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# Systematic Review on Recent Challenges in Artificial Skin for Sensory Feedback in Hand Prosthetics

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ABSTRACT

The development of sensory feedback through artificial skin holds significant technological challenges, despite the importance of bidirectionality in hand prosthetics. This systematic review examines recent advancements and the remaining hurdles in creating artificial skin that can provide realistic sensory feedback in modern hand prosthetics. The sensory mechanisms, which detect stimuli and translate them into a coherent signal for the device, include triboelectric nanogenerators, piezoelectric pressure sensors, and hydrogel skin simulators. The feedback mechanisms, which transmit these signals to the user, include transcutaneous electrical nerve stimulation, haptic feedback, and intraneural stimulation. Having compiled a series of recent developments in artificial skin and sensory feedback, it will provide an overview of challenges in sensory and feedback mechanisms. On top of individual problems with each mechanism ranging from manufacturing difficulty to scalability, the review found that the lack of research and development is likely due to the novelty of sensory feedback in prosthetic devices. The review evaluated the feasibility and potential of integrating these technologies into practical, user-friendly prosthetic hands, demonstrating the need for scalable, efficient solutions to enhance user comfort and functionality.

## Introduction

Limb loss is consistently growing in frequency as time passes, with the prevalence of traumatic amputations worldwide growing from 370 million in 1990 to more than 550 million in 2019 (Yuan et al., 2023). To maintain autonomy, most amputees seek the only existing solution for regaining some level of function in lost limbs: prostheses. Among the devices used to replace lost limbs, lower limb prostheses are much more common due to the prevalence of vascular diseases, which primarily affect the lower limbs (Swaminathan et al., 2014). Contributing to this disparity, upper limb prosthetics are relatively complex and require advanced systems to fulfill elevated functionality standards. The high requirements of upper limb sensation create many challenges for connecting the robotic limb to the human body. Due to the challenges of developing bidirectional communication between the user and the prosthetic limb, modern prosthetic hands lack bidirectional communication that would allow a user to control the prosthetic and receive sensory feedback accordingly.

Significant progress has been made in the control of prosthetic hands, mainly through myoelectric signals (Marinelli et al., 2023). Commercially available hand prosthetics, such as the VaryPlus Speed by Ottobock (Ottobock, n.d.), Motion Control Hand by Fillauer (Fillauer LLC, n.d.), i-Limb by Ossur (Ossur, n.d.), and TASKA Hand by Taska Prosthetics (TASKA, n.d.), can function mechanically at a level nearing natural hand movement (Marinelli et al., 2023). This variety of advanced models covers a range of effective strategies for maximizing comfort and usability, from optimizing size and weight to ensuring adequate prehensile ability (Han & Harnett, 2024). These innovative strategies have provided significant improvements to the field of prosthetics and greatly improved user comfort. For example, the direct attachment of a prosthesis to bone, otherwise known as osseointegration, consistently boosts the quality of life for patients and demonstrates drastic improvement from the traditional socket design (Tropf & Potter, 2023). On the other hand, targeted muscle reinnervation, which involves the surgical relocation of residual nerves

HIGH SCHOOL EDITION
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from the amputated limb to less functionally relevant muscles, has been thoroughly practiced for upper limb prostheses with high degrees of success (Cheesborough et al., 2015).

Researchers have nearly perfected communication from the user to the device in modern prosthetic hands (Han & Harnett, 2024). However, these same models can not fully harness sensory feedback mechanisms (Marinelli et al., 2023). This would include a user receiving feedback from the device due to external stimuli, making the prosthesis bidirectional. Figure 1 illustrates the three steps at the core of an ideal sensory feedback loop in a bidirectional hand prosthesis, demonstrating the process in which a user controls the device based on external stimuli.

