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POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Development of a Non-Invasive Proprioceptive Feedback Strategy for Upper-Limb Robotic Prosthesis Users

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Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*
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Cette thèse intitulée :

Development of a Non-Invasive Proprioceptive Feedback Strategy for Upper-Limb Robotic Prosthesis Users

présentée par **Olivier LECOMPTE**
en vue de l'obtention du diplôme de *Philosophiæ Doctor*
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DEDICATION

To my family and friends.

À ma famille et mes amis.

ACKNOWLEDGEMENTS

During my doctoral studies, I was fortunate to work in an environment that offered great freedom for scientific exploration, while knowing that I could count on the support of those around me when needed. I would like to sincerely thank Professor Abolfazl Mohebbi and Professor Sofiane Achiche for their guidance throughout my studies under their supervision. I greatly appreciate everything you have done for me, both academically and personally.

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Thank you to Tamar, Allie, Hristo, and the entire team at the Plasticity Lab at the University of Cambridge, who welcomed me and taught me so much during my visit to the lab. I consider myself very fortunate to have met you and to have the opportunity to continue our collaboration.

As I write this section of my thesis, I find it very difficult to find the right words to express my admiration and gratitude to my family. While my doctoral studies have been accompanied by many questions and doubts, you have always been there for me. Thank you for everything.

Finally, thank you to Marie-Hélène, without whom none of this adventure would have been possible. I could not have hoped for a better partner in my life. I hope that the future holds many wonderful things in store for us.

RÉSUMÉ

Les membres supérieurs sont essentiels à un large éventail d'activités quotidiennes impliquant l'atteinte, la préhension et la manipulation d'objets. Chez les personnes ayant subi une amputation transradiale, la perte de la main et d'une partie de l'avant-bras compromet l'exécution d'actions permettant l'interaction avec l'environnement et entraîne des compensations fonctionnelles importantes.

Les prothèses myoélectriques sont conçues pour restaurer ces capacités en décodant les intentions de mouvement des utilisateurs à partir de l'activité musculaire mesurée au niveau du membre résiduel. Malgré des avancées technologiques majeures, leur adoption demeure limitée, notamment en raison de l'absence de rétroaction sensorielle physiologique, indispensable à la fermeture de la boucle sensorimotrice. Essentiellement, les utilisateurs doivent être en mesure de ressentir leur main robotique. Privés de retour proprioceptif et tactile, ils dépendent fortement de leur vision, subissent une charge cognitive accrue et doivent suivre un entraînement long et exigeant. Ces éléments compromettent la précision des mouvements effectués et l'acceptabilité de la prothèse.

La rétroaction sensorielle artificielle fait ainsi l'objet d'un intérêt croissant dans la recherche sur les prothèses robotiques. La majorité des travaux se sont concentrés sur la rétroaction tactile. Toutefois, la proprioception, essentielle au contrôle moteur et au développement du sentiment d'autonomie, demeure moins représentée dans la littérature. Les approches actuelles se répartissent sur un spectre allant de la substitution sensorielle, comme la stimulation vibrotactile, aux stratégies biomimétiques, visant à recréer la sensation originale.

Cette thèse propose une approche intermédiaire bioinspirée, entre la substitution sensorielle et le biomimétisme, reposant sur l'utilisation de la neurostimulation électrique transcutanée pour transmettre l'information proprioceptive liée à la configuration de la main. La stimulation est appliquée par l'entremise d'électrodes de surface afin d'interagir avec les nerfs médian et ulnaire, ce qui induit des sensations référées en aval du site de stimulation, perçues dans la main amputée. Cette stratégie offre une rétroaction proprioceptive qui est spatialement cohérente, tout en évitant d'avoir recours à des interventions chirurgicales.

La réalisation des objectifs spécifiques de cette thèse a permis de faire évoluer progressivement l'interaction homme-machine entre les utilisateurs et la main robotique. Une première étude a porté sur l'élaboration d'une preuve de concept afin d'évaluer la capacité de la stratégie de rétroaction développée à transmettre de l'information proprioceptive pertinente à l'utilisateur d'une main robotisée. Les participants ont identifié avec régularité les positions des doigts

transmises par la stimulation du nerf médian ou ulnaire, ainsi que différents types de préhension transmis par la stimulation simultanée des deux nerfs, avec des taux de classification respectifs de 96,5% et 88,3%.

Suite à cette démonstration, les travaux subséquents se sont concentrés sur l'intégration de cette stratégie de rétroaction au sein d'une architecture de contrôle myoélectrique. Le développement d'un cadre méthodologique reposant exclusivement sur le filtrage logiciel a permis la génération de commandes motrices fiables à partir de l'activation musculaire et la fermeture de la boucle sensorimotrice, malgré la présence d'artefacts dus à la stimulation. Une étude de cas portant sur une tâche de préhension a permis de valider ce cadre méthodologique en comparant la précision du contrôle d'une main robotique et le contenu fréquentiel de l'enveloppe électromyographique utilisée pour la génération des commandes, avec et sans stimulation électrique. Aucune différence significative n'a été observée entre les conditions.

