SSRG International Journal of Medical Science
ISSN: 2393 – 9117 / https://doi.org/10.14445/23939117/IJMS-V10I1P101

Volume 10 Issue 1, 1-5, Jan-Feb 2023

Original Article

Towards Artificial Proprioception in Prosthetic Devices

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Received: 22 November 2022 Revised: 25 December 2022 Accepted: 07 January 2023 Published: 18 January 2023

Abstract - *The human proprioception is one of the mechanisms utilized to recognize the location of the different segments or body parts, also identify them in space; the problem comes when the loss of a nervous pathway (e.g., due to amputation of a limb). Given the background in literature and technological development, this work's purpose is to establish a definition and to demarcate a methodology for Artificial Proprioception in persons who have lost their natural proprioception. Although this work can be applied to a wide variety of disorders, this work is aimed to be implemented in Prosthetic Devices to assist people with amputation, and the major example is the loss of the lower limb at the transfemoral level. We see Artificial Proprioception as the integral incorporation of a mechatronic system to the person, not only for the prosthesis but also for neurological rehabilitation purposes to regain lost abilities that can help the patient to achieve activities or avoid accidents (e.g., a fall during gait).*

Keywords - *Artificial proprioception, Rehabilitation auxiliary devices, Biomechatronic, Prosthetics, Orthotics.*

1. Introduction

One of the major problems with limb amputation is the absence of somatosensory pathways that normally provide feedback to the central nervous system. The proprioception in a complete individuum identifies conditions and restrictions about the different body parts for proper functionality. Still, for patients with lower-limb amputation, the proprioception needed for recognising the current gait cycle and walking symmetry is absent [1], which is a major problem in these patients. In patients with a transfemoral amputation, the main non-existent parameters are knee and ankle joint conditions, and plantar pressure, among others. Some work done around prostheses to aid these patients during the gait is to propose active or semiactive knees, ankles, and feet [2–7]. Yet another approach is the design of a lower limb exoskeleton for rehabilitation to aid with neurologic injuries [8]. But in this research, we focus on how the emerging technology can provide a solution to the lost proprioception; therefore, our main goal in this paper is to define Artificial Proprioception to establish this new concept for a new family of prostheses that seeks to improve rehabilitation and quality of life among patients with amputation.

2. Background

The amputation of a lower limb is one of the most life-changing events for a person because it takes away the walking ability and causes many other consequences, such as the loss of independence or chances to practice some sports; nevertheless, prostheses have been an option for a long time. Recently, the literature is found efforts to improve prosthetic mechanisms in human kinesiology [9], where the analysis focuses on the patient's movements to propose new knees or ankles. Other authors have been compared passive conventional transfemoral sockets (Ischial Ramus Containment, Dynamic Socket and Sub ischial) regarding skeletal motion, walking, stability, and predilection [10], [11]. Nevertheless, these clinical trials have found that there are no improvements or enhancements between the different sockets. Due to the emergence of biomechatronic areas, powered prostheses are explored different approaches over the years, which are to implement automatic responses from the prosthetic device using the analysis of gait conditions[12], other works use electromechanical elements (brushless DC servo motor, hydraulic cylinder, bidirectional gear pump) in transfemoral prostheses to provide stabilization, buffer and power when walking[13], yet another approach is to use sensors and actuators to provide biofeedback whether for sensitive or muscle pathways. For example, a proposed transtibial prosthesis capable of adapting to uneven terrain can provide the user with feedback when a slope is detected by using sensors and actuators that transmit *stimuli* [14]. In 2021, a review of sensory feedback restoration was conducted by Raspopovic et al. that included different technological advances suggested for enhancing devices for arm and leg amputees [15], where the main goal is to provide information to the patient and help with their rehabilitation. Finally, in 2022, Basla et al. described a wearable biofeedback system designed for a transfemoral prosthesis to improve the balance and gait symmetry in lower limb amputees using pressure, inertial, and vibrational sensors actuators [16]. Nevertheless, there is a gap between the ideas about what and how to name or understand proprioception; for example, it has been called "*neuroprosthesis*" or vibrotactile biofeedback or haptic systems, but we propose to unify the concept towards an Artificial Proprioception on the one hand, we start by defining it and establish a model to systematically apply this new knowledge to the design of a new kind of upper or lower limb prostheses. We will use transfemoral prostheses to illustrate the concept and exemplify the method.

2.1. The Human Proprioception

Proprioception, as a nervous subsystem, is one of the main mechanisms that the human being uses to recognize the location of the different segments or body parts, identify them in space, and train them towards the execution of movements that guarantee performance suitable for activities. The senses related to proprioception are originated at nervous endings attached to muscle fibers, tendons, joints, and ligaments; the main structures are annulospiral and flower-spray endings, Golgi, Ruffini, and Pacinian nerve endings [17]. Other senses that help in the feedback are: kinesthesia, stereognosis, and vibratory sense, in which nerve fibers and sensorial structures are related and travels along the spinal medulla to the brain to be consciously managed.

