Design of a Hybrid Haptic Wearable Device for Upper Limb Amputees to Recover the Missing Sensation

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DECLARATION

Special dedication to my beloved father and mother for their boundless efforts and support

To my entire friends

Thanks for everything

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Firstly, all praise and thanks to Allah for His Divine Guidance and help in completing this research project.

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ABSTRACT

A hybrid haptic feedback stimulation system that is capable of sensing surface texture, and temperature, simultaneously, was designed in this work for prosthetic hand to provide a tactile sensation to amputation patients. In addition, the haptic system was developed to enable the prosthetic's users to implement withdrawal reflexes due to the thermal noxious stimulus in a quick manner, i.e. in a fast and effective technique. The re-sensation is achieved by non-invasively feedback stimulating the skin of the patients' residual limbs, based on the type and the level of tactile signals provided by the sensory system of the prostheses. Accordingly, a novel hybrid pressure-vibration-temperature feedback stimulation system was design to provide a huge information regarding the prostheses environment to the users without brain confusion or require long pre-training. Evaluations of sensation and response were performed with healthy volunteers to evaluate the ability of the haptic system to stimulate the human nervous system. The results in term of Stimulus Identification Rate (SIR) show that all the volunteers were correctly able to discriminate the sensation of touch, start of touch, end of touch, and grasping objects. While 94%, 96%, 97%, and 95.24% of the entire stimuli were successfully identified by the volunteers during the experiments of slippage, pressure level, surface texture, and temperature, respectively. In addition, the results verified the ability of the haptic system to excite the human brain at the abnormal noxious stimulus and enable the volunteers to perform a quick withdrawal reflex within 0.32 seconds. The test results and the volunteers' responses established evidence that amputees are able to recover their sense of the contact pressure, the surface texture, and the object temperature as well as to perform thermal withdrawal reflexes using the solution developed in this work.

ABSTRAK

Sistem stimulasi maklum balas haptik hibrid yang mampu merasakan tekstur permukaan, dan suhu, secara serentak, dirancang dalam karya ini untuk tangan prostetik untuk memberikan sensasi sentuhan kepada pesakit yang diamputasi. Di samping itu, sistem haptik dikembangkan untuk membolehkan pengguna prostetik melaksanakan refleks penarikan kerana rangsangan berbahaya termal dengan cepat, iaitu dengan teknik yang cepat dan berkesan. Sensasi semula dicapai dengan merangsang kulit anggota badan pesakit secara tidak invasif, berdasarkan jenis dan tahap isyarat taktil yang disediakan oleh sistem deria prostesis. Oleh itu, sistem stimulasi maklum balas tekanan-getaran-suhu hibrid baru dirancang untuk memberikan maklumat yang besar mengenai persekitaran prostesis kepada pengguna tanpa kekeliruan otak atau memerlukan pra-latihan yang lama. Penilaian sensasi dan tindak balas dilakukan dengan sukarelawan yang sihat untuk menilai kemampuan sistem haptik untuk merangsang sistem saraf manusia. Hasil dalam istilah Stimulus Identification Rate (SIR) menunjukkan bahawa semua sukarelawan dapat membezakan sensasi sentuhan, permulaan sentuhan, akhir sentuhan, dan objek menggenggam dengan betul. Sementara 94%, 96%, 97%, dan 95.24% dari keseluruhan rangsangan berjaya dikenal pasti oleh para sukarelawan semasa eksperimen tergelincir, tahap tekanan, tekstur permukaan, dan suhu, masing-masing. Di samping itu, hasilnya mengesahkan kemampuan sistem haptik untuk membangkitkan otak manusia pada rangsangan berbahaya yang tidak normal dan membolehkan para sukarelawan melakukan refleks penarikan cepat dalam 0.32 saat. Hasil ujian dan tindak balas sukarelawan membuktikan bukti bahawa amputees dapat memulihkan rasa tekanan mereka, tekstur permukaan, dan suhu objek serta melakukan refleks penarikan haba menggunakan penyelesaian yang dikembangkan dalam karya ini.