Ayant désormais une interaction bilatérale entre l'utilisateur et la prothèse myoélectrique, une dernière étude a porté sur le contrôle en boucle fermée de l'ouverture d'une main robotique lors d'une tâche de préhension. Les participants recevant une rétroaction artificielle par neurostimulation électrique transcutanée ont présenté de manière constante des erreurs de contrôle de l'ouverture de la main significativement plus faibles que ceux n'en bénéficiant pas. Cet effet a été observé tant sous des conditions visuelles alternées ($p < 0{,}001$) qu'en situation de privation visuelle prolongée ($p = 0{,}017$). De plus, lors de l'exécution d'une tâche concurrente sollicitant l'attention visuelle, les participants recevant une rétroaction artificielle ont maintenu leurs performances cognitives tout en améliorant la précision du contrôle de l'ouverture de la main. Ces résultats soulignent le potentiel de l'approche proposée pour faciliter l'intégration fonctionnelle des prothèses myoélectriques et contribuer au développement de dispositifs plus intuitifs et mieux adaptés aux besoins des utilisateurs.

ABSTRACT

The upper limbs are essential for a variety of daily activities involving reaching, grasping, and manipulating objects. In individuals who have undergone transradial amputation, the loss of the hand and part of the forearm compromises the ability to perform actions that enable interaction with the environment and leads to significant functional compensations.

Myoelectric prostheses are designed to restore these abilities by decoding user movement intentions based on muscle activity measured from the residual limb. Despite major technological advances, their adoption remains limited, partly due to the lack of physiological sensory feedback, which is essential for closing the sensorimotor loop. Essentially, users need to be able to feel their robotic hand. Deprived of proprioceptive and tactile feedback, they rely heavily on their vision, experience increased cognitive load, and must undergo long and demanding training. These elements compromise movement accuracy and prosthesis acceptance.

Consequently, artificial sensory feedback is attracting interest within the field of robotic prosthetics research. The majority of studies have focused on tactile feedback. However, proprioception, which is essential for motor control and the development of a sense of autonomy, remains underrepresented in the literature. Current approaches range from sensory substitution, such as vibrotactile stimulation, to biomimetic strategies, aiming at reproducing the original sensation.

This thesis proposes an intermediate bioinspired approach, between sensory substitution and biomimicry, based on the use of transcutaneous electrical nerve stimulation to transmit proprioceptive information related to hand configuration. Stimulation is applied via surface electrodes to interact with the median and ulnar nerves, inducing sensations downstream of the stimulation site and perceived in the amputated hand. This strategy provides spatially coherent proprioceptive feedback while avoiding the need for surgical intervention.

Achieving the specific objectives of this thesis has allowed for the gradual evolution of human-machine interaction between users and the robotic hand. An initial study focused on developing a proof of concept to evaluate the ability of the feedback strategy developed to transmit relevant proprioceptive information to the user of a robotic hand. Participants consistently identified finger apertures conveyed via median or ulnar nerve stimulation and grasp types conveyed through concurrent stimulation of both nerves, with respective classification accuracies of 96.5% and 88.3%.

Following this demonstration, subsequent work integrated this feedback strategy into a myoelectric control architecture. The development of a methodological framework based exclusively on software filtering enabled the generation of reliable motor commands from muscle activation to close the sensorimotor loop, despite the presence of stimulation-related artifacts. A case study featuring a grasping task validated this framework by comparing robotic hand control precision and the frequency content of the electromyographic envelope used for command generation, with and without electrical stimulation, revealing no significant differences between conditions.

Building on the established bilateral interaction between the user and the myoelectric prosthesis, a final study investigated closed-loop aperture control of a robotic hand during a grasping task. Participants receiving artificial feedback via transcutaneous electrical nerve stimulation consistently achieved significantly lower hand aperture control errors than those without feedback. This effect was observed under both alternating visual conditions ($p < 0.001$) and prolonged visual deprivation ($p = 0.017$). Also, when executing a concurrent visually-demanding task, participants receiving artificial feedback maintained cognitive performance while improving aperture control. These outcomes highlight the potential of the proposed approach for facilitating the functional integration of myoelectric prostheses and contributing to the development of more intuitive devices that are better suited to the needs of users.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ACRONYMS

ANOVA	Analysis of Variance
DOF	Degree of Freedom
EMG	Electromyography
FES	Functional Electrical Stimulation
FINE	Flat Interface Nerve Electrodes
H	Hypothesis
ICMS	Intracortical Microstimulation
IQR	Interquartile Range
LIFE	Longitudinal Intrafascicular Electrodes
MRI	Magnetic Resonance Imaging
NSERC	National Research Council of Canada
PID	Proportional-Integral-Derivative
POLAR	Polytechnique Laboratory for Assistive and Rehabilitation technologies
sEMG	Surface Electromyography
SO	Specific Objectives
TENS	Transcutaneous Electrical Nerve Stimulation
TIME	Transverse Intrafascicular Multichannel Electrodes
USEA	Utah Slanted Electrode Arrays

CHAPTER 1 INTRODUCTION

1.1 Context

The upper limbs are essential for a wide range of daily activities that involve reaching, grasping, and object manipulation. These coordinated actions are essential for autonomy and central to how humans interact with their environment, including activities of daily living, occupational tasks, and social interaction [1, 2].