The maturation of proprioception starts from intrauterine development thanks to stimuli such as maternal movement, amniotic fluid pressure, caresses or vibrations that cause reactions in the *fetus*. This maturation is related to the kinetic aptitude of the individual. It is essential for the improvement of the gait since it is essential for the interaction and integration of the visual, vestibular, and proprioceptive systems. Additionally, during childhood, proprioception is the basis for the first automatic and voluntary movements, evidencing an intimate relationship between motor skills and proprioception; in addition, proprioceptive and tactile sensations are expressed in the change of the body scheme and, as a result, a body consciousness that will allow the individual to develop fully functional during life. On the other hand, when an injury occurs in any body segment, the sensory information distinguishes certain alterations, causing the proprioceptive system to have a deficit in the information it obtains, which often conditions the body to respond inadequately and is susceptible to new injuries, this due to the emission of altered information in the joint mechanoreceptors after the decrease in the number of receptors and responses emitted. But specifically in patients with amputation, the process is different due to the lack of information, and it is when the ***Artificial Proprioception*** is both useful and necessary.

2.2. The Nervous Territory Segments in the Human Body

There are at least three sections of the innervation of the body at the level of sensations and coordination of movements, which are: a) the Dermatomes, which are the representation in the skin of each nerve root of the peripheral system; b) the Myotomes, which are the muscular representation of the nerve root, and c) Osteotendinous Reflex, which represents an unconscious response (which does not reach the central nervous system) of a nerve root. These sections together provide a map of the territory of the body structures where a nerve root is acting. The superficial territory that will help the artificial proprioception to target an area to place the technological system in the body is guided by the dermatomes, even when the nerve roots supplying adjacent dermatomes may clinically overlap [18]. Also, the muscular and articular structures related to the same nervous root will be considered, considering the targeted nervous territory segment.

3. What is Artificial Proprioception?

In summary, human proprioception is a series of somatosensory nervous pathways involved in providing awareness of location, action, and other parameters of the body parts in normal conditions [18], [19], and our concept of Artificial Proprioception is a system to provide alternative sensorial stimulus to an individual who has lost its normal proprioception by using technological systems and to use such stimulus for further rehabilitation.

3.1. The Methodology to Achieve Artificial Proprioception Includes the Next Steps

1. Define the parameters needed to artificially provide to the individual, accordingly to the missing body part.
2. Establish the missing sensory pathway or the lost, nervous territory segment.
3. Find and target the nervous pathway responsive to carrying sensitive and motor information.
4. Design the system in two parts:
    a. The instrument that artificially acquires the parameter (e.g., sensor).
    b. The artificial media emulate the stimulus (e.g., actuator).
5. Use the technological devices to install the system in the individual.
    a. The sensor is placed where the parameter is missing (e.g., the prosthetic foot).
    b. The actuator is placed over the remaining trajectory dermatome (e.g., along the foot-sensitive pathway).
6. Enter a rehabilitation program to use the new sensitive information.

Figure 1 is shown an image of the dermatomes for the spinal nerves from the lower human body as a visual aid to implement Artificial Proprioception. The dermatomes divisions illustrated are approximations because of the intertwined nervous branches and adjacent spinal segments [17]; also, from a clinical viewpoint, we are going to adjust the positions for the artificial system.

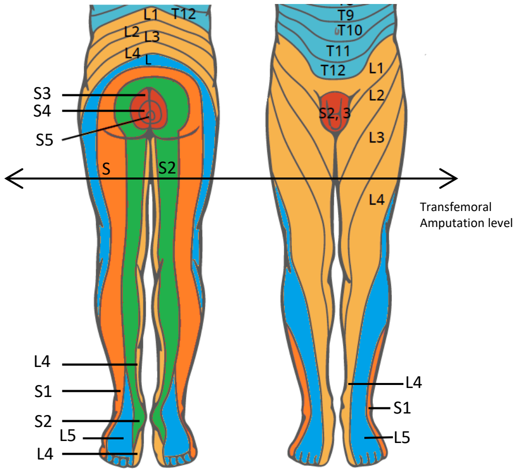

Fig. 1 Dermatomes from the lower human body and the approximate level of transfemoral amputation which varies in every patient. Consider that there are differences between authors [17].

In a transfemoral amputation, the affected dermatomes are L2-L5 and S1-S2; however, the target dermatome is selected according to the required proprioceptive information to be artificially replaced. Table 1 shows a compilation of the main dermatomes in the lower limb; for example, the dermatomes involved in foot sensitivity are L4, L5, S1, and S2.

Table 1. Main dermatomes are associated with the main anatomical structures in the lower limb, considering that adjacent spinal segments may be intertwined

Anatomical structure	Dermatomes
Hip	L2, L3, L4, L5
Thigh	L2, L3, L4, L5, S1, S2
Knee	L3, L4, L5, S1
Leg	L3, L4, L5, S1, S2
Ankle	L4, L5, S1, S2
Foot	L4, L5, S1, S2

The Artificial Proprioception targets a missing sensitivity in a structure and relocates it in an upper level along the affected dermatome, for example, to replace sensitivity from a missing foot, specifically the plantar view (there are four nervous roots implicated in the foot), the target dermatomes are L5 and S1. Technologically, it has been used as a collection of sensors [21] (e.g., Force Sensitive Resistors or piezoelectric sensors) that can acquire information and transfer it to an upper level, such as the anatomical area of the sacrum (superficially) with the aid of an actuator (e.g., a vibrator motor with different frequencies to emulate).

3.2. Example to illustrate Artificial Proprioception

The materials used in a particular case to demonstrate *Artificial Proprioception* are: a) the piezoelectric sensor, b) a vibration motor, c) a microcontroller, and d) an energy source. The setup of the materials can be seen in the next Figure 2; notice that the microcontroller and its energy source may be designed to be located somewhere in the prosthesis, given ergonomic conditions and space. Also, in Figure 2, we place the sensor in the foot to acquire information during the gait and the vibration motor is placed above the prosthesis along the remanent dermatome; in this case, we target L5, which will receive a proportional stimulus to be processed in the central nervous system.

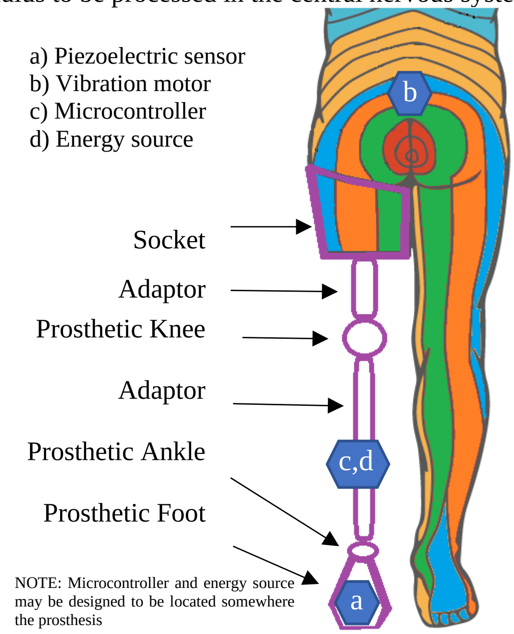

Fig. 2 Elements and setup for the Artificial Proprioception system.

The program in the microcontroller converts the sensor's data into a proportional signal sent to the motor. This signal is customized because each patient has different perceptions of the proportional magnitude of vibration. The system is tested on each patient, and the therapist determines the rehabilitation program to incorporate the vibration information for regaining functions (e.g., stability during gait).

As exposed in the introduction, the information that the Artificial Proprioception will determine the difference between having some information and having none of it in the rehabilitation and regaining some abilities that help in the corporal projection or self-perception to walking and other activities. Since it is a process of readaptation, the new information arriving in the brain will need training. In other words, the new information from the Artificial Proprioception will require that the brain process it and readjust muscular control to the new feedback. It is important to emphasize that our main goal is to provide the substitution of the missing nervous information from the lost limb or body segment. Still, the adjustments will need a rehabilitation process, which the therapist will guide in the interdisciplinary team.

4. Conclusion

In this paper, we introduce the concept of Artificial Proprioception, which provides new opportunities in the field of the prosthesis. This work also establishes a series of steps for an iterative methodology to embody an artificial system to provide the brain with sensorial information from a missing body part, for example, in a patient with amputation. For this purpose, we exemplify a transfemoral amputation and the system for the Artificial Proprioception that was designed with three main parts: a sensor, an actuator, and a processor, which integrates with any kind of prosthesis. The system can be an accessory for each patient to be used during rehabilitation, also can be programmed according to the patient's needs and sensorial assessment from the therapist. Introducing this kind of compensation and readjustment for the lost proprioception will improve gait balance and reduce the risk of falling, among other benefits. The implication of the existing feedback systems is to unify the term into Artificial Proprioception. It opens to future work that extends the concept not only to the prosthesis but also to orthoses. Additionally, in our laboratory, we have the proposed system of Artificial Proprioception that has already been tested with real patients and outcomes are in progress.

Acknowledgements

Authors thank the support to DGAPA of UNAM, given by the project PAPIIT TA100622, titled: "Estudio sobre la sustitución de la realimentación propioceptiva de miembros inferiores en pacientes amputados para prevenir caídas durante el uso de prótesis", during the realization of this project.

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