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Scientific and Technical overview about Artificial Proprioception in Prosthetics

Panorama Científico y Técnico sobre Propiocepción Artificial en Prótesis

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ABSTRACT
Proprioception is the body's ability to perceive its position and movement, which plays a crucial role in motor control, and its loss following amputation presents significant challenges for prosthesis users. Artificial Proprioception is an innovation that enhances sensory feedback and motor control in prosthetic devices. This review presents a comprehensive overview of current research and technological developments in Artificial Proprioception, focusing on sensory feedback mechanisms, neural interface systems, and the integration of biomechatronic technologies. With a growing interest in restoring sensory feedback for amputees, this work explores key innovations such as electrotactile and vibrotactile stimulation, artificial intelligence, and neural interfaces that enable a more natural and intuitive prosthetic control. The methodology included reviewing studies from databases like Scopus, Web of Science, and PubMed on proprioceptive feedback in prosthetics in recent years. It evaluates research related to sensory feedback, amputation levels, neural interfaces, and technological advancements, classifying papers by feedback mechanisms. The paper concludes by discussing potential future developments, including more advanced, user-centered prosthetic devices that address the sensory needs of amputees and improve their quality of life.

KEYWORDS: artificial proprioception, biomechatronic devices, prosthetics, rehabilitation technology, sensory feedback

RESUMEN

La propiocepción es la capacidad del cuerpo para percibir su posición y movimiento, que desempeña un papel crucial en el control motor, y su pérdida tras una amputación plantea importantes retos a los usuarios de prótesis. La propiocepción artificial es un avance innovador para mejorar la respuesta sensorial y el control motor de las prótesis. Esta revisión presenta una visión global de la investigación actual y los avances tecnológicos en Propiocepción Artificial, centrándose en los mecanismos de retroalimentación sensorial, los sistemas de interfaz neural y la integración de la biomecatrónica. Con un interés creciente en la restauración de la retroalimentación sensorial para amputados, este trabajo explora innovaciones clave como la estimulación electrotáctil y vibrotáctil, la inteligencia artificial y las interfaces neurales que permiten un control protésico más natural e intuitivo. La metodología incluyó la revisión de estudios de bases de datos como Scopus, Web of Science y PubMed sobre retroalimentación propioceptiva en prótesis en los últimos años. Se evalúa la investigación relacionada con la retroalimentación sensorial, los niveles de amputación, las interfaces neurales y los avances tecnológicos, analizando los artículos por mecanismos de retroalimentación. El artículo concluye con un debate sobre posibles desarrollos futuros, incluidos dispositivos protésicos más avanzados y centrados en el usuario que aborden las necesidades sensoriales de los amputados y mejoren su calidad de vida.

PALABRAS CLAVE: dispositivos biomecatrónicos, propiocepción artificial, prótesis, retroalimentación sensorial, tecnología de rehabilitación

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INTRODUCTION

Normal sensory feedback

Humans can perform daily tasks like opening doors with a lock, navigating obstacles in a hallway, and operating a car efficiently because touch, proprioception, and vision all contribute to the closed-loop motor control system. People can benefit from knowing the anatomical and physiological basis of the tactile, proprioceptive, and visual sensory systems and how they affect movement control and limit human motor skill performance in all these skill performance scenarios. Sensory information's role in regulating action is fundamental to all motor control theories. Out of all the senses, touch, proprioception, and vision play significant roles in the motor control of abilities. Touch and proprioception are considered senses of the somatic sensory system in the study of human sensory physiology, while vision is the sense related to the visual sensory system[1]. The sense and awareness of one's own body's location and motion is known as proprioception. Proprioception is one of our fundamental senses that is frequently disregarded. However, it provides sensory data regarding movement properties like direction, location in space, velocity, and muscle activation to the central nervous system. Proprioceptive feedback is essential in closed-loop models of movement control because it can help adjust while moving when proprioceptive information is used to facilitate closed-loop control.

Human Proprioception and enhanced feedback

Proprioception involves several essential physiological elements; proprioceptors are specialized sensory receptors in muscles, tendons, and joints crucial to this "sixth sense." Golgi-tendon organs, found at the junction of muscles and tendons, check tension, while muscle spindles by sensing variations in muscle length and tension. Joint receptors provide information on joint angle and movement. Through sensory neurons, these receptors send signals to the central nervous system, where the brain combines the data to construct a coherent perception of movement and position inside the body[2]. People can access two general forms of performance-related information (feedback) when they execute a motor skill, which will "tell" them something about the result of the performance or the reason behind it. One is the sensory-perceptual data obtained from executing a task naturally, known as task-intrinsic feedback. The sensory systems (proprioception included) can deliver this kind of feedback. But there is a second type of feedback, which is "Task-intrinsic," and the name used in the literature is "enhanced feedback"[3]; even though other names for this kind of input have been proposed, such as task-extrinsic feedback and external feedback.

Amputation and prosthetics

Amputation of a limb is a tragic occurrence that negatively affects the individual's health and quality of life. The lack of comprehensive and up-to-date global data complicates figuring out the exact number of amputees worldwide. However, some estimates can be provided based on available studies and data. According to the World Health Organization (WHO), it is estimated that there are more than forty million people in the world living with an amputation. This number includes amputations caused by accidents, disease, medical complications, and armed conflict. In some countries, the figures may be more specific. For example, In the United States, it is estimated that around two million people are living with an amputation, and approximately 185,000 amputations are performed each year. In Europe, the number of amputations varies between countries, but it is estimated that there are hundreds of thousands of people living with amputations[4].