Hands are specialized organs for grasping, which relies on the integration of both afferent sensory pathways that carry sensory information to our brain, and efferent motor pathways that transmit movement commands to muscles that produce the action [3–6]. For individuals with transradial amputation, the loss of the hand and part of the forearm [7] severs this closed-loop motor control, impairs grasping capabilities [2], and often requires substantial functional compensation [8].

Myoelectric prosthetic hands are designed to restore volitional control by providing an alternative pathway for motor commands. Muscle activation in the residual limb is inferred from electromyographic signals (EMG) [9], which enables decoding of movement intent and translation into corresponding prosthetic hand actions.

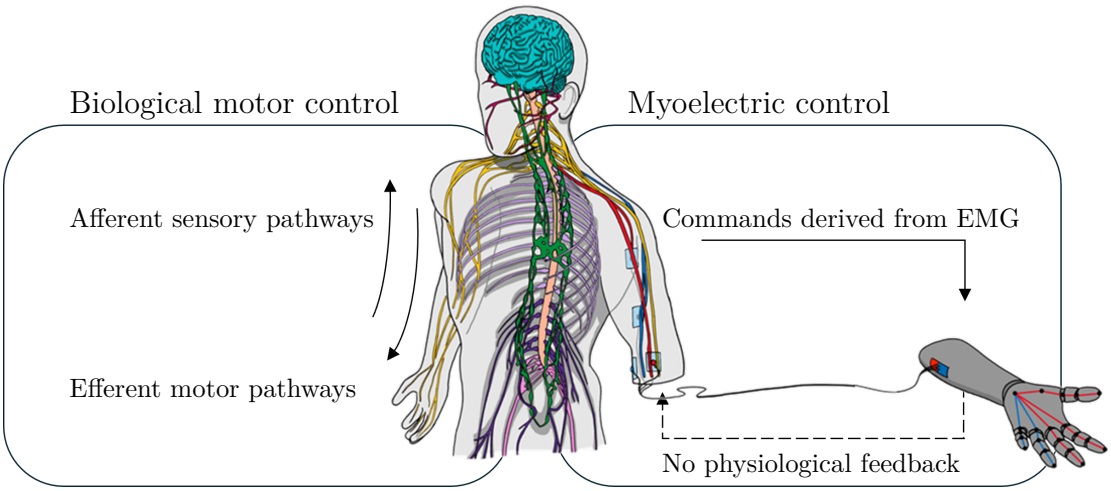

Figure 1.1 Comparison between biological motor control and myoelectric control following upper limb amputation. In the biological system, efferent motor commands and afferent sensory pathways are part of a closed-loop sensorimotor system. Myoelectric prostheses aim to restore volitional control (motor pathway only), using commands derived from EMG signals, without providing physiological sensory feedback.

Despite continued advances in this direction, prominent challenges to adoption remain. Users must learn to generate reliable control signals while receiving little to no explicit physiological feedback from the artificial limb (see Figure 1.1), which becomes especially limiting when visual attention must be shared with concurrent tasks [10, 11].

Even when socioeconomic conditions allow access to prosthetic care, a notable proportion of individuals with upper limb amputation do not rely on any prosthesis (between 10% and 25%), and fewer than 45% of users adopt a myoelectric device [12, 13]. Insufficient sensory information leads to inconsistent control [14–16], which forces users to rely mainly on visual monitoring and on incidental cues produced by the device, such as interactions at the socket or mechanical noise [17]. This reliance increases cognitive load, the mental effort required to monitor and control the system [18], constrains performance in natural environments, and often reduces trust in the device [15]. As a result, many individuals prefer body-powered prostheses, deliberately prioritizing informative implicit sensations of movement and force generation over the high level of mechanical dexterity achieved by robotic hardware [19].

Although myoelectric prostheses have seen considerable engineering progress, the functionality of prosthetic hands is ultimately determined by the quality of the human-machine interface [2]. Clinicians and users consistently identify the lack sensory feedback as one of the most significant barriers to adoption of current prosthetic technology [10, 20].

1.2 Definitions and key concepts

This section outlines the fundamental concepts needed to support the formulation of the problem statement. A more complete literature review is presented in Chapter 2.

1.2.1 Somatosensory feedback for motor control

Biological movements rely on a continuous sensorimotor loop that links motor commands from the central nervous system with incoming sensory information conveyed through the peripheral nervous system [21]. During movement, somatosensory feedback provides the somatosensory cortex with updated information about limb state and interaction with the environment [22]. These inputs support online functions such as planning and real-time correction of movement, allowing the motor system to adjust actions as they unfold [23–26]. Sensory feedback further supports offline motor learning processes, promoting the acquisition and consolidation of more accurate and stable movement patterns. Its critical role becomes evident in individuals with severe sensory loss, who display pronounced impairments in coordinating and regulating movements [27–29].

To close the loop during a grasping task, the biological hand provides two complementary submodalities of somatosensation that are central to motor control: tactile perception and proprioceptive perception [30].