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CHAPTER 1

INTRODUCTION

1.1 Background

The world population of amputees is estimated to be around 10 million persons, in which 30% of them are upper limb amputees [1]. This number is increasing especially in industrialized countries. In the United States, for example, the population of amputees increases around 185,000 persons each year [2]. A prosthetic hand that helps amputees to perform Activities of Daily Living (ADL) is a necessity in order for amputees to reintegrate and coexist with the society. Critical design requirements for hand prostheses have emerged such as lightweight, low power consumption, quiet operation, high degrees of freedom and sensitive haptic feedback [3]. Numerous researches have attempted to develop prosthetic hand that can sense and reproduce the touch sensation as close as possible to a biological hand. Providing a feeling of the hand grip to the amputees helps them to control the applied contact force to prevent objects from slipping away from their new hand. Additional desired functionality for the hand prostheses include the detection of surface type, roughness, temperature, and even humidity. The choosing type of the sensory information entirely depends on the design requirements of the tactile sensory system.

In general, prostheses are artificial devices used to replace these missing body parts. However, it can be separated into multiple categories depending on the level of amputation, i.e. below or above elbow amputation, ranging from a single finger to amputation of the whole arm and shoulder. Prostheses can be further classified into those simply aiming to restore aesthetic properties and those restoring functionalities of the limb as well. In order to restore functionality, prosthetics must have the option to be actuated. For instance, the most crucial function regarding the below elbow amputations is to allow opening and closing of an artificial hand [4]. This enables the patient to grip, hold, and manipulate objects.

The main goal of designing a modern prosthesis is to compensate a lost hand with the other prosthetic hand as close as possible to a real human’s hand, and it has the possibility to achieve the most vital functions. It should also imitate a human's hand both optically and technically. Therefore, prostheses are designed with cosmetic gloves imitating the human skin and Electromyogram (EMG) controlled finger movement systems. Unless completely implemented yet is how to recover the feeling through his own prosthesis. The feeling restore gives a wide range of information regarding the touch, grasp, slippage, surface texture, surface material, and the object’s temperature.

1.2 The concept of the haptic feedback stimulation system

The artificial prosthetic hand is the best solution for amputees to coexist in the society. Many problems rose after wearing the prosthetic hand for many hours such as the heavy weight and sensory feedback requirement [3]. Thus, numerous researches on the haptic feedback system tried to develop prosthetic that can feel as close as possible to the real hand, and can perform identical activities with a high number of degrees of freedom as near as possible to the real hand ability.

The importance of providing feeling from the tactile prosthetic hand to the patient is not only limited to transferring the feeling of the handgrip, but it also helps the user to control the applied contact force to prevent sliding of objects. In addition, the main important function of the haptic system is to enable the user to detect surface type, roughness, temperature, humidity, and rigidity, depending on the sensing types that are used in the tactile system. Usually, the tactile sensors mount on one or more fingertip of the prosthetic hand or sometimes cover the entire prosthetic hand. The main function of the tactile sensory system is to measure the environmental parameters and provide it to the microcontroller as analog signals, in order to process the data. The decision orders that outputs from the microcontroller is used as a manipulating signal to drive the haptic feedback actuators, in order to excite the nervous system of the amputee's residual limb. Such excitation transfers the feeling to the patient's brain and enables the user to recognize the environment through the use of prosthetic hand. For example, the main steps of the force-pressure detection in a haptic feedback stimulation system are presented in Figure 1.1