In Mexico, Amputations are a significant health issue, primarily because of the country's high diabetes and trauma injury rates. With almost twelve million affected, Mexico has one of the highest rates of diabetes worldwide, according to the Mexican Diabetes Federation[5]. Amputations are often caused by diabetic complications such as foot ulceration and peripheral vascular disease. According to estimates, the risk of having an amputation is up to fifteen times higher in individuals with diabetes than in those without the condition. Between 70,000 and 100,000 amputations are thought to be conducted in Mexico each year, the majority of which are connected to diabetes and its consequences[6][7].

The importance of proprioceptive feedback in amputees

Since all sensory feedback is lost in an amputee, proprioception has been suggested to be one of the most important senses for movement and the ability to perform specific tasks. Considering that it is possible to provide "augmented feedback," it is possible to give the prosthesis wearer a series of controlled proprioceptive stimuli through technological means, that is, to obtain artificially generated proprioceptive feedback. In 1999, the importance of providing sensory feedback in upper limb prosthetics was addressed[8]. This is how Artificial Proprioception has been proposed to be a breakthrough in the rehabilitation of amputees. For this reason, Artificial Proprioception has been proposed as a means of retrieving somatosensory feedback that is helpful in the performance of tasks through an electronic system that causes the brain to perceive important information from the activities performed. One of the most relevant issues is the recovery gait control of individuals with lower limb prostheses[9]. In previous work, we studied and defined Artificial Proprioception[10], and a method was proposed. However, in this review, we have investigated the trend of science and technology worldwide to give an overview of the current state of artificial proprioception.

The review's main aim is to find relevant or comparable work on Artificial Proprioception worldwide, as well as information on the technology employed, advantages noted, and actions taken to enhance the quality of life of prosthesis users.

MATERIALS AND METHODS

Eligibility criteria

The studies will be related to sensory feedback generated by external devices that have been developed around the world. The keywords used in the searches are detailed below. The population of interest is amputees using upper and lower limb prostheses, regardless of socket type or amputation level, e.g., transfemoral, transtibial, transhumeral, or transradial. In addition, information is sought on the technologies being used worldwide or what has been new in recent years, such as artificial intelligence or actuators to carry out sensory feedback.

Search strategy

Data sources such as Scopus, Web of Science, and PubMed will be used for searches. The search terms are: a) Proprioception, b) Sensory feedback, and c) Prosthesis, with which the basic searches are done with the different search engines. The documents to search are in English, and we will retrieve records from the last 20 years.

Study selection

The Selection Process for the studies found will include a review of titles, abstracts, full text, methodology, findings, conclusions, and future work. Finally, Mendeley will be the reference manager.

Data extraction

The variables extracted from the included studies will be extracted from the documents related to proprioceptive feedback in the prosthesis, e.g., by level of amputation, proprioceptive feedback mechanisms, neural interface systems, and advancements in prosthetic control. Figure 1 provides a guide to extracting information for analysis, showing the two ways of classifying information related to the document's general and research data.

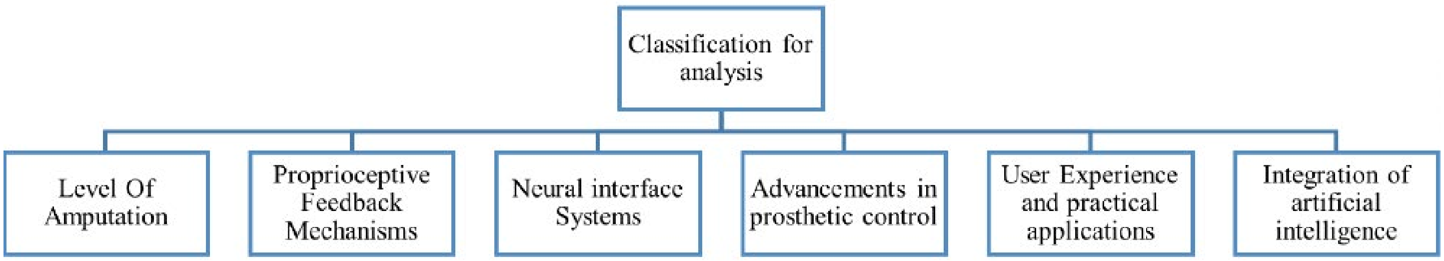

FIGURE 1. A proposed data extraction classification according to general information and related to the theme of the review: Proprioception feedback in prosthesis.

RESULTS AND DISCUSSION

While searching for studies in Scopus, PubMed, and Web of Science, other databases, such as Nature or SpringerLink, produced repetitive results. The keywords used were proprioception, feedback, and prosthesis. Figure 2 shows a flowchart of the study selection.