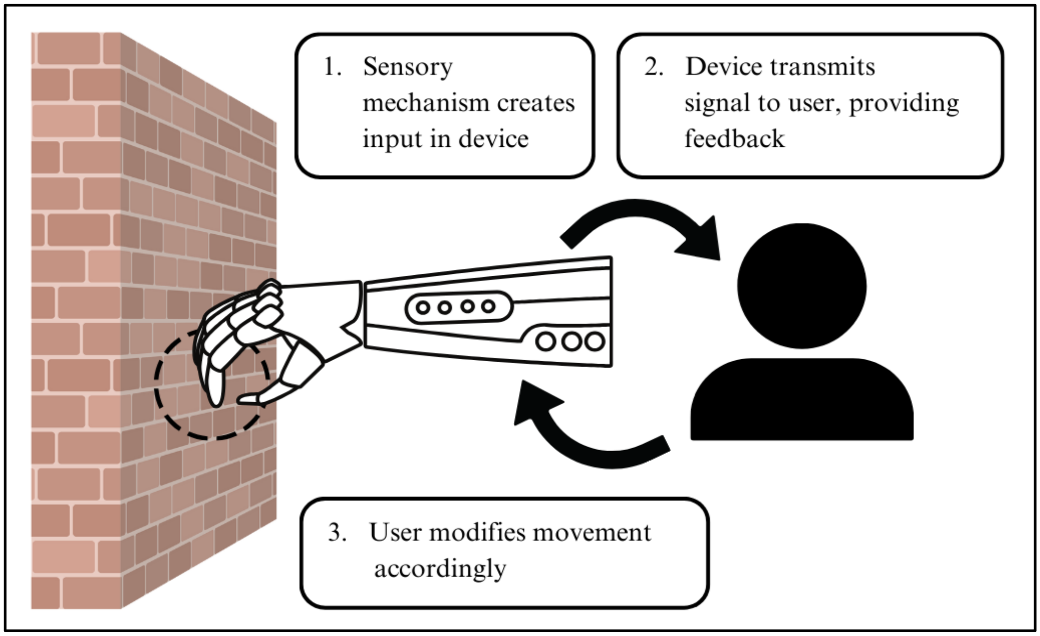


**Figure 1.** Visual representation of systematic components of sensory feedback loop in hand prostheses.

This review paper focused primarily on mechanisms relating to steps one and two, which are signal detection and transmission, respectively, as these features depend largely on the mechanisms designed to accomplish these tasks.

It is important to first understand the role of sensation in the hand, which stems from the primary organ responsible for this function: the skin. Permitted by sensors located throughout the layers of the skin depicted in Figure 2, sensory feedback is at the core of human hand functionality as it enables the fine motor skills and prehensile capabilities that humans rely on. Furthermore, the constant communication between the limb and the brain allows for proprioception and dexterity, which is key for safety. Previously, researchers found that those who lost their sense of touch were more susceptible to bruising, burns, and broken bones (Goldstein, 2010). Similarly, subjects in a study by Dahiya et al. (2010) could not gauge appropriate levels of grasping strength using a prosthetic hand lacking sensory feedback, leading them to apply more force than necessary in carrying out tasks using the device. Valle et al. (2022) also found that, generally, sensory feedback reduced harmful consequences of amputation such as phantom pain and prosthesis rejection. Sensation is thus central to the functionality of all limbs, particularly the hand.

The sensitivity of the skin comes from the abundance of receptors, which are minuscule organs sensitive to temperature and pressure, located throughout the epidermis, dermis, and hypodermis. These receptors are more concentrated in the fingertips compared to most other regions of the body, creating a higher level of sensation (Hancock, 1995). There are over 3000 mechanoreceptors, which are tactile receptors, in each fingertip alone (Hancock, 1995).

Among the many types of tactile receptors, each features a specific niche and sensitivity, culminating in a comprehensive signaling system for tactile stimuli. In addition to tactile receptors, there are thermoreceptors for temperature and nociceptors for pain. With skin being the thickest on the palm at 1.5mm, these miniature receptors are all delicately and precisely arranged (Lundström et al., 2018). The interconnectedness of the skin and its components with the neural system makes it crucial for sensation and a clear target for replication in sensory feedback.

This paper aimed to review recent approaches in developing artificial skin and integrating it into hand prosthetics. This was performed by evaluating a range of conceptual and practical limitations in the mechanisms fulfilling steps one and two of the feedback loop – signal detection and transmission.