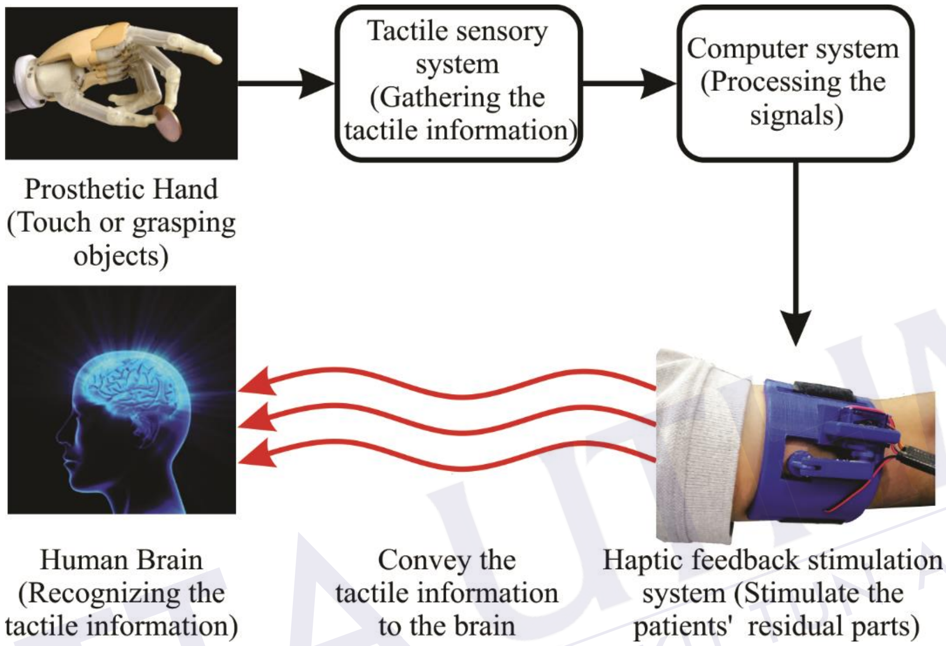

Figure 1.1: The concept of the haptic feedback stimulation system.

1.3 The classification of haptic feedback stimulation system

The creation of accurate connection between the sensing system signals of the artificial hand and the physiological nerve channels of patients' residual limbs is still the main challenge faced by the industry of tactile prosthetic hand. Indeed, amputees can feel the recreated sensation from hand prostheses in two ways. The first method is invasive and requires a direct connection with the neural structures via surgical access to the nerves of the amputees [5, 6]. The second method deploys the non-invasive feedback stimulation using devices attached on the residual limbs to excite the nerves that originally serves the lost hand [7, 8]. A long training hours is often required for a patient of upper limb amputation to get familiar with a prosthetic hand equipped with haptic feedback stimulation system [9]. The haptic system comprises of tactile sensors which then transmits the measurement signals as the input signals to the feedback stimulation system.

The tactile system consists of three main parts: the sensing system, the feedback stimulation system, and the computer processing system. Measuring different parameters from the surrounding and converting it to the electrical signals are the main function of the sensing system. Pressure of sensors are used to measure the contact force or pressure between the prosthetic hand and the object, for instance, QTC [10], Force Sensitive Resistors (FSR) [11], piezoelectric sensor [7], and biotac sensor [12]. The tactile sensory system can be classified into five classes based on its function which consists of the pressure detection sensory system [13], slippage detection sensory system [14], the surface texture detection sensory system [15], the material detection sensory system [16], and the temperature detection sensory system [17]. Two or more types of the tactile sensors can be merged to create hybrid sensory systems which have the ability to measure multi types of information at the same operation time [18], as shown in Figure 1.2.

The grasp force is measured and transferred to a pressure stimulation on the forearm skin to excite the patient's brain. The haptic feedback stimulation system can be further classified into six displays, depending on how to stimulate the patient's skin and provide the information of the tactile sensory system to the amputee's brain. The six haptic feedback displays are the pressure feedback display, the vibration feedback display, the skin stretch feedback display, the squeeze feedback display, the electro feedback display, and the thermal feedback display [19]. The combination of two or more types of haptic feedback displays lead to create an unusual multi-mode feedback technique where such a system is called the hybrid feedback display, as shown in Figure 1.3.