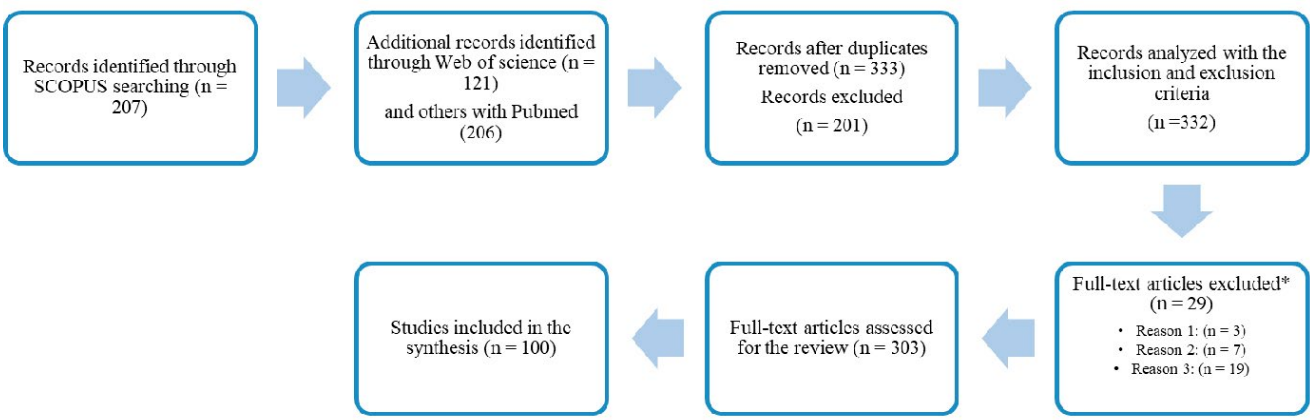

FIGURE 2. Flowchart of study selection. * Reason 1: animal-related studies; Reason 2: other types of prostheses; Reason 3: different areas of study.

We found 207 from SCOPUS, 206 from PubMed, and 121 from the Web of Science. Five hundred thirty-four documents were registered; however, 202 duplicates were removed, leaving 332 works for the database gathered in Mendeley.

Analysis related to proprioceptive feedback in prosthesis

The studies were grouped into key themes: advances in upper and lower limb prosthetics, proprioceptive feedback mechanisms, neural interface systems, advancements in prosthetic control, user experience and practical applications, and the integration of artificial intelligence

Upper limb

To transmit hand aperture or wrist rotation angle during sequential prosthesis control, a study by Dideriksen J., Siebold E., *et al.* (2024)[11] describes and assesses a feedback system with four vibration motors incorporated in the prosthesis socket. A functional task involving the manipulation of delicate objects with different compliance (with vibrotactile and/or visual or neither) was conducted by ten non-disabled and two amputee volunteers. The results for the amputee participants were similar because all participants perceived the vibrotactile feedback as helpful, dependable, and simple to perceive and utilize. However, the researchers noticed that it took longer to use the vibrotactile feedback than the visual. In conclusion, even when visual feedback is not entirely available, the proprioceptive feedback in this paper offers a valuable way to support object manipulation.

Research by Federico Masiero *et al.* (2024)[12] presents an example of a human-machine interface (HMI) that uses permanent magnets implanted in amputees' remaining muscles to control robotic limb prosthetics; they have called it a “pyrokinetic interface.” This interface uses the selected vibrations created by carefully regulated magnetic fields from external coils to activate muscle-tendon proprioceptors. A problem solved was the real-time tracking of several moving magnets under vibration. The outcomes demonstrate the feasibility of a system that can monitor and move several magnets in three dimensions, producing highly effective torsional vibrations at frequencies that provide the impression of movement.

The study of Yichen Han *et al.* (2023)[13] addresses the need for enhanced proprioceptive feedback in upper-limb prostheses, focusing on the position and movement of a prosthetic wrist. An electrotactile scheme was developed to encode these proprioceptive cues, and an experimental platform was designed for testing. Preliminary experiments determined sensory and discomfort thresholds, followed by two main proprioceptive feedback experiments: position sense and movement sense. The study demonstrates that the electrotactile stimulation scheme can effectively provide proprioceptive feedback for the position and movement of a prosthetic wrist.

Matthieu Guémann and Christophe Halgand *et al.* (2022)[14] evaluate vibrotactile feedback for myoelectric control of virtual elbow in prosthetic users, comparing performance in healthy subjects and transhumeral amputees. They interviewed sixteen healthy participants and seven transhumeral prosthesis users who performed myoelectric control of a virtual arm under four different conditions of feedback: Vision alone (VIS), Vibration alone (VIB), Vision plus vibration (VIS + VIB), and No feedback (NO). The study measured reach accuracy through angular errors during discrete and continuous movements. With extended training, the effectiveness of VIB alone is expected to improve, potentially reducing reliance on vision for closed-loop prosthesis control.

Marasco PD, Hebert JS, Sensinger JW, *et al.* (2021)[15] presented a complex neurorobotic touch feedback system for the prosthetic hand that involves advanced modifications and precise engineering to provide comprehensive sensory feedback. They investigated how the neurorobotic fusion of these sensory modalities in bionic upper limbs can enhance functional integration with the user's neural and sensory systems. Participants in this study previously underwent targeted reinnervation for proximal limb amputation and were habituated to myoelectric prosthesis usage. Each participant was fitted with an experimental prosthesis using modified commercial components integrated with sensors. Small, robust robotic four-bar haptic touch tactors were installed in the prosthetic socket and transmitted proportional pressure and contact transients (tap detection) from the hand to the appropriate touch percept sites in the reinnervated skin. These tactors generate up to 10 N forces with a 10-ms latency closed-loop position control, ensuring rapid and accurate feedback. Monitoring and analyzing brain activity revealed that participants exhibited brain activation patterns similar to those observed with natural limb use, indicating a more intrinsic and natural control over the bionic limbs. This enhanced sensory integration led to improved motor control and more intuitive use of the prosthetic limbs, with participants reporting a more natural and seamless interaction with their bionic limbs. The findings suggest that the neurorobotic fusion of sensory feedback promotes intrinsic brain behaviors, potentially leading to significant advancements in the design and functionality of bionic limbs, thereby improving the quality of life for prosthetic users. Developing a neurorobotic interface that integrates touch, kinesthesia, and movement feedback mechanisms was central to the study, involving individuals using bionic upper limbs.