Tactile perception

Tactile perception provides awareness of mechanical stimulation applied to the surface of the body. This capability depends on cutaneous mechanoreceptors embedded within the skin [31], which detect local events and relay this information through tactile afferent pathways. The nervous system then interprets these signals to determine both the site of stimulation and its intensity. These properties of the stimulus are inferred from the firing rate of afferents tied to distinct receptive fields and from the number of recruited fibers [32].

This tactile information plays a central role in grasping because it supports the estimation of object properties and location, enables the detection of contact onset, and informs the regulation of force required for stable interaction [33, 34].

Proprioceptive perception

Proprioceptive perception provides continuous information about joint position and limb movement (bodily awareness), allowing us to perceive how our limbs are configured in space during both active and passive conditions [35].

As illustrated in Fig. 1.2, proprioception arises from the integration of signals generated by a network of biological sensors distributed throughout the musculoskeletal system. Intrinsic sensors form the primary source of proprioceptive information and include muscle spindles, which encode changes in muscle length and velocity, as well as mechanoreceptors located in joint capsules and surrounding connective tissues that respond to ligament and tendon stretch [36].

When a muscle is stretched over multiple joints, its ability to accurately represent length changes decreases, reducing the reliability of the signal [37]. To compensate for this loss of precision, the nervous system incorporates extrinsic cues from cutaneous mechanoreceptors situated in the skin around the joint. These receptors detect local skin stretch, which reflects changes in joint configuration and complements the inputs from muscle and joint afferents [35, 38, 39]. By integrating all these signals, the somatosensory cortex generates a robust estimate of limb posture and movement [40].

This proprioceptive estimate is critically relevant to grasping because it provides the information required to regulate and adjust finger movements [36]. Without reliable proprioceptive

cues, grasping becomes less precise and more dependent on vision, reducing stability and increasing cognitive effort [10, 41].

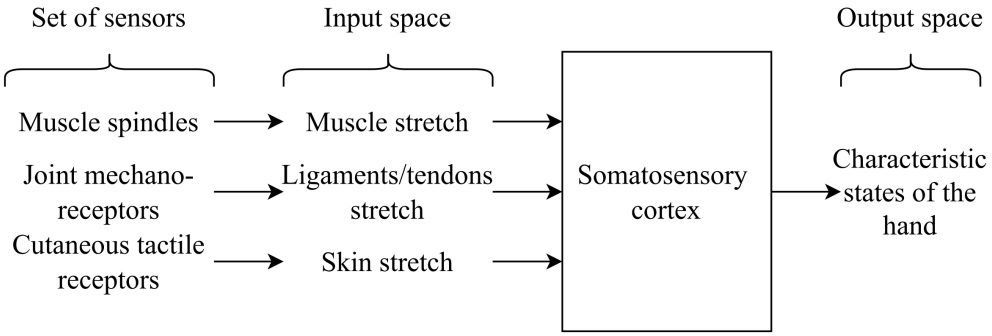

Figure 1.2 Schematic representation of the integration of intrinsic and extrinsic sensors required for proprioception perception. This image is adapted from *A Review of Proprioceptive Feedback Strategies for Upper-Limb Myoelectric Prostheses*, by Lecompte *et al.* [42].

1.2.2 Artificial feedback

The introduction of artificial feedback has been put forward in the research literature to address challenges associated with open-loop prosthetic technologies [43] aimed at the extension, substitution, or restoration of human motor function [33, 44]. Closing the sensorimotor loop by implementing engineered sensory feedback in the design of a myoelectric prosthesis can meaningfully improve how users interface with the technology. Such feedback has the potential to increase confidence and performance, including accuracy, speed, and reliability, during control of the device, while alleviating cognitive and muscular strain [10, 45]. Despite the increasing interest, only a few commercial robotic hand prostheses, such as the Psyonic Ability Hand [46] and the Vincent Evolution [47], provide artificial sensory information to the user [48].

Although these advances have not yet translated into widespread commercial availability, substantial research has been dedicated to restoring somatosensory feedback for users of upper-limb prostheses. Figure 1.3 illustrates the standard architecture favored in the literature, a framework composed of three subsystems [30, 41]. First, a preprocessing algorithm extracts the states of the prosthetic hand from the data provided by its embedded sensors. These states are then passed to an encoding algorithm that transforms them into a format suitable for user interpretation, referred to as features. Finally, the encoded information is converted into a stimulus that conveys the selected feedback modality to the user, typically through interaction with the peripheral nervous system.