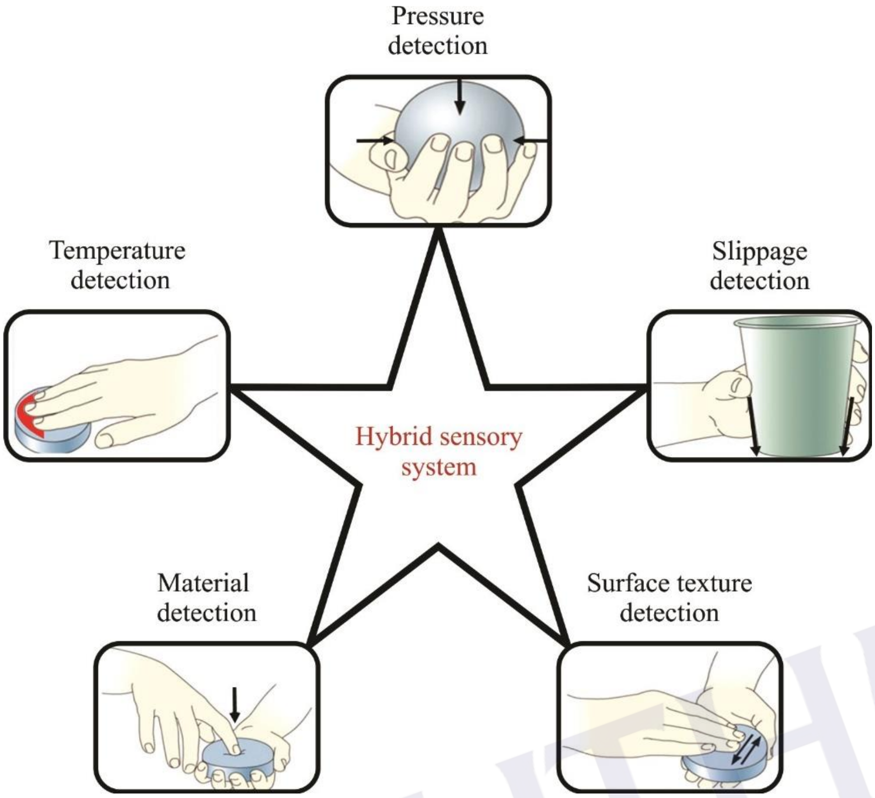

Figure 1.2: The classification of the tactile sensory system.

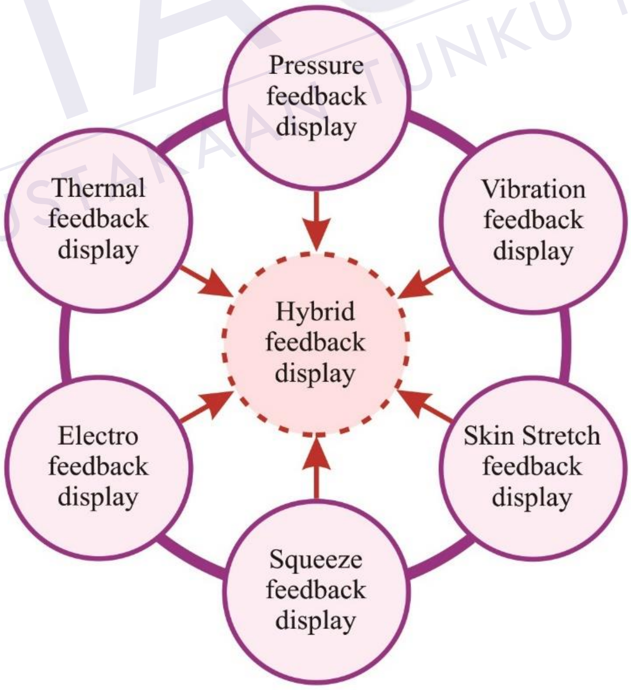

Figure 1.3: The classification of the haptic feedback stimulators.