## Methods

### Literature Review

A literature search was performed to collect research published by May 2024 in peer-reviewed scientific journals available in English that focused on the topic of sensory feedback in hand prosthetics. The search was conducted in the full-text database ScienceDirect, operated by Elsevier. The following keywords were used in this combination alone: prosthetic + hand sensory + feedback skin.

### Data Curation

To be selected, the studies must follow the parameters presented in Figure 2. The inclusion parameters were: publication in the years 2020, 2021, 2022, 2023, and 2024; must not be theses, dissertations, conference publications, reviews, and papers with no full text available online; must fulfill criteria that the publications must be directly applicable to either a sensory or feedback mechanism. From the 48 automatically filtered papers, each paper was fully read and assessed using the inclusion criteria, leading to the exclusion of 34 papers.

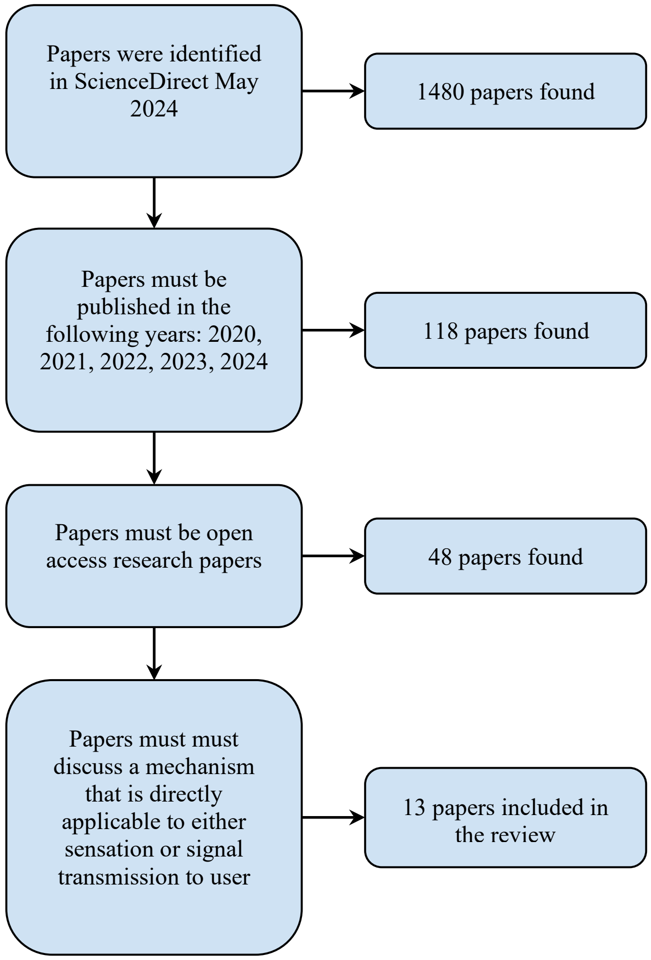


**Figure 2.** Flowchart of search and the inclusion and exclusion process

The resulting 13 research papers cover a large range of mechanisms, such as transcutaneous electrical nerve stimulation (TENS), various haptic feedback processes, pressure sensors, hydrogels, and triboelectric nanogenerators (TENG), that have been proposed or tentatively implemented in hand prosthetics or similar prostheses.

## Results

### Literature Analysis

The 13 research papers selected were divided into two main article categories (Table 1) and five subcategories based on the main subject discussed by the authors.

**Table 1.** Categorization of research papers into sensory and feedback mechanisms

| **Article Category** | **Articles** |
|---|---|

| | |
|---|---|
| ***Sensory Mechanisms*** | |
| Triboelectric Nanogenerators | (Hajira et al., 2023; Wei et al., 2022) |
| Pressure Sensors | (Kyberd et al., 2022; Shaner et al., 2022) |
| ***Feedback Mechanisms*** | |
| Transcutaneous Electrical Nerve Stimulation | (Khan et al., 2024; Risso et al., 2022; Starke et al., 2022; Yichen et al., 2022) |
| Haptic Feedback | (Campanelli, 2024; Christie et al., 2022; Cutipa-Puma et al., 2023) |
| Intraneural Stimulation | (Cimolato et al., 2023; Valle et al., 2022) |