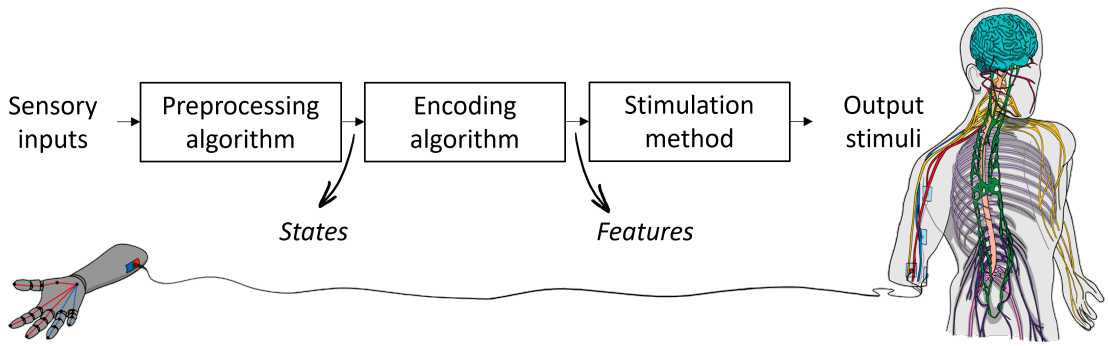

Figure 1.3 Schematic representation of the standard architecture used for artificial sensory feedback. This image is adapted from *Non-Invasive Somatotopic Proprioceptive Feedback for Closed-Loop Robotic Hand Position Control*, by Lecompte *et al.* (Article 1, [49]).

This architecture can support both tactile and proprioceptive modalities, yet most implementations focus on restoring or substituting tactile perception [41], which has led to documented benefits in both controlled laboratory settings and in-home settings [50, 51]. In contrast, progress in developing proprioceptive feedback strategies has been more limited, creating a gap in the advancement of the technologies associated with these two modalities [52].

Several factors help explain why progress in proprioceptive feedback has been slower than advances in tactile feedback. Artificially evoking proprioceptive-specific sensations is inherently difficult given the constraints of current actuation technologies, a challenge that will be discussed further in Section 1.3. In addition, the cortical mechanisms underlying proprioceptive perception remain less well understood than those associated with tactile sensations [17, 53]. This limited understanding is evident in the relative scarcity of comprehensive reviews addressing artificial proprioceptive feedback, despite its importance for informed and intuitive motor control [54, 55].

The inclusion of proprioceptive feedback would theoretically allow for the characterization of relative static position and dynamic movement [56, 57], improving coordination and the success rate in performing movements [58]. Moreover, proprioceptive cues support the formation of a coherent relationship between movement intention and the resulting sensory feedback, promoting a sense of agency that is a key element for user acceptance [59–62]. For these reasons, the integration of artificial proprioceptive feedback is widely viewed as the next critical step toward more intuitive and effective sensory feedback for upper-limb prostheses [63].

1.3 Problem statement

We previously highlighted several limitations associated with myoelectric hand prostheses, including poor control performance, overreliance on visual feedback, increased cognitive load, and long, complex training periods. These issues reduce user confidence, which in turn is reflected in the low adoption rates and limited long-term use of these devices.

The introduction of artificial feedback has been widely recognized as a key element for enabling the progress achieved in EMG-based control to translate into practical benefits for users. By providing physiological information that supports more intuitive control, artificial feedback could mitigate the issues that currently limit myoelectric prosthesis use, allowing these devices to integrate more naturally into daily life and encouraging broader adoption.

A review of the commercial landscape and the state of research reveals a clear gap in available solutions and points to a significant opportunity for innovation in proprioceptive feedback for myoelectric hand prostheses. Addressing this unmet need calls for a feedback strategy that provides physiologically meaningful information and is shaped by two development challenges. The first involves the inherent difficulty of evoking proprioceptive sensations, and the second concerns user acceptability given the constraints of available stimulation methods.

Challenge 1: Evoking proprioceptive sensations through stimulation remains a fundamental challenge for the development of artificial proprioceptive feedback. Whether stimulation is delivered at the level of peripheral nerves or the primary somatosensory cortex (reviewed in Chapter 2), proprioceptive sensations are rarely reported, inconsistent over time, and often difficult to reproduce across individuals [63–65]. Unlike tactile percepts, which can be elicited through the activation of cutaneous afferents, microneurography studies suggest that sensations of limb movement or joint position require coordinated activation patterns rather than simple fiber recruitment [10, 66]. Although stimulating large populations of proprioceptive afferent fibers can sometimes produce illusory movement [67], their anatomical organization within peripheral nerves, where they are clustered with motor neurons [68, 69], complicates selective targeting and increases the risk of inducing involuntary muscle contractions. These observations suggest that effective proprioceptive feedback strategies must either rely on highly selective and coordinated neural targeting or leverage alternative approaches that can be integrated by the nervous system despite imperfect control over neural activation.

Challenge 2: Invasive stimulation methods represent a major obstacle to the practical implementation of artificial proprioceptive feedback. Effective proprioceptive feedback strategies specifically designed for prosthetic hands have been implemented pri-

marily through invasive electrical stimulation methods [19, 70]. These approaches introduce significant barriers to adoption, including surgical risks, concerns about long-term stability, and reluctance from users [71–74]. These limitations have motivated increased interest in non-invasive alternatives capable of providing functional proprioceptive information without compromising safety or acceptability. This thesis investigates an alternative approach that leverages existing neural infrastructure to convey spatially meaningful proprioceptive feedback, thereby mitigating issues associated with open-loop control without the risks inherent to invasive stimulation methods.

CHAPTER 2 LITERATURE REVIEW

This chapter presents the theoretical background and the scientific literature that informed the development of the methodology used in this thesis to address the research objectives. We begin by defining a set of criteria against which artificial feedback strategies can be evaluated. Using these criteria as a template, we then review all approaches documented in the literature for conveying proprioceptive information in upper limb prosthetic systems. This is followed by an analysis of current stimulation technologies that exposes a significant gap in the available methods. Building on considerations related to technological embodiment, we integrate insights from the identified criteria to introduce a coherent framework that motivates the feedback strategy proposed in this work. Finally, we outline the essential steps required to close the control loop and demonstrate how the proposed approach mitigates key limitations of myoelectric prostheses identified in Chapter 1.

2.1 Foundational concepts for reviewing artificial feedback strategies

In the context of artificial sensory feedback, the notion of "optimal" feedback is used to describe strategies that emulate biological somatosensory function. Within this framework, three criteria are commonly used to define how a feedback modality can approximate natural proprioceptive and tactile perception [10, 71]. Although Section 2.4 will address why this biomimetic perspective may not directly mitigate the key limitations of myoelectric prosthesis control, it nonetheless offers a conceptual vocabulary and a useful foundation for comparing existing strategies.

1. **Homologous:** The feedback corresponds to the natural sensory input it restores. Evoked sensations are of the same modality (or nature) as the biological sensations normally produced.

2. **Somatotopic:** Feedback preserves anatomical consistency. Evoked sensations align with the natural somatotopic map of the body, which means that the perceived location of the feedback corresponds to the area of the body that is represented.

3. **Real Time:** The feedback does not introduce perceptible delays that disrupt the natural sensorimotor loop. Reported thresholds compatible with a real-time perceptual experience vary across the literature and depend on the executed task and conveyed sensory modality [75–77].

Beyond biomimetic considerations, non invasiveness emerges as an important factor, repeatedly highlighted by users in the prosthetic feedback literature and identified as Challenge 2 in Section 1.3. Prior work consistently reports reluctance to undergo surgical implantation or maintenance procedures [71], along with concerns regarding long term stability and biocompatibility of implanted interfaces [72–74]. Non-invasive approaches also present advantages such as reduced cost and shorter certification pathways, which can contribute to broader clinical adoption [78]. For these reasons, non invasiveness is included here as a fourth evaluative criterion. Combined with the three biomimetic criteria, it provides a coherent template (see Figure 2.1) for reviewing the proprioceptive feedback strategies documented in the literature and for situating the approach developed in this thesis.

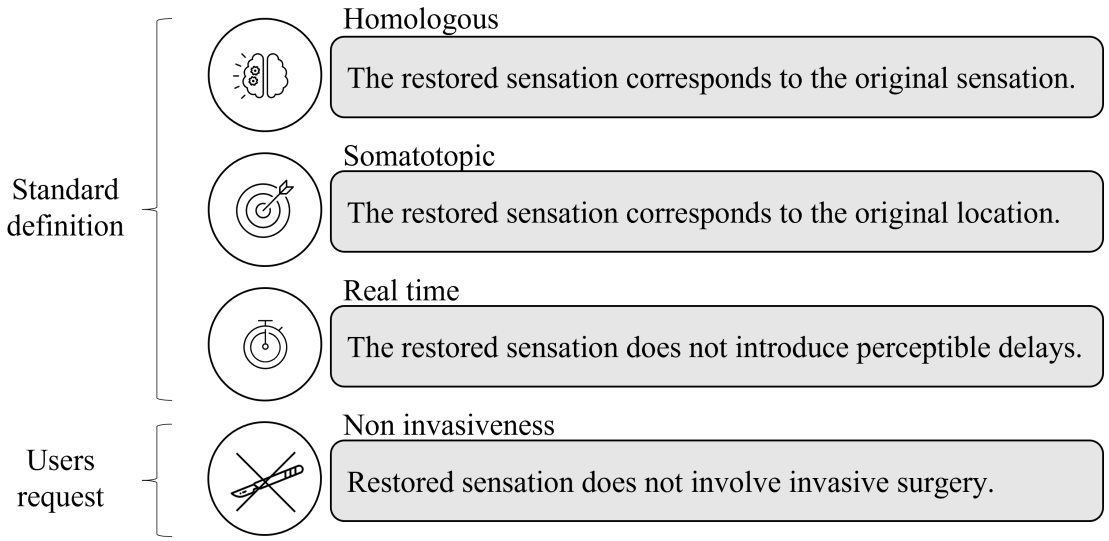

Figure 2.1 Summary of the criteria used to compare proprioceptive feedback strategies for upper limb myoelectric prostheses. The first three elements represent the standard properties associated with optimal or biomimetic feedback, while non invasiveness is included to reflect user preferences and the practical challenges identified in this thesis. This image is adapted from *A Review of Proprioceptive Feedback Strategies for Upper Limb Myoelectric Prostheses*, by Lecompte *et al.* [42].

2.2 Artificial proprioceptive feedback strategies for upper limbs

In this section, we review the methods documented in the literature for conveying proprioceptive information in upper limb prosthetic systems. For clarity, the strategies are organized according to the stimulation method employed, and their characteristics are examined using the four evaluative criteria introduced earlier. This structure allows a systematic comparison of the strengths and limitations of each approach.

2.2.1 Vibrotactile stimulation

Vibrotactile stimulation is a stimulation method that uses vibrating tactors applied superficially to the skin of the user to convey real-time proprioceptive information (see Figure 2.2) [79]. Within this approach, evoked sensations associated with limb positions are integrated through natural tactile afferent pathways rather than the original proprioceptive modality. Because of that, vibrotactile stimulation is considered to be a sensory substitution technique. As reflected in Table 2.1, this terminology is used in the literature to describe stimulation methods that elicit percepts that do not correspond to the original location (not somatotopic) or quality of the biological sensation (not homologous).

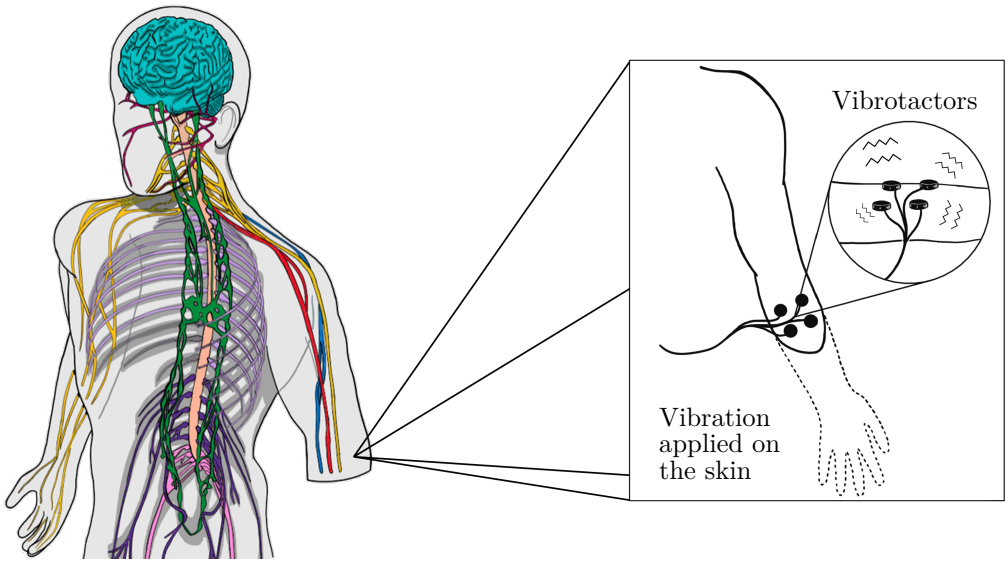

Figure 2.2 Vibrotactile stimulation to convey proprioceptive feedback for hand myoelectric prostheses.

While sensory substitution methods have been shown to support prosthesis-related embodiment following an appropriate familiarization period [80, 81], the conveyed feedback is generally considered to be non-intuitive and difficult to integrate for closed-loop myoelectric control [82]. Real-time interpretation of proprioceptive information through vibrotactile stimulation is associated with increased cognitive load [83], especially when the feedback describes multiple degrees of freedom.

The perceived intensity of sensations evoked via vibrotactile stimuli is easily compromised because it depends heavily on actuator placement and mounting pressure. In order to improve feedback consistency and reinforce user confidence during myoelectric control [54], several studies have favored the use of vibrotactor arrays. Distributing the stimulation across multiple tactors allows proprioceptive information to be conveyed through spatial patterns, which

prevents users from having to identify subtle variations in the amplitude or frequency of vibrations.

Beyond reliability, spatial encoding also affects long-term usability. Vibrotactile sensations are frequently reported as uncomfortable, and prolonged exposure can induce sensory adaptation, diminishing perceptual sensitivity and the capacity for effective interpretation of the conveyed feedback [84]. Increasing the number of stimulation sites partially alleviates these limitations by reducing localized skin irritation. Moreover, because spatial encoding does not rely on fine variations in perceived intensity, it also limits the impact of habituation on feedback interpretation [85].

The number of vibrotactors that can be implemented is limited by the spatial acuity of tactile perception, which varies across individuals and locations on the body [86–88]. Working with this constraint, Vargas *et al.* implemented a circumferential arrangement of four tactors around the upper arm [89]. Each actuator delivered square-wave vibrations with fixed frequency and pulse width, while amplitude modulation was restricted to two distinct levels. By combining stimulation from medial and lateral tactors, users were able to identify up to eight discrete finger positions.

A similar strategy was adopted by Pena *et al.*, who positioned five vibrotactors on the dorsal surface of the forearm. Rather than modulating vibration parameters, proprioceptive feedback transmission relied on simultaneous activation of adjacent tactors. This combinatorial approach enabled both single and paired stimulations to encode up to nine distinct feedback levels [86].

2.2.2 Skin stretch

Researchers also investigated linear and rotational skin stretch as a way to convey proprioceptive information related to the hand. Figure 2.3 illustrates a typical application of this approach. Feedback transmission relies on a device attached to the skin of the user, usually via an adhesive interface, which mechanically deforms the skin based on the configuration of the artificial limb. Once again, this stimulation method is characterized as a sensory substitution method, utilizing cutaneous receptors and afferent neural pathways to transmit proprioceptive cues that are neither homologous nor somatotopic.

A recurring implementation challenge reported across multiple applications of this method lies in achieving reliable and repeatable adhesion to the skin [90]. Nevertheless, skin stretch has been shown to provide more reliable and precise proprioceptive feedback than vibrotactile stimulation [91]. This advantage is partly attributed to the familiarity of the stimulus, as

skin deformation constitutes a natural component of the sensory inputs integrated by the nervous system to estimate limb state, combined with an evoked sensation that is generally perceived as comfortable by users [92].

The Rice Haptic Rocker, introduced by Battaglia *et al.*, is a device that uses skin stretch to convey proprioceptive information related to hand aperture. The system is worn around the upper arm, secured using Velcro straps, and uses a servomotor driving an eccentric rocker to deform the skin. The rocker angle is linearly mapped to measured robotic hand apertures, enabling users to discriminate between different object sizes with an accuracy of $73.3\% \pm 11.2\%$ [93]. While effective, this approach is limited to hand configurations described by a single degree of freedom.

Akhtar *et al.* deployed three linear skin stretch actuators on the forearm, located on the ulnar, central, and radial sides. These actuators conveyed proprioceptive information related to the middle finger, index finger, and thumb, respectively. With this approach, users were able to identify six hand configurations with an accuracy of $88.0\% \pm 5.6\%$ [94].

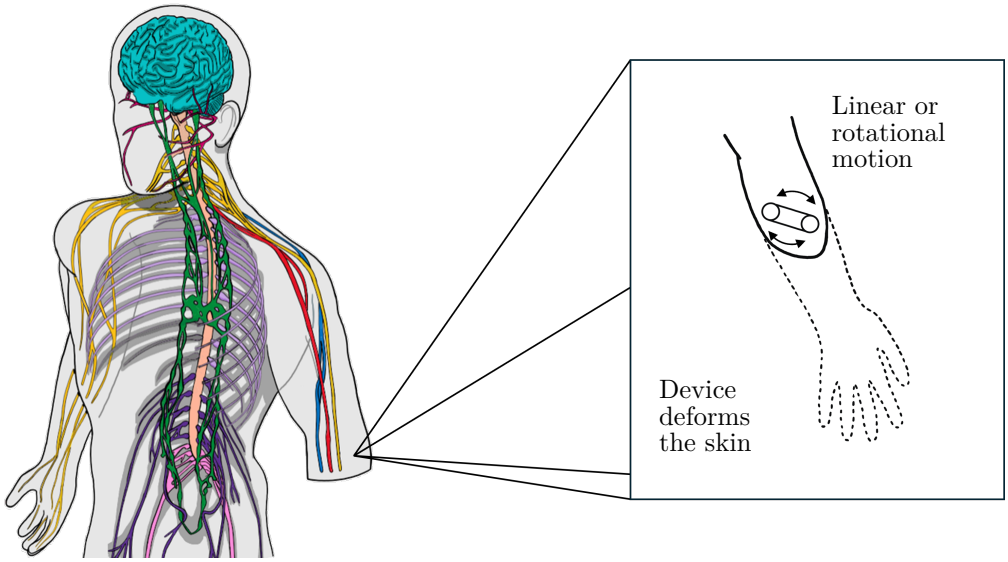

Figure 2.3 Skin stretch to convey proprioceptive feedback for hand myoelectric prostheses.

Prior work has also combined vibrotactile stimulation with skin stretch to improve feedback reliability through concurrent stimulation using different modalities. This approach approximates the sensory input space illustrated in Figure 1.2 [95, 96]. While increasing the number of stimulation channels can improve feedback reliability through redundant or complementary cues, it may also come at the expense of communication efficiency and overall performance [45].

2.2.3 Electrotactile stimulation

Electrotactile stimulation has been extensively explored as a non-invasive approach for conveying artificial sensory feedback. As was the case with the two previous stimulation methods, it falls under the category of sensory substitution, as this time superficial electrodes are used to evoke distinct cutaneous sensations through electrical stimulation of the skin [17]. Consequently, evoked sensations are neither homologous nor somatotopic.

One limitation highlighted in clinical studies is the quality of the evoked sensations, which can be uncomfortable and even painful, depending on stimulation parameters and individual sensitivity to the electrical stimulation [10, 97].

The most common electrode placement is on the arm, as illustrated in Figure 2.4, but alternative locations have also been considered. Arakeri *et al.* conveyed hand aperture by electrically stimulating the dorsal surface of the neck, a region that retains tactile sensitivity while avoiding interference with other functional demands of the upper limb [97, 98]. Hand aperture was delivered with a square-wave stimulation signal and encoded through an inverse linear relationship with current amplitude in an effort to be more intuitive for users [98]. While electrotactile stimulation could theoretically be used to deliver multimodal information through modulation of multiple signal parameters, this approach was not implemented in this work due to the limited perceptual variation elicited by changes in pulse frequency [99].