1.4 Withdrawal reflex of the human's upper limb

In general, the upper limb withdrawal is accomplished by mean of the shoulder extension, elbow flexion, and wrist extension [20], by mean of direct connection with motor neurons of the human [21]. In fact, the human’s brain recognizes an abnormal temperature rise in the objects in contact with the hand by the mean of the thermal’s information provided by the thermoreceptors under the hand’s skin. After that, the brain controls the upper limb’s neural circuits to direct the arm’s muscles and then drive the arm’s joints, in order to move the limb in the best manner from the painful environment [22], as shown in Figure 1.4. The response of the upper limb has not been studied in the same detail as the lower limb; however, it has been shown that the reflex response can modulate with the phase of movement, as occurs with reaching tasks in the upper limb.

To enable the amputees to implement fast withdrawal reflexes, against the thermal noxious stimulus has become an effective requiring step in developing the prosthetic arms. Furthermore, to accomplish the main purpose of creating a prosthetic arm comparable to the mechanism of the real arm, the amputee who wears the prosthetic arm must feel the change in temperatures of the environment through his own prosthetic and recognize the painful stimulus. The noninvasive feedback stimulation system of the haptic prosthetic arm assists the amputees to recognize the thermal shock by utilizing its temperature sensors mounted on the prosthetic fingertips. Then, the tactile information about the abnormal thermal situation is conveyed to the amputee’s brain by mean of the haptic wearable device [23], which is fixed on the amputee’s residual limb. Lastly, the brain orders the prosthetic arm’s joints to rapidly drag the arm away from the danger zone. For the purpose of developing a good withdrawal reflex of the feedback stimulation system, the actuating motors of the prosthetic’s arm joints, and the controller of the prosthetic arm have to be designed to work, as possible, in high response to achieve a fast withdrawal reflex:

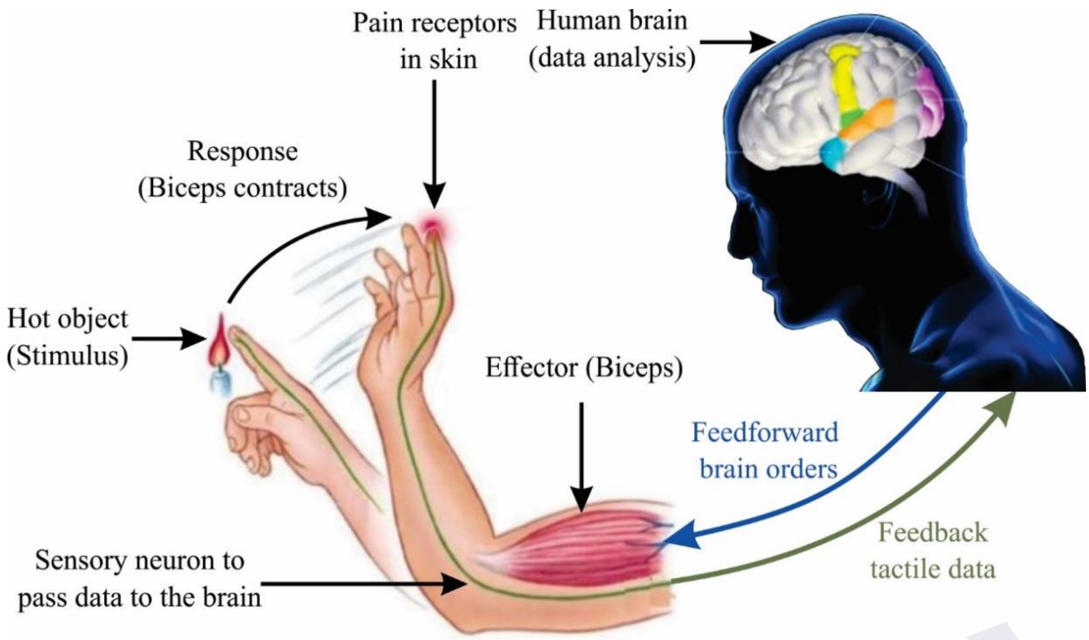

Figure 1.4: The thermal withdrawal reflex of human's upper arm [23]

1.5 Problem statement

Amputees wish to live a normal life similar as other healthy human beings. An ideal prosthesis should help amputees in making progress and try something new in their daily life. While actually, they feel like robots when they use their own upper limb prostheses because of the lack of the sensation. Subsequently, the amputees need to recover the missing sensation in order to get information from their surroundings and improve their activities. The prosthetic hand should be integrated with the feedback stimulation system, in order to convey the touch sensation to the patients' brain and enable them to recover useful information about their surroundings.

Normally, the easy activities, like holding and manipulating objects, become very hard work at the absence of the touch information. In this case, the amputees will not be able to decide how much the hand must open or close, or to determine the strength of the grasp force. The high applied grasping force leads to damaging or trashing of the grasped object, while the light force causes the object to slip out of the hand. Through the same point of view, the inability of the amputees to perceive the surface texture and temperature sensations through their own prostheses deprives them of getting a wealth of information about the environment around them. Without the surface texture sensation, it would be very hard to identify the types and the kinds of the surfaces. Furthermore, the absence of temperature sensitivity leads to prevent the amputees from useful tactile information such as material discrimination, extreme temperature avoidance, and psychological comfort. In addition, the lack of temperature feedback may cause damage to the prostheses through exposure to high temperatures without the knowledge of the users.

Part of the reason for this condition is that developments in prosthetic technology have only focused primarily on improving the actuation, dexterity, and control [24-26], with less work directed at providing feedback channels outside of vision [21, 27]. Moreover, researchers in literature investigated several issues related to equipping the artificial prosthetic hand with the haptic feedback stimulation system. Firstly, issues related to the problems that make the amputees feel uncomfortable when using the haptic prosthetic hand, like the heavyweight [28], the high noise of actuators [29], and absence of sensation through the prostheses [30] were discussed. Meanwhile the increase in energy consumption due to using the auxiliary equipment of the haptic feedback stimulation system is diagnosed as the second issue [12, 31]. Besides, issues concerned with the ability of the patient's brain to recognize and analyze the multi-information delivered from the sensory system at the same time [32], for example, when using two or more different type of sensors lead to the reduction of the recognition accuracy. Finally, issues regarding the deficiency of design of a haptic prosthetic hand having the ability to accomplish all the sensory tasks and functions comparable to the human real hand, for instance, lack of the ability for implementing a withdrawal reflex due to the painful noxious stimulus [33] were also discussed. In general, it can be concluded that the main three disadvantages of haptic feedback stimulation system are: (i) patient's brain may get confused due to the massive amount of data analysis from the sensory system during the operating of hand prostheses, (ii) the need of long hours of pre-training on how to recognize the sensory information, (iii) the prosthetic's user is unable to perform entire tasks due to the prosthetic design limitation.

The previous studies mainly investigated the ability to enhance the performance of the prosthetic arm by mean of recovering only one type of the missing sensation using one type of feedback stimulator, for instance, detecting the contact pressure by the prostatic hand, which integrated with pressure sensors, by mean a vibration feedback stimulation system [4, 19], as shown in Figure 1.5.

Nevertheless, there appears to be no clear research on the ability of recovering the entire missing sensation by using a hybrid feedback stimulation system without brain confusing, in addition to producing a functional prosthetic arm, which has the ability to perform multitasks similar to a healthy human arm. However, this gap, in particular, has not been investigated clearly in the existing literature. Therefore, due to this, a study is required to design and evaluate a hybrid haptic feedback stimulation system to enable the amputees of upper limb mutilation to recognize a multi-information about the environment in an easier way without any issues related to brain confusing or long pre-training requiring. In addition, such system will be able to detect the thermal noxious stimulus which enable the amputees to implement a withdrawal reflex in a quick manner.

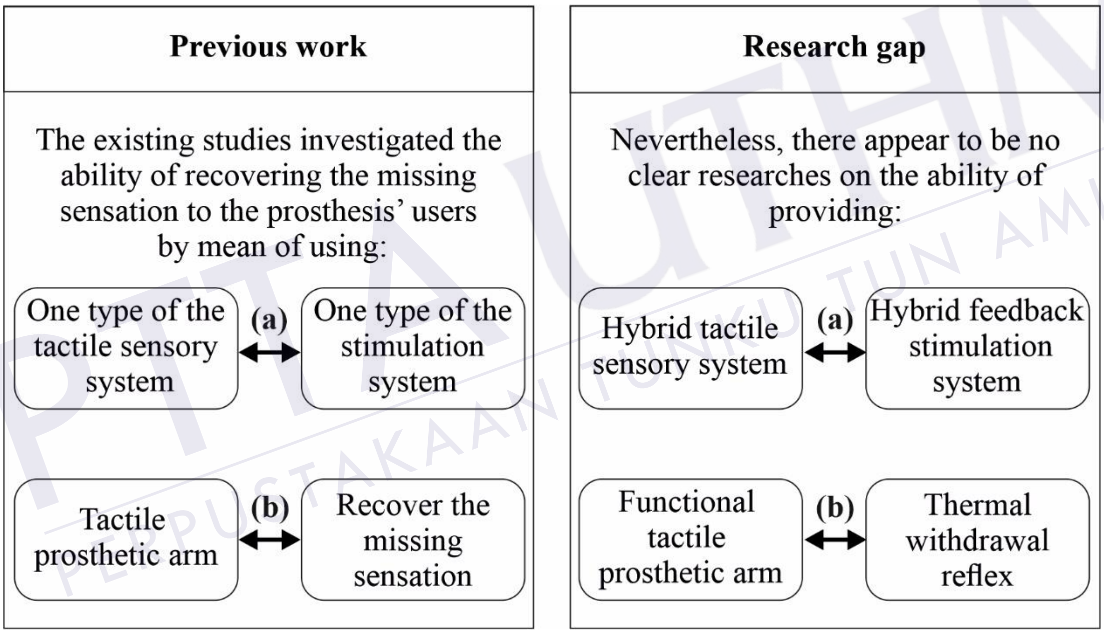

Figure 1.5: The research gap.

1.6 Research Objectives

In specific, the main research objectives of this study are listed as follows:

(i) To enable amputees for recognizing the multi tactile sensation by using the hybrid haptic feedback stimulation.

(ii) To develop a new functionality for detecting the thermal noxious stimulus by using the hybrid haptic feedback stimulation system, which is in charge of enabling the amputees to implement withdrawal reflex quickly.

(iii) To evaluate the functionality and accuracy of designed tactile prosthetic arm and its haptic system for detection of the tactile sensations and noxious stimulus using healthy volunteers.

1.7 Scopes

The scope of this research is limited to study the interaction between the upper limb prostheses and its users, which includes the following:

(i) The design of the wearable feedback stimulation devices have been performed via Solidwork 2018 program and Raise 3D N2 Dual Plus printer of 305 x 305 x 610 mm maximum size using Acrylonitrile Butadiene Styrene (ABS) material.

(ii) The prosthetic hand was modified with a new hybrid haptic feedback stimulation system, in order to enable the amputees to clearly identify the missing sensation. The detection accuracy, brain confusion, and pre-training requiring are chosen as the main factors of evaluating the proposed haptic system. Thus, the patient's brain perceives the information by a wearable hybrid feedback stimulator. The wearable hybrid device consists of a single pressure actuator, three vibration actuators, and one thermal actuator.

(iii) The hybrid haptic feedback stimulation system was programmed to enable the amputees to perform a fast withdrawal reflex and rapidly remove the tactile prosthetic arm away from the painful stimulus like a hot stove.

(iv) The interfacing between the tactile sensory system and the haptic feedback stimulation system with the computer system have been done by using Matlab GUI program and Matlab/Simulink program updated with Simulink support package for Arduino hardware toolbox. While, the calculation and the results have been accomplished by using Matlab 2018b code. Finally, healthy body volunteers have been compensated for the lack of amputees, in order to verify the functionality of the designed haptic system and prove the scientific contribution.

1.8 Significant of Research Study

The Significant of research study can be proved by performing a comparison study between the SIR results of the current work and previous studies, as summarized in Table 2.1. The selected previous studies were selected as similar as possible to this work, in which spot pressure, vibration, and temperature sensors were developed in the respective works. Actually, 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 2.1 also summarizes the information about the installation position of the previous haptic feedback displays and type of volunteers.

The SIR results indicated that the current work present the best results in all the experiment examinations. In fact, it should be noted that, as compared to previous studies, no initial exercise and pre-training were included in this work in order to increase the recognition rate of the volunteers during the experiments. However, it is concluded that the performance of the proposed hybrid feedback stimulation system to help the amputees to recover the sensation is more effective than using each feedback display individually.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

The rapid advances in medical science in recent decades are notable. Unfortunately, few effective researchers have been performed to overcome the problems of the amputations of the upper limbs. A statistical study was conducted on 2477 participants of upper limb amputation [34-36]. The study concluded that the patient's requirement is to allow him to manage the size of the various objects as normally as possible. Besides, to create an artificial hand that is very similar to a healthy human hand in appearance and functionality.

The main aim of this review is to highlight the essential techniques and the classification of the non-invasive feedback stimulation system. Such a system has been developed to assist the patients of their upper limb amputation to regenerate the missing sensation through his prosthetic arm. In general, the functionality, wearability, effectivity, and comfort criteria were selected as the main comparison points between the previous studies, as shown in Figure 2.1.

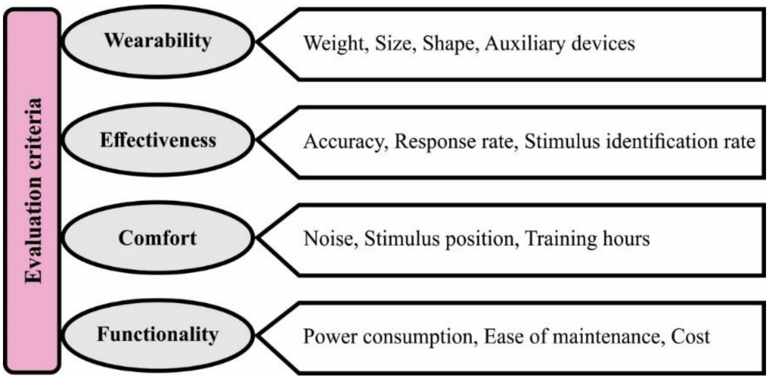

Figure 2.1: Evaluation criteria for literature review.

2.2 Types of Non-Invasive Feedback Stimulation wearable device

Normally, the noninvasive tactile stimulation system is a wearable medical device manufactured to pass the measurable sensory information to the haptic sensation by emulating the mechanoreceptors of the human skin [37]. In general, we can say that the noninvasive feedback stimulation system is a mechanical, vibrational system, or electro system that in response to stimulating the patient’s skin in his residual parts of the amputation body.

2.2.1 Pressure Feedback Display

The pressure feedback display means passing the tactile sensory information to the patient's brain by mechanically pressing the skin of the patient's residual part [38]. The installation of the pressure feedback stimulation device on the forearm of healthy participants was studied, to augment the performance of the myoelectric prosthetic arm and recreate the missing sensation of touch [38]. The 15 mm plastic beams with 12 mm diameter plastic buttons of a circular shape are driven by 5 DC servo motors of type Graupner DS281. The motors were used to directly apply pressure on the patient’s arm. The applying pressure is generated in proportional amounts with the value of the sensed contact pressure, as described in Figure 2.2.

A similar technique has been utilized in the second article [39] to study the best location of the pressure device to install and the optimum pressure level of, to

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