Shiyong Su *et al.* (2023) conducted a thorough investigation into the brain mechanisms underpinning the integration of sensory feedback in myoelectric prosthesis control[16]. Their study, which comprised fifteen participants doing standard prosthesis control tasks, showed that visual feedback is crucial for manipulating blocks and grasping force control. The study also demonstrated the importance of tactile feedback for proprioceptive location perception tasks. Confirmed by concurrent EEG recordings and behavioral evaluations, these results offer vital insights into the significance of multisensory integration for efficient prosthesis control.

The study by Nikita Piliugin *et al.* (2024)[17] emphasizes how the modulation of PNS parameters—specifically stimulation frequency and pulse width—affects evoked sensations, including their intensity, naturalness, and impact on phantom limb pain suppression. The authors employed a combination of site mapping and impulse mapping techniques with two transhumeral amputees, each equipped with implanted cylindrical electrodes on the median nerve. These methods allowed the researchers to establish correlations between electrode stimulation zones and perceived sensations and evaluate how different spectral parameters of stimulation influenced the quality of feedback. This study contributes to the growing literature on neuromodulation in neuroprosthetics, offering a novel approach to mapping and analyzing evoked sensory feedback through behavioral data and advanced computational methods. However, its small sample size and variability among subjects signal the need for further research to generalize findings and refine PNS techniques.

In 2022, Enzo Romero and Dante A. Elias[18] published a conference paper that presented the conceptual design of a haptic palmar-finger feedback system for a transradial myoelectric upper limb prosthesis that allows an amputated person to acquire the sensations related to force-gripping, object-sliding, and pressure of the prosthetic fingers. The designed system has a monitoring unit arranged on the prosthetic hand and an actuation unit embedded in a bracelet around the user's forearm; they use tree vibration modules. It was a design exercise, with no manufacturing nor patient test.

The study of Marco Gallone and Michael D. Naish (2022)[19] examines the development and evaluation of a head-worn Wearable Haptic Feedback Device (WHFD) designed to transmit sensory information from upper-limb prostheses. The suggested WHFD is a skullcap worn on the head that has 30 vibratory units stitched into it. A 14-week study involving 18 participants explored the learning process associated with interpreting haptic patterns conveying joint proprioception. The study compared three different haptic stimulation methods, revealing insights into the effectiveness and potential of each approach for enhancing sensory feedback in prosthetic users. Participants in this work demonstrated significant learning and improved ability to interpret the haptic information throughout the study. The spatiotemporal stimulation group showed a slight advantage in interpreting the haptic patterns compared to the other groups. The spatiotemporal stimulation refers to a sensory feedback technique that integrates spatial and temporal patterns to encode information through haptic signals.

In this context, vibratory actuators activate in a sequential, sweeping pattern, where the sequence's duration and direction convey specific data, such as the magnitude and motion of a joint. This method allows complex proprioceptive information to be represented effectively, leveraging the brain's ability to interpret dynamic patterns, as demonstrated in applications like prosthetic control.

Trujillo *et al.* (2022)[20] proposed a skin-stretching actuator to transmit proprioceptive information to a person with an amputation to provide feedback, and they evaluated the efficacy of two fixation methods using a longitudinal skin-stretching haptic device. One is neoprene foam, and the second is a double-sided adhesive tape. Ten participants without amputation were interviewed for the study, and the proprioceptive information was transmitted using a skin-stretching actuator. Two quantitative surveys were conducted based on the mirror box to measure the effectiveness of the fixation methods. They found no statistically significant differences between neoprene foam and double-sided adhesive tape. However, neoprene foam was preferred due to its non-adhesive nature and was perceived as a more natural stimulus. These authors suggest foam is a viable option to transmit sensory feedback more naturally. As another university proposal, this conference paper didn’t evaluate the device with prosthetic users or amputees but suggested further research should focus on long-term studies and testing with amputee participants to confirm these findings.

In 2022, Magbagbeola *et al.*[21] investigated how vibration patterns can improve the perception of tactile information in prosthetic limbs, aiding in the long-term use of prosthetics and neuropathic pain management. The researchers employed a deep-learning algorithm to categorize the dissipation of vibration artifacts in Electromyographic (EMG) signals. Using two vibration motors, four different texture patterns were applied to seven participants in the experiment; each pattern was repeated three times. After post-processing, each participant's unseen data was effectively classified using a Recurrent Neural Network (RNN) to identify the artifact features across equidistantly separated EMG electrodes. By enhancing the precision and usability of sensory feedback in prosthetic devices, this effort may lead to a higher rate of long-term adoption. Nevertheless, the study was on non-disabled persons.

Cha *et al.* (2022)[22] presented a closed-loop control system for robotic prosthetic hands, combining EMG-based intention recognition with proprioceptive feedback to enhance control. This study explores the power of a robotic prosthetic hand by combining intention recognition via Electromyography (EMG) classification with sensory feedback through a rule-based haptic device. A Convolutional Neural Network (CNN) model was designed to classify EMG signals from multiple channels, achieving over 97 % accuracy in recognizing user intentions across ten different grip states. The integrated system, which merges the CNN-based EMG classification with the haptic feedback device, was evaluated on able-bodied subjects and demonstrated high accuracy in both intention recognition and sensory feedback.