## Sensory Mechanisms

### *Triboelectric Nanogenerators*

Triboelectric nanogenerators (TENGs) have incredibly high potential in transforming artificial skin systems as a result of their unique ability to convert mechanical energy into electrical energy. This takes place through triboelectrification and electrostatic induction, which is ideal for the actuation of movement, grasping, and overall sensation, creating a broad range of applications. Conceptually, the studies by Hajira et al. (2023) and Wei et al. (2022) are similar in addressing the implementation of TENGs on sensory systems and mimicking biological sensors. Additionally, there is a large emphasis on the efficiency and reliability of these devices, particularly with pressure sensors.

TENGs are incredibly relevant to sensory mechanisms due to their ability to act as self-powered sensors. Various tactile stimuli ranging from pressure and vibration to displacement can be effectively detected using these TENG-based sensors. Furthermore, they do not require an external power source, which reduces the overall system requirements despite their high sensitivity. The mechanisms that incorporate TENGs recreate biological sensors more accurately as they are highly efficient and precise, making this technology very promising for artificial skin creation (Hajira et al., 2023; Wei et al., 2022).

All of these benefits are important to sensory mechanisms in hand prosthetic research. The lack of an external power source increases autonomy, leading to enhanced user comfort. Moreover, the high sensitivity of sensors improves safety, reliability, and dexterity, particularly in sensitive regions such as the fingertips. Using TENGs would be beneficial for this core aspect of hand prosthesis functionality.

### *Pressure Sensors – Piezoelectric & Hydrogel*

Kyberd et al. (2022) describe the creation of an affordable silicone glove designed with robustness and sensation in mind. Both qualities are rare in gloves made for prosthetic hands, as there is a difficult balance that must be reached between flexibility and robustness. Furthermore, traditional sensory detection is simply based on movement obstruction rather than the use of sensors. This study proposed a glove that has been fortified with nanoclay fillers, enhancing its resistance to cuts and punctures while maintaining flexibility and sensitivity. Next, a piezoelectric pressure sensor was incorporated based on EEonyx conductive fabric, a copper-based resistance detection mechanism.

The glove's integration of sensors that detect pressure and force is directly relevant to sensory feedback mechanisms. These sensors allow the prosthetic to relay tactile information to the user, mimicking the natural sense of touch. This feedback is crucial for improving the usability and functionality of prosthetic hands, enabling users to perform tasks that require precise grip and manipulation (Kyberd et al., 2022).

The development of this sensorized and robust glove is significantly advantageous for hand prosthetics. Many outer layers of prior hand prosthetics could not adequately accommodate sensory mechanisms such as pressure sensors while being fully functional. One unique feature in this study that permits such high efficiency is the use of sensors embedded in the glove rather than externally or internally, which is significantly more inconvenient (Kyberd et al., 2022). This innovative solution is therefore absolutely relevant to the development of sensory feedback in artificial skin.

### *Hydrogel Skin Simulator*

Finally, Shaner et al. (2022) explore the development and application of electrically conductive, metal-free electrodes for skin stimulation and recording. Traditional metal electrodes, such as silver-silver chloride (Ag/AgCl), have limitations including expense, rigidity, inefficiency in electron-ion transduction, and production of toxic by-products. This study combined laser-induced graphene (LIG) and conducting polymer hydrogels (PEDOT) to create an economical, soft, and organic alternative. The article highlights the improved electrochemical stability and prolonged stable potentials of these electrodes during long-term direct current (DC) stimulation. Their performance in recording and stimulating human participants' biopotentials rivals that of conventional Ag/AgCl electrodes, making them a promising alternative.

Sensory mechanisms rely on efficient, reliable, and stable electrodes for both recording and stimulating biopotentials. The study demonstrates that the metal-free electrodes, specifically those made from LIG and PEDOT hydrogels, provide improved electrochemical stability and prolonged stable potentials (Shaner et al., 2022). These characteristics are crucial for maintaining consistent and accurate sensory feedback, particularly in applications involving continuous or long-term stimulation and recording, such as neuroprosthetics. The enhanced performance in myoelectric pattern recognition and stimulation threshold tests highlights the potential of these electrodes to provide more effective sensory mechanisms.

The development of metal-free electrodes has significant implications for hand prosthetic development, where reliable and efficient communication between the user's nervous system and the device is key. The bidirectional communication capability of LIG and PEDOT hydrogel electrodes, allowing both recording and stimulation, can enhance the functionality of prosthetic hands. The improved electrochemical stability and reduced risk of skin irritation make these electrodes suitable for long-term use, providing more consistent and accurate control of prosthetic hands (Shaner et al., 2022). Additionally, the flexibility and softness of the hydrogel materials increase user comfort, potentially leading to better adoption and integration of prosthetic devices in daily life (Shaner et al., 2022).

## Feedback Mechanisms

### *Transcutaneous Electrical Nerve Stimulation (TENS)*

Transcutaneous Electrical Nerve Stimulation (TENS) is a method used to deliver electrical currents through the skin to stimulate nerves, creating sensations that can substitute for natural sensory feedback (Khan et al., 2024). The articles explore various aspects of TENS and related feedback mechanisms in prosthetic development. Yichen et al. (2022) investigate the use of TENS for sensory substitution in prosthetic wrists, showing improved recognition rates of wrist positions through induced skin sensations. On the other hand, Starke et al. (2022) examine the integration of different feedback mechanisms such as electrotactile, vibrotactile, proprioceptive feedback, visual sensors, and pattern recognition algorithms to enhance prosthetic control systems. Khan et al. (2024) highlight the effectiveness of TENS in providing sensory feedback to users of hand prosthetics, focusing on enhancing tactile perception by stimulating residual nerves. Finally, a study by Risso et al. (2022) on multisensory stimulation combines VR and ECS to improve sensory performance and reduce phantom limb distortions in lower-limb amputees.

These studies are highly relevant to sensory feedback mechanisms as they demonstrate various ways to communicate signals from prosthetic devices to the body. TENS, in particular, is used to evoke skin sensations that correspond to different positions or movements, enhancing the user's perception and control of their prosthetic limb (Khan et al., 2024). Other methods, like vibrotactile feedback, provide positional awareness through vibrations, while proprioceptive feedback directly communicates limb position and movement to the user's nervous system (Starke et al., 2022; Yichen et al., 2022). The integration of visual and tactile feedback in multisensory stimulation further improves sensory processing and embodiment, making the interaction between the user and their prosthetic device more natural and intuitive (Starke et al., 2022).

The findings from these studies have significant implications for hand prosthetic development. Implementing TENS and other feedback mechanisms can enhance proprioception, allowing users to have a better sense of their limb's position and movements (Yichen et al., 2022). This leads to more natural and intuitive control over prosthetic hands, improving the ability to perform delicate tasks. Enhanced sensory feedback reduces cognitive load and increases psychological comfort, resulting in higher user satisfaction and acceptance (Starke et al., 2022; Khan et al., 2024). The non-invasive nature of these methods makes them practical for integration into existing prosthetic designs without major modifications. Additionally, the potential to reduce phantom limb pain through multisensory feedback can improve overall user experience (Risso et al., 2022). Future research and development can focus on refining these systems for long-term stability, scalability, and customization, driving the evolution of more advanced and user-friendly prosthetic devices.

### *Haptic Feedback*

Haptic feedback systems play a crucial role in enhancing the functionality and usability of prosthetic devices by providing users with sensory information about their environment. In their study, Christie et al. (2022) investigate the relative latency at which tactile sensations are perceived when induced by cutaneous vibration or intracortical microstimulation (ICMS) in the human somatosensory cortex. The results state that while cutaneous vibration is perceived faster, the latency difference is small when the stimuli are intensity-matched, suggesting ICMS's potential for somatosensory feedback in neuroprosthetics. Similarly, the Multi Vibrotactile and Skin Stretch (MuViSS) haptic device by Campanelli et al. (2024) details the development of a system providing proprioceptive and contact feedback through skin stretch and vibrotactile sensations, integrated with the Taska Hand to enhance sensory feedback for prosthetic users. Lastly, the development of the Zero Arm by Cutipa-Puma et al. (2023), a low-cost robotic hand prosthesis controlled by electroencephalographic (EEG) signals, is discussed, featuring a haptic feedback system to simulate touch, making it a cost-effective and accessible option.

These studies and developments are highly relevant to sensory feedback mechanisms as they explore various methods of providing tactile information from prosthetic devices to the user. The research on cutaneous vibration and ICMS reveals that both methods can effectively convey tactile sensations, with ICMS showing promise for real-time applications in neuroprosthetics (Christie et al., 2022). The MuViSS device's dual-modality approach, combining skin stretch and vibrotactile feedback, ensures comprehensive sensory input, crucial for intuitive prosthetic use (Campanelli, 2024). Similarly, the Zero Arm's haptic feedback system simulates mechanoreceptors in the skin, allowing users to perceive touch, which enhances control and interaction with their environment (Cutipa-Puma et al., 2023).

These advancements have significant implications for hand prosthetic development. The findings on ICMS suggest its practicality for real-time sensory feedback in neuroprosthetics, essential for tasks requiring fine motor control. The MuViSS device's ability to provide proprioceptive and contact feedback helps users perform tasks with greater precision and confidence, driving innovation in prosthetic design. The Zero Arm's integration of EEG signals and haptic feedback represents a significant advancement, particularly for those with neuromuscular disorders, and its low-cost, open-source design democratizes access to advanced prosthetic technology. Together, these developments pave the way for more sophisticated, functional, and user-friendly prosthetic solutions, improving the quality of life for amputees (Campanelli, 2024; Christie et al., 2022; Cutipa-Puma et al., 2023).

### *Intraneural Stimulation*

Intraneural stimulation, which involves direct electrical stimulation of sensory nerve fibers, is the focus of recent research aimed at enhancing sensory feedback in prosthetic devices. The following articles explored advanced neural interfaces and stimulation techniques to improve prosthetic perception and control. Cimolato et al. (2023) made ProprioStim, a framework that replicates natural proprioceptive activity using detailed electro-neural models to restore natural sensations for amputees. A study by Valle et al. (2022) examines Transversal Intrafascicular Multichannel Electrodes (TIMEs) implanted in the tibial nerve of transfemoral amputees, providing insights into the quality and stability of sensations evoked by intraneural stimulation.

These studies are relevant to sensory feedback mechanisms as they provide accurate and intuitive feedback from prosthetic devices to the user. ProprioStim's multichannel stimulation mimics natural neural activity, enhancing proprioceptive feedback and enabling more precise control of prosthetics (Cimolato et al., 2023). Similarly, the TIMEs study shows how intraneural stimulation can evoke distinct sensations, improving the user's ability to perform sensorimotor tasks (Valle et al., 2022).

These findings have significant implications for hand prosthetics. Enhanced proprioceptive feedback and varied sensory feedback through intraneural stimulation can lead to prosthetics that are more intuitive and easier to control. Improved biocompatibility and stability of neural implants ensure long-term functionality and user satisfaction. Additionally, customizable stimulation parameters allow for personalized prosthetic devices that better meet individual needs. Overall, advanced sensory feedback mechanisms can significantly enhance the functionality and user experience of hand prosthetics, improving the quality of life for amputees (Cimolato et al., 2023; Valle et al., 2022).

# Discussion

## Sensory Mechanism Challenges

Many obstacles stand in the way of these promising sensory and feedback mechanisms, preventing their successful integration into a hand prosthetic providing effective sensory feedback.

Firstly, many of the methods outlined only cover one primary aspect of sensation – the detection of touch – with little development of other sensations such as temperature (Hajira et al., 2023; Wei et al., 2022; Kyberd et al., 2022; Shaner et al., 2022). The proposed hand with piezoelectric sensors requires a specific material throughout all surfaces of the device (Kyberd et al., 2022). This feature, along with a lack of research due to the novelty of each subject in its application to artificial skin, poses several challenges for the users of devices implementing such mechanisms. With minimal results from the database search, it seems that there are not enough results from current research for the development of sensory feedback.

While TENGs may seem to be an effective solution for sensation in a hand prosthetic (Wei et al., 2022), difficulties may arise from the complexity of sensor integration, as a fully functional sensing hand would require an enormous array of TENGs, potentially creating problems with wiring, packaging, and data processing. Hajira et al. (2023) support these claims, mentioning a lack of efficiency in TENGs in larger robotic systems limiting the upscaling of TENG-based systems. This is a result of the space required by the mechanisms, as well as the high manufacturing requirements (Lai et al., 2023).

The piezoelectric pressure sensor glove and hydrogel skin simulator, on the other hand, share some challenges in terms of having strict material selection and being expected to remain stable over time, particularly with the constant use that a normal hand undergoes (Wilson, 1999). The EEonyx fabric must remain flexible and functional, which may be affected by different circumstances such as moisture, temperature changes, and general overuse. These same factors could induce chemical changes in the hydrogels as they have not been tested to endure unfavorable situations, only the mechanical load of arm movement (Shaner et al., 2022).

Finally, research efforts in developing a sensory mechanism have ignored the crucial aspect of proprioception, the internal awareness of body parts. This involves sensing the position of various components of the hand prosthetic relative to itself, meaning the communication of device flexion and extension. While many different research directions are being explored, most have not been investigated in depth by multiple institutions, leading to a lack of concrete, applicable results.

### Feedback Mechanism Challenges

Although recently proposed feedback mechanisms aim to maximize the user's comfort, the principle of transmitting these signals through a different medium than the biological path, with direct innervation, forces the user to adapt and integrate new instincts and habits into their lives (Starke et al., 2022; Campanelli et al., 2024).

With TENS, the placement of electrodes above the skin's surface causes relative inaccuracy, as each electrode's stimulation is hindered by the heightened resistance of the skin (Bounds et al., 2023). Furthermore, the distance from actual nerves creates obstacles for detailed and complex sensations, making users interpret signals independently and leading to a bigger mental burden. Lastly, TENS are primarily used for pain relief rather than signal transmission, so a significant portion of previous TENS development will not fit the application of artificial skin as effectively (Vance et al., 2014).

For both TENS and haptic feedback mechanisms, a relevant concern is the abundance of potential factors influencing the surface of the skin, such as skin conditions and the addition of various substances. This could damage the electrodes or haptic mechanisms, reduce skin sensitivity, or create a range of similarly detrimental results. Another concern that arises with the lack of direct communication is latency, as signals must traverse multiple steps before reaching the body's neural network. Physical signals such as vibrations necessitate rapid reactions and processing, or they would otherwise be ineffective (Sariyildiz et al., 2023).

The method of intraneural stimulation may cover all the problems associated with other feedback mechanisms, with direct transmission between nerves ideally providing highly accurate and timely signals (Valle et al., 2018). However, the invasive procedure for surgically connecting nerve endings is extremely tenuous and the minimal development in this direction makes it very risky to proceed with at its current stage. The translation of the signals must be perfect, as mistakes would directly influence the user's sensations, potentially causing pain or mental damage. In addition, the constant growth and change of the body over time could get in the way of long-term stability and functionality.

### Overall Difficulties

A common theme throughout the challenges of the various mechanisms is the complexity and cost of production (Efanov et al., 2022). To produce a low-cost model, such as the Zero Arm, researchers must compromise crucial functional aspects (Cutipa-Puma et al., 2023). Moreover, complete integration of the sensory and feedback mechanisms would likely be challenging due to the strict requirements of each component. Lastly, potential hand prosthetics created using these mechanisms would require extensive user training for accurate signal detection, excluding the intraneural stimulation method.

## Conclusion

Overall, it is clear that there is an abundance of obstacles in the way of developing sensory feedback in hand prosthetics, rendering it difficult to create. Thus, this systematic review has outlined recent technological challenges in artificial skin development specifically relating to hand prosthetics to determine that skin mimicry is not currently realistic for commercial hand prosthetics. This is due to an extensive focus on developing user control of prosthetic devices rather than sensation. The research for creating sensory feedback through artificial skin is still in the early stages, with many methods and mechanisms each containing its unsolved problems, and has not yet come up with an efficient, applicable solution.

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