論 文 の 内 容 の 要 旨
Abstract of Dissertation

論文題目 **Development of a multi-channel functional electrical stimulation system for prosthetic applications of limbs**
（四肢の運動機能補助のための多チャンネル機能的電気刺激システムの開発）

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The present thesis explains the development of an integral system solution for the required motor and sensor function restoration to support people with disabilities in activities of daily living. Humans complete tasks in daily activities in which they are unconscious of the bodily control processes as they interact with the environment. The interaction between the sensor and motor modalities in the human body forms a sensory-motor coupling that allows us to adapt to the world around us. However, this sensory-motor coupling can be disrupted by illness, such as stroke, neural damage, paraplegia, or hemiplegia, and by accidents, including those that result in amputations. When the communication between motor and sensor modalities is broken, what once was done effortlessly requires the application of continuous conscious effort or cannot be done at all. In other words, the brain loses the ability to control and adapt to changes in the environment.

In this respect, rehabilitation engineering has focused on the recovery of lost function after illness or accident. In general, the efforts made to support the daily activities were focused on the transmission of sensorial information or the support of movement. These two areas of study have been developed separately. However, most tasks in daily activities require both sensor and motor capacity. Therefore, this dissertation proposes an integral solution to provide both sensorial information and motor function support using electrical stimulation. In order to fulfill the different requirements for sensory and motor functions a functional electrical stimulation device is proposed. Electrical stimulation of the nerves and the muscle

fibers presents 3 challenges: 1) low muscle selectivity due to the use of high voltages; 2) habituation to the electrical stimulus; 3) Difficulty in predicting the reaction of the human body to the electrical stimulation due to the nonlinear nature of the skin impedance. To deal with the 3 challenges described before, a multichannel functional electrical stimulation system is proposed. With the interaction of the different communication channels, we propose the use of an integral system to increase the efficiency in the restoration of lost function considering both sensory and motor function.

From previous studies involving walking assistance and sensory feedback systems, we identified three channels for bodily interaction: sensory, motor and reflexive. The sensory channel relates to the afferent nerve system for communication with the central nervous system (CNS). The motor channel can be actuated using the body's efferent channel. The reflexive system allows the generation of movement by stimulating afferent nerves. The electrical stimulation of the nerves can be used to interact with the three different channels.

Recently, several researchers have addressed the need for an integral system for function restoration. Most neuroprostheses are currently open-loop systems, where the lack of sensory information produces user fatigue. The introduction of closed-loop systems allows the nervous system to adapt to different situations, something that open-loop systems do not provide. In previous studies, electrical stimulation has been used to provide the required sensory feedback in neuroprostheses. Ambulation systems benefited from the insertion of sensory feedback by promoting body awareness in the paraplegic patients.

To increase the effectiveness of the sensor and motor function recovery, the brain needs to take an active role in the motor function control and the sensory feedback process. Even though current rehabilitation systems, mostly neuroprosthetic systems, make use of prediction methods to automate the control of the electrical stimulation, the patient does not have control of the pre-programmed stimulation patterns, which limits the efficiency of the system. Recently, the importance of the volitional involvement of the patient for the rehabilitation process has been addressed. The introduction of a control strategy called "patient-driven motion reinforcement" (PDMR), address the problem of lack of involvement of a patient in the rehabilitation process. The "patient-driven motion reinforcement" use an inverse dynamic model to predict the electrical stimulation pattern required to continue the volitional movement started by the patient in an FES-supported standing-up and sitting-down application for paraplegic patients. The involvement of the patient in the control system allowed the optimization in the insertion timing of the stimulation patterns. However, the calculations of the inverse dynamic model for each patient require cumbersome and time-consuming parameters adjustment which limits its functionality.

Since the nervous system requires the interaction of the motor and sensor modalities to form a closed-loop control system, we think that in order to increase the remaining function in the body for sensory and motor function restoration we need to treat both modalities together. For an individual to recover the ability to perform ADL, the system needs to be portable and safe, have low power consumption, and be capable of providing the appropriate stimulation configurations for each function modality.

In this dissertation we propose the use of surface electrical stimulation or transcutaneous electrical stimulation to avoid trauma to the body caused by the surgery required for electrode placement. Surface electrical stimulation has several advantages over implanted electrodes; for example, it does not require a surgical procedure for placement, there is no bodily rejection, and the electrodes are easily replaced when necessary. Caution is necessary when using small electrodes because of the high voltages required for eliciting the current level for the generation of nerve action potentials.

To interact with the different channels in the human body, we propose the use of a high-frequency squared waveform as carrier signal for a burst-controlled electrical stimulation method for recovery of motor and sensory functions.

The present dissertation consists of a total of 6 sections: Introduction, Conclusions, and 4 chapters. The contents of each section are described below.

The Introduction describes the need for an integral solution for recovery of sensory and motor modalities in prosthetic applications for activities of daily living using transcutaneous electrical stimulation.

Chapter 2 explains of the basics of transcutaneous electrical stimulation for nerve & muscle stimulation. Electrical stimulation is preferred over other interaction means due to its capacity to interact with the afferent and efferent neural paths. Transcutaneous electrical stimulation reduces the trauma received by the human body since it does not require the insertion into the body to produce nerve's action potentials. In addition, it presents the efforts done up to now in order to transmit information into the human body using electrical stimulation of the mechanoreceptors in the skin for sensory feedback.

Chapter 3 describes the development of a low voltage multichannel electric stimulation system for prosthetic applications. We proposed a high-frequency squared carrier signal to reduce the voltage requirements for transcutaneous electrical stimulation to restore motor control and sensory feedback. The insertion of a carrier signal permit reduction of adaptation to electrical stimulation, and integral muscle contractions. We confirmed its functionality for muscle contraction using low voltage with a lower limb paralyzed patient. For sensory feedback, different stimulation patterns were tested to increase the amount of information transmitted from the artificial sensory system to the user of either a prosthetic device or a neuroprosthesis.

Chapter 4 presents the evaluation of motor function recovery in prosthetic applications with a hemiplegic walking support system case study. In order to develop an integral system it shall cover the needs of muscle contraction in the different body parts as well as to administer sensory feedback. The system is evaluated in a lower limb hemiplegic patient. The patient presents higher neural damage on the left leg than the right leg. People with spinal cord damage present some neural reorganization which affects the way their body reacts to the electrical stimulation compared with healthy persons. We tested the multi-channel functional electric stimulation system motor function recovery capabilities with a lower limb semi-paralyzed patient. To increase the patient involvement in the rehabilitation process, we applied the minimum required stimulation parameters to elicit the withdrawal reflex in the paralyzed leg. We tested the volitional control of the paralyzed leg with stairs climbing and changes in the walking speed over a flat surface.

Chapter 5 presents the evaluation of the integration of motor and sensory function using a functional magnetic resonance imaging (fMRI) study. Although there are several studies on the brain activation resulting from manipulating an EMG-controlled prosthetic hand, there are no studies on the activation in the brain when the manipulation of the EMG-controlled prosthetic devices includes sensory feedback. The inclusion of sensory feedback opens new areas of understanding in the interaction of the brain with the environment. To test the correlative behavior of the brain we used an fMRI device to measure the changes in hemoglobin consumption in the brain. The changes in hemoglobin in the brain show the areas in the brain with higher activity. By detecting these changes, we can know approximately where the activation of the brain neurons for a given task. We used statistical parametric mapping (spm) tools version 2000(spm2) to analyze the data acquired from the fMRI scanning. We used an EMG-controlled robot hand for the motor function recovery. The use of the EMG signals permits the acquisition of the user’s intention. Pressure sensors were placed on the robot hand to detect the interaction with surrounding objects. The signal from the sensors was translated into electrical stimulation of the skin to transmit the tactile information. Our results show that the inclusion of sensory feedback, even a simple on-off signal, allow the adaptation of the brain to the prosthetic system, developing a tactile illusion, that is, the person using the system is convinced that is touching the objects with the robot system. Since the lack of sensory feedback increase fatigue in the control of our body, this system can be applied to both prosthetic and neuroprosthetic systems. This helps us solve the "disembodiment" problem that many spinal cord injured people and amputees experiment. Since upper limbs sensory requirements are higher than lower limb functions, we decided to test the electric stimulation on upper limbs prosthetic applications. We pursued further understanding of the relation between motor and sensor modalities by stimulating in different body areas, subtracting sensor modalities (visual feedback) and inserting a time delay between the activation of the pressure sensors and the application of electrical stimulation on the skin.

The conclusions contain the summary of the contributions made by this study. We introduced the need for an integral system for motor and sensory function recovery to increase the rehabilitation process. We proposed a high-frequency squared carrier signal for a burst-controlled transcutaneous electrical stimulator to comply with the motor and sensory function stimulation requirements. We presented the contributions made by the developed system by reducing the peak voltage to elicit the electrical stimulation of the nerves and the use of functional electrical stimulation to transmit tactile information through the skin. The proposed system presented a reduction on the habituation to the electrical stimulation problem, with an average discrimination rate of 90%.

Following, we presented the evaluation of the integral method in two instances: Walking assistance system and a FMRI study of an upper limb EMG controlled prosthetic system with feedback. First we evaluated the proposed system in walking assistance system for lower-limb semi-paralyzed patients. We presented the improvement in volitional control from using the proposed system with minimum stimulation requirement, and introduce the use of multi-scale information transference to measure the balance in the walking gait.

In order to measure directly the effects of the integral system, we presented an fMRI study of an upper limb EMG-controlled prosthetic system. This study opened new insights on how the brain process simultaneous events. We discuss the apparition of a tactile illusion when the persons while using the EMG-controlled prosthetic system, received sensory feedback in the form of electrical stimulation. We presented the increase in brain activation when actively using both sensory and motor system. Although this study has limited test subjects, the results points the importance of active involvement in an integral system for rehabilitation.