Battaglia *et al.'s* (2017)[23] research addresses the challenge of restoring hand functionality in upper limb amputees using myoelectric prostheses, which often lack intuitive control and haptic feedback. To improve user experience, the authors introduce the Rice Haptic Rocker, a device designed to provide proprioceptive feedback through skin stretch, integrated with the Pisa/IIT Soft Hand. The results showed that the device is a feasible tool for enhancing proprioceptive feedback in prosthetic hands, improving task performance requiring object size discrimination.

The study of Mulvey *et al.* (2014)[24] investigates how the perceptual incorporation of an artificial limb can improve the manual control of prosthetic devices. It studies explicitly whether transcutaneous electrical nerve stimulation (TENS) can simplify the perceptual embodiment of artificial limbs. Findings discovered that combining visual, tactile, and TENS stimuli significantly heightened the intensity of perceptual embodiment, with the most noticeable effect occurring when all three stimuli were used together. Additionally, the strength of this effect augmented over time. The study concluded that TENS can modestly enhance the sensation of embodiment in artificial limbs.

Papalos *et al.*[25] wrote a review in 2023 about proprioceptive feedback in upper limb prostheses using non-invasive approaches, emphasizing the uses and difficulties related to proprioceptive restitution in upper limb prostheses. This work establishes that when an artificial stimulus is given to a user, and it comes from the same sensory system and modality as the missing information, it is said to be homo-modal feedback (e.g., transmitting touch with devices that provide pressure feedback). On the other hand, hetero-modal feedback requires a sensory channel that differs from the one used physiologically (producing angular movement through hearing, for example) or uses the same channel but modifies the input stimulus's modality (producing limb position through vibration instead of skin stretch, for example). It turns out hetero-modal stimulation is less intuitive than homo-modal techniques, making it a valuable option for feedback restitution.

Lecompte *et al.* (2024)[26] provide a vision focused on proprioceptive feedback approaches for upper-limb myoelectric prostheses. It deals with numerous methods for incorporating proprioception into prosthetic devices and explains the significance of this capacity. The techniques enlist the most common so far in the literature: a) skin stretching, b) auditory input, c) electrotactile stimulation, d) kinesthetic illusions, e) direct brain stimulation, f) vibrotactile stimulation, and g) intracortical microstimulation. The document emphasizes the downsides and restrictions of these techniques, mostly the struggle of obtaining real-time, non-invasive, anatomically consistent feedback that closely resembles sensory input from the environment. For example, the ineffectiveness of embodiment systems to perfectly imitate sensory integration may intensify the cognitive load necessary during the use, as well as uncomfortable sensations and even distress.

Lower Limb

Petersen *et al.* (2023)[27] explored the relationship between somatosensory impairments and functional performance in individuals with lower-limb amputation. Despite significant differences in balance and gait between amputees and able-bodied controls, the study found that existing clinical measures were insufficient to differentiate between levels of sensory impairment within the amputee group. This suggests that more sophisticated and challenging metrics are necessary to accurately assess sensory impairments' effects on functional abilities.

Canton Leal *et al.* (2022)[28] developed an innovative haptic feedback system called HapticLink, designed to enhance balance and proprioception in individuals with lower-limb amputations. The system, which uses force sensors and vibration motors to convey weight distribution information, was assessed with promising results. This development highlights the potential of haptic feedback technology to improve the quality of life for amputees by providing them with enhanced sensory feedback and greater control over their prosthetic limbs.

Di Zubiena *et al.* (2022)[29] focused their research on the static characterization of a novel stretchable strain sensor created through 3D printing, aiming to restore proprioception in lower-limb amputees. The sensor, which combines an elastomeric material with a metal alloy sensitive to deformation, demonstrated excellent sensitivity, repeatability, and response to strain. These characteristics make it a promising candidate for developing wearable proprioceptive devices that could significantly enhance balance and gait stability in amputees. Also, Zubiena et al. (2021)[30] conducted a Finite Element Modeling (FEM) analysis to investigate the potential application of an elastomeric strain sensor for restoring proprioception in transtibial prostheses. The study found areas of maximum deformation within the prosthesis during gait, which could be best for sensor placement. These findings are encouraging, as they support the future development of proprioceptive feedback devices that could improve balance, gait stability, and overall mobility for lower-limb amputees.

Gardetto *et al.* (2021)[31] presented a case series demonstrating the effectiveness of Targeted Sensory Reinnervation (TSR) in reducing phantom limb pain and improving proprioception in patients with lower-limb amputations. The surgical technique involved rewiring sensory nerves and pairing them with a specialized prosthetic device that provided sensory feedback from the prosthesis. Remarkably, the intervention resulted in significant pain reduction, with some patients becoming completely pain-free and others able to discontinue pain medication. This study provides compelling evidence for the benefits of TSR, particularly when combined with advanced prosthetic technologies, in enhancing the quality of life for amputees.

Foster *et al.* (2020)[32] examined the accuracy and precision of foot placement during a targeted stepping task in Individuals with Unilateral Transtibial Amputation (IUTAs). The study revealed that these individuals exhibited reduced accuracy and precision compared to able-bodied controls, particularly with their intact limbs. This finding suggests that the disruption of sensory information and the characteristics of prosthetic components may contribute to difficulties in dynamic balance and foot placement during everyday activities.

Charkhkar *et al.* (2020)[33] investigated how sensory neuroprostheses affected the balance of amputees who had lost limbs. The device mimics sensory feedback equivalent to plantar pressure beneath prosthetic feet by placing non-penetrating cuff electrodes around the remaining nerves. According to the results obtained from two transtibial amputees, the neuroprostheses significantly improved postural stability when ocular and intact leg somatosensory inputs were disrupted. This represents a breakthrough in prosthetic technology since it implies that neuroprostheses may enhance balance and lower the risk of falls.

