressure), and 5 V (heavy pressure), see Figure 14.a. In turn, the excitation signal of the pressure FSS differs (according to Eq. 2) to drive the servomotor to change its position, as follow: 0 degrees (no touch), 7.5 degrees (light pressure), 15 degrees (middle pressure), and 25 degrees (heavy pressure), see Figure 14.b. While the vibration motors of the vibration FSS are excited with a square-wave (according to Eq. 3), as follow: 0 PWM (no touch), 140-174.5 PWM (light pressure), 140-204 PWM (middle pressure), and 140-255 PWM (heavy pressure), see Figure 14.c. The results show that the pressure and vibration excitation signals are varied according to the changing in the pressure sensory signal.

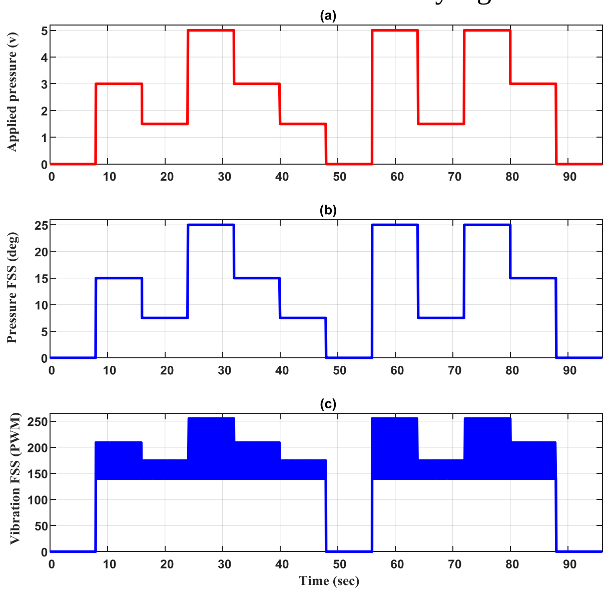

Figure 14. The evaluation results of the pressure level detection experiment.

5.2. User experience evaluation for hybrid haptic feedback stimulation system

The functionality and the effectiveness of the hybrid haptic wearable device were evaluated by meaning of two experiments. These two experiments examine the subjects' detection ability of the touch, start of touch, end of touch, grasp, slippage, and pressure level. The evaluation results in terms of stimuli identification rate (SIR) are shown in Figure 15. The SIR presents the detection accuracy rate of the volunteers' response during the evaluation experiments.

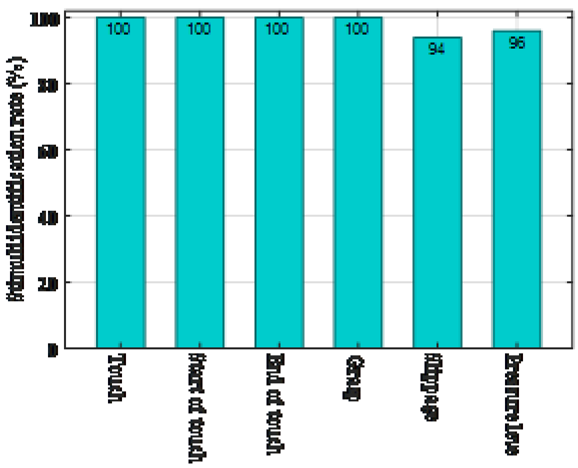

Figure 15. Detection accuracy rate of the volunteers' response.

For the contact pressure detection experiments, the volunteers recorded 100 % detection accuracy rate for the touch, start of touch, end of touch, and grasping objects. While 94% of the slippage stimulus were successfully answered by the participants. The results were collected during 120 stimuli per each detection case (40 volunteers and three stimuli per each case). The statistical analyses have been performed by recording the volunteer's answer, yes: for the correct detection and no: for the wrong detection. Then, the correct answers rate were calculated for the entire stimulus answers. The high detection accuracy rates refer to the extremely good ability of the hybrid haptic pressure - vibration feedback stimulation system to convey the tactile contact pressure information to the user's brain in high response, low confusion, and without pre-training requiring.

On the other side, the confusion matrix was used to analyse a set of data for the pressure level, surface texture, and temperature level detection experiments, based on volunteers' answers during the testes. It is a performance measurement for calculating the accuracy of the correct detection answer to the total detection answer for all the stimuli during the single test, as shown in Figures 5.40 - 5.42. The main diagonal of the matrix (pink cells) describes the number of correct answers over a total of stimuli per each excitation target. The last row and column (light greenery cells) of the matrix represent the detection accuracy and the true positive rates, respectively. The bottom - right corner (dark green cell) highlights the average accuracy, i.e. SIR. The remaining elements (white cells) correspond to the incorrect answers.

For the pressure level detection experiment, the confusion matrix of figuring out the SIR of the pressure level detection test was evidenced in Figure 16. The characters L, M, and H refer to the light, middle, and heavy pressure levels, respectively. While no touch indicates to the idle state when no touch or grasp occurs between the prosthetic hand and the manipulating objects. The main diagonal of the matrix performs the number of correct answers over a total of 120 stimuli per each pressure level (40 volunteers and 3 repetitions). The find out of the confusion matrix indicates that 96 % of the pressure levels were identified successfully. The design of the HHPVFSS wearable device totally contributes for this highly acceptable result, since the pressing force and the vibration frequency change proportionally with the applied pressure, the change of the amplitude could effortlessly be recognized.

Subjects answers \ Target pressure level	No touch	L	M	H	
No touch	120	2	0	1	97.56%
L	0	114	4	0	96.6%
M	0	3	114	6	92.68%
H	0	1	2	113	97.41%
	100%	95%	95%	94.17%	96%

Figure 16. Confusion matrix shows the statistical analysis of the pressure level detection experiment.

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6. Conclusions

At the evaluation experiments, forty able-body volunteers were engaged to evaluate the ability of the haptic system to stimulate the human nervous system. The results showed that all the participants were correctly able to discriminate the feeling of touch, stare of touch, end of touch, and grasping objects. While 94%, and 96%of the entire stimuli were successfully identified by the volunteers during the experiments of slippage, and pressure level, respectively.

The overall conclusions and recommendations from this study, based on the evaluation results and the volunteers' experience, are:

a) It is possible to recover the missing feeling to the amputees, whom unfortunately lost, partially or entirely, their upper arm, by non-invasively stimulate the skin of the remaining parts from the amputees' arms or any others spots in their bodies.
b) The capability of the proposed haptic feedback stimulation system to convey the huge tactile information to the users' brain without the brain's confusion or requiring long hours of pre-training.
c) The proposed tactile prosthetic arm and the haptic feedback system have low cost and its entire tools available on the market.
d) The final size of the haptic wearable device depends completely on the user's body size and degree of the comfort feeling.

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