Christie *et al.* (2019)[34] investigated the temporal perception of stimulation-induced sensations in amputees, mainly focusing on how these sensations synchronize with visual cues. The study found that stimulation-induced sensations can be perceived as synchronous with vision, similar to natural somatosensation when timed correctly. This research provides valuable insights into the design of sensory neuroprostheses, emphasizing the importance of temporal alignment in creating sensations that feel natural to the user.

Coker *et al.* (2019)[35] used computational modeling to compare the stimulation artifacts produced by different Peripheral Nerve Interfaces (PNIs) used in prosthetic limbs. Their findings indicated that micro-channel sieve electrodes generated fewer artifacts than other configurations, such as thin-film Transverse Intrafascicular Multichannel Electrodes (tfTIMEs). This reduction in artifacts is crucial for achieving concurrent sensory feedback and motor control in neuroprosthetics.

Plauché *et al.* (2016)[36] proposed that providing feedback based on the Center Of Pressure (COP) under the prosthetic foot can enhance proprioception and improve phase sensing in above-knee amputees. Their work introduces a device that delivers vibrotactile feedback derived from the COP of the prosthesis, aiming to restore proprioception and enhance phase awareness. Experiments conducted with novice users (non-disabled individuals) of a transfemoral prosthetic leg showed that the device significantly reduced variability in stride length, step width, and trunk sway during treadmill walking. This suggests that the haptic device effectively improves gait stability in users.

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Yang *et al.* (2012)[37] studied a real-time feedback system called the Lower Extremity Ambulatory Feedback System (LEAFS), designed to improve gait symmetry in individuals with transtibial amputation. The system provides auditory feedback to correct asymmetries in gait, with promising results for rehabilitation gait asymmetries, with promising rehabilitation results. LEAFS is a wearable wireless gadget that uses the stance time symmetry ratio between the right and left limbs to generate real-time aural feedback. The outcomes were inconsistent; two individuals had notable increases in gait symmetry. The results imply that LEAFS may help people with transtibial amputations achieve better gait symmetry, despite the small sample size. The study highlights an inconsistency in outcomes among the three participants, explicitly noting that while two subjects showed marked improvements in gait symmetry and trunk sway, the third did not demonstrate any objective enhancements. This inconsistency is attributed to individual differences, such as residual limb sensitivity or adaptation capabilities. For instance, the third subject exhibited numbness in the intact limb, potentially limiting their ability to respond to the feedback system. Such variability underscores the need for further investigation with larger sample sizes to account for individual factors influencing the effectiveness of the LEAFS system.

Ghiami *et al.* (2024)[38] report research on the sensorimotor parameters related to powered lower limb prostheses through walking movements of individuals with ankle amputation. Based on a review of 29 articles, the study outlines how amputees struggle to feel sensations through disintegrated nerves. This work focuses on prosthetic knees as the most capable component of a mechanically passive prosthesis for minimum energy expenditure walking. It focuses on proprioception created by integrated mechatronic systems to assist nervous rehabilitation and improve movement accuracy. This review includes our work from 2023[10].

Proprioceptive feedback mechanisms

A substantial part of the research applications is developing and refining proprioceptive feedback mechanisms, and in this section, we highlight some of the most representative ones. Early studies, such as those by Wall and Kentala (2005)[39], explored vibrotactile feedback to aid postural control in patients with deficits. Farrell *et al.*[40] examined the effects of static friction and backlash on the control of powered prostheses, emphasizing the importance of feedback in extended physiological proprioception. Later research delved into more sophisticated feedback systems. Kuchenbecker *et al.* (2007, 2009)[41][42] and Blank *et al.* (2008)[43] investigated the effects of visual and proprioceptive feedback on human control of targeted movements and virtual hand prostheses, respectively. These studies laid the groundwork for understanding how sensory cues can enhance prosthetic control.

In recent years, research has continued to evolve with studies like those by Plauche *et al.* (2016)[36] and Wendelken *et al.*[44], which presented advanced haptic feedback systems for prosthetic leg users and the restoration of motor control and sensation in amputees using Utah Slanted Electrode Arrays. Lima and Hammond[45] further advanced the field by examining simultaneous rotary skin stretch and vibrotactile stimulation for proprioceptive feedback, and the findings showed that participants could identify the dial angle when skin stretch feedback was provided. Additionally, Mablekos-Alexiou *et al.* (2015)[46] suggested a biomechatronic system that uses Extended Physiological Proprioception (EPP), a form of subconscious sensory feedback, to present a novel method of operating multi-joint prostheses. This architecture activates an implanted micro servo actuator, which offers similar control capabilities without the functional and aesthetic limitations of older approaches that rely on Bowden cables and cineplasty. The authors imply that this method will be more acceptable to users and could be a basis for more sophisticated and highly controllable multi-degree-of-freedom prosthetic devices.

Neural interface systems

Neural interface systems represent another critical area of research, and in this section, we highlight some of the most representative ones. Weber *et al.* (2012)[47] highlighted essential considerations for interfacing the somatosensory system to restore touch and proprioception. Ramos-Murguialday *et al.* (2012)[48] explored brain-computer interface-based neuroprostheses with proprioceptive feedback, providing a foundation for integrating neural signals into prosthetic control. Studies by Gaunt *et al.* (2009)[49] and Tabot *et al.* (2015)[50] examined the microstimulation of primary afferent neurons and the restoration of tactile and proprioceptive sensation through brain interfaces. This study investigates the long-term stability of intracortical microstimulation (ICMS) as a method for providing sensory feedback in upper limb neuroprostheses. Tabot experimented with non-human primates that could detect ICMS, which remained stable over the years, even with extensively used electrodes. These findings suggest that ICMS could be a viable and reliable approach for restoring somatosensation in neuroprosthetic devices, potentially improving their usability and effectiveness. Other recent research, such as that by Srinivasan *et al.* (2021)[51], explored the implementation of regenerative agonist-antagonist myoneural interfaces for preserving joint function and perception in above-knee amputations. This line of research underscores the potential for advanced neural interfaces to improve prosthetic devices' functionality and user experience. All these studies contributed to the understanding of how neural stimulation can be used to enhance sensory feedback in prosthetics.

Advancements in prosthetic control

The research also highlights significant advancements in prosthetic control mechanisms, and in this section, we highlight some of the most representative ones. Kuiken *et al.* (2007)[52] introduced targeted reinnervation, a technique to redirect cutaneous sensation, enhancing sensory feedback in amputees. Subsequent studies, such as those by Li and Kuiken (2008)[53] and Akhtar *et al.* (2014)[54], focused on modeling prosthetic limb rotation control and proprioception with numerous degrees of freedom via passive mechanical skin stretching, respectively. Brown *et al.* (2015)[55] and Schiefer *et al.* (2018)[56] explored the regulation of grip force control using a myoelectric prosthesis with low impedance and the improvement of object identification tasks through artificial tactile and proprioceptive feedback. These studies demonstrate the ongoing efforts to refine control mechanisms to enhance prosthetics' functionality and user experience. Rouse *et al.* (2011)[57] introduce the Osseo-Magnetic Link (OML), which is a unique control system intended to maintain in prosthetic devices, notably for humeral or wrist rotation. The OML system places sensors in the prosthetic socket to measure magnetic field vectors and implant a magnet within the residual bone. With this configuration, people can rotate their bones voluntarily to operate a prosthetic rotator.

User experience and practical applications

A key theme in the research is the focus on user experience and practical applications, and in this section, we highlight some of the most representative ones. For example, Cuberovic *et al.* (2019)[58] emphasized the long-term home use of sensory-enabled prostheses, displaying real-world applicability and user adaptation. Marasco *et al.*[59] showed that illusory movement perception could enhance prosthetic hands' ability to manage their motor function, highlighting the importance of creating intuitive and effective user interfaces. Studies like those by Sienko *et al.* (2018)[60] and Bates *et al.* (2020)[61] investigated the potential mechanisms of sensory augmentation systems on human balance control and the technological advances in prosthesis design and rehabilitation. These studies contribute to a better understanding of how prosthetic devices can be optimized for user comfort and effectiveness.

Integration of artificial intelligence

Integrating Artificial Intelligence (AI) into prosthetic systems represents an innovative area of research; in this section, we highlight some of the most representative ones. For example, Luu *et al.* (2022)[62] explored how AI enables real-time and intuitive control of prostheses via nerve interfaces. The neuroprosthetic system presented in this paper uses a Recurrent Neural Network RNN-based artificial intelligence agent to decode movement intent for amputees in real-time from peripheral nerve signals. Experiments with three human amputees showed that technology allows intuitive control of a prosthetic hand with up to 97-98 % accuracy in individual finger and wrist movements. The AI agent's long-term resilience was verified over 16 months, and its real-time performance was verified using assessments of reaction time and information throughput. The results show how AI-enabled nerve technology can be used to create the next generation of prosthetic hands that are intuitive and dexterous. Other recent studies, such as those by Vargas *et al.*[63] and Berger *et al.*[64], have explored closed-loop control of prosthetic fingers via evoked proprioceptive information and the use of AI for texture recognition based on multi-sensory integration of proprioceptive and tactile signals. These studies highlight the transformative potential of AI in the field of prosthetics. This topic proves the potential for AI to significantly enhance the functionality and user experience of prosthetic devices by providing more natural and responsive control mechanisms applying sensory feedback.

Our work in Mexico

In 2019, the Universidad Nacional Autónoma de México (UNAM) started offering a bachelor's degree in orthotics and prosthetics with a curriculum aligned with the country's needs. Amongst the university's goals are research, design, and technological development in this transdisciplinary area. Regarding sensory feedback for prosthesis users, we have progressed with the Artificial Proprioception proposal in work published in 2023[10]. We were trying to fill a truly relevant perspective in the current state of the art about the proprioceptive feedback applied to prostheses. The aim was and still is to integrate biomechatronic devices that imitate the sensory feedback lost due to limb loss. In our paper of 2023, we focus the application on the rehabilitation of amputees, active or passive, because proprioceptive feedback constitutes a significant obstacle in this field.

Discussion: interpretation of the main findings

Neural Interface Systems

One of the most significant and essential prosthetic advancements is neural interface systems that directly interface with the user's nervous system to provide sensory feedback. These systems are critical for the user to feel the sensation used to manage and command prosthetic devices more naturally and intuitively. For example, Weber *et al. (*2012)[47] emphasized important considerations for interfacing with the somatosensory system to restore touch and proprioception, such as electrode design and the need for selective activation of specific neural pathways and drawing on experience from other neuroprosthetic systems. In addition, Srinivasan *et al.* (2017, 2019, and 2021)[51][65][66][67][68] developed and published the use of regenerative agonist-antagonist myoneural interfaces to maintain joint function and perception in above-knee amputations. This is a massive leap into what is described as "natural-like" since the approach not only restores partial levels of natural sensations but also maintains the structural integrity of the residual limb, making good use of a prosthetic device.

Advancements in prosthetic control mechanisms

Prosthetic limb control has reached a new dimension by incorporating sophisticated feedback mechanisms that send actual sensations to the user in real time. Kuiken *et al.* (2027, 2008, and 2011)[52][53][57] showcased targeted reinnervation, a method through which cutaneous sensation is rerouted to enhance sensory input for amputees. The control method has been crucial in optimizing the functionality of myoelectric prostheses to enable users to execute skills with increased precision and confidence.

Further studies, as conducted by Plauche *et al.* (2016)[36], for instance, introduced a haptic feedback system for above-knee prosthetic leg users that substantially enhanced gait stability through the provision of vibrotactile feedback related to the center of pressure under the prosthetic foot. The innovation underlines that sensory feedback is crucial for upper-limb prosthetics and lower-limb devices, in which the ability to maintain balance and gait is essential.

Artificial Intelligence and Machine Learning in prosthetics

AI integration has opened new frontiers in prosthetic systems' functional and user experience-based development. Artificial intelligence allows for real-time control over prostheses intuitively and exquisitely responsive to the user's intentions. For example, Luu *et al.* (2022)[62] demonstrated how an AI-based system could use Neural Networks to decode movement intention from peripheral nerve signals with high accuracy and enhance prosthetic hand control. This AI-driven approach makes the prosthetic device more dexterous, self-improving, and adjusted to the user's needs. The application of AI in this matter does much good, as it can learn and improve with time, hence giving out prosthetic devices that are more considerate of human movement.

Proprioceptive feedback mechanisms

Effective proprioceptive feedback mechanisms have been central in prosthetics. The position sense and movement of the prosthesis are part of activities involving fine motor skills. Research by Dideriksen *et al.* (2020, 2023, and 2024)[11][69][70] introduced a feedback system that uses vibrotactile stimulation to convey proprioceptive information, and this indeed enhances the manipulation of objects with the prosthetic hand.

Besides that, electrotactile feedback has also been explored as a method to enhance the proprioceptive input from upper-limb prostheses. Using a developed electrotactile stimulation scheme that could effectively convey information about the flexion-extension position of a prosthetic wrist, Han *et al.*[13] demonstrated how such technology could enhance the precision of prosthetic control.

Innovative feedback devices and user experience

There is a growing interest in developing feedback devices that provide users with more natural and intuitive sensory feedback. Such examples include the Rice Haptic Rocker, designed by Battaglia *et al.* (2017 and 2019)[23][71][72], which integrated skin stretch feedback into a myoelectric prosthesis and significantly improved the perception of object sizes. This device stands out as an ideal example of how novel feedback mechanisms can substantially enhance functionality and usability for prosthetic devices.

Marasco *et al.* (2021)[15] introduced a neurorobotic system that combines the sense of touch with prosthetic control, allowing users to feel a more seamless and natural interaction with their prosthetic limbs. This system's added benefit includes enhanced motor control in users while providing an improved sense of embodiment, whereby the prosthetic limb feels like a natural body extension.

Implications for clinical practice

The advances in prosthetics related to artificial proprioception have profound implications for clinical practice by facilitating rehabilitation and improving the quality of life for individuals with limb loss. There are areas where the platform could improve clinical outcomes when it develops further. The most critical clinical implication would be the possibility of more personalized prosthetic solutions. For example, advanced neural interface systems, AI-driven prosthetics, and customized feedback mechanisms like vibrotactile and electrotactile feedback will allow clinicians to better match prosthetics with each patient's needs. These technologies restore sensory feedback to the user and enable better motor control and balance, allowing for smoother movement with reduced cognitive load required to control prosthetic devices.

CONCLUSIONS

Advancing artificial proprioception for prosthetics represents a leap into the future, where biomedical engineering will play an essential role in ensuring a more excellent livelihood for amputees. The stride of research has been underpinned by high underpinning in collaboration across disciplines, technological innovation, and raising the quality of life for prosthetics users. At the heart of this advancement has been embedding proprioception and other forms of sensory feedback into the prosthetic device, which allows users to regain a sense of normalcy in their daily activities by extending functionality, control, and overall usability.

The development in this field fundamentally highlights the role played by neural interface systems, involving direct interaction with the user's nervous system to restore sensation and proprioception. These systems have shown great promise in enhancing the intuitiveness and responsiveness of prosthetic limbs and providing users with more significant, more natural control over their movements. In the same way, integrating AI and machine learning into prosthetic systems has opened new perspectives for real-time, personalized control to make the prosthetic device more adaptable to each user's specific needs.

The counterpoint for lower-limb devices besides upper-limb prosthetics was when the proprioceptive feedback mechanisms are essential to maintain balance and gait. Vibrotactile feedback systems and more recent electrotactile stimulations strongly enhanced stability and functionality in lower-limb prosthetics, enhancing mobility in amputees and instilling more confidence in the activities.

Surgical advances must incorporate proprioceptive feedback and increased control to maximize the functional utility of prosthetic use. These findings highlight the necessity for continued innovation in more natural prostheses to improve life quality and rehabilitation.

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AUTHOR CONTRIBUTIONS

O. D.-H. conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, software, resources, supervision, validation, visualization, writing-original draft, and writing-review & editing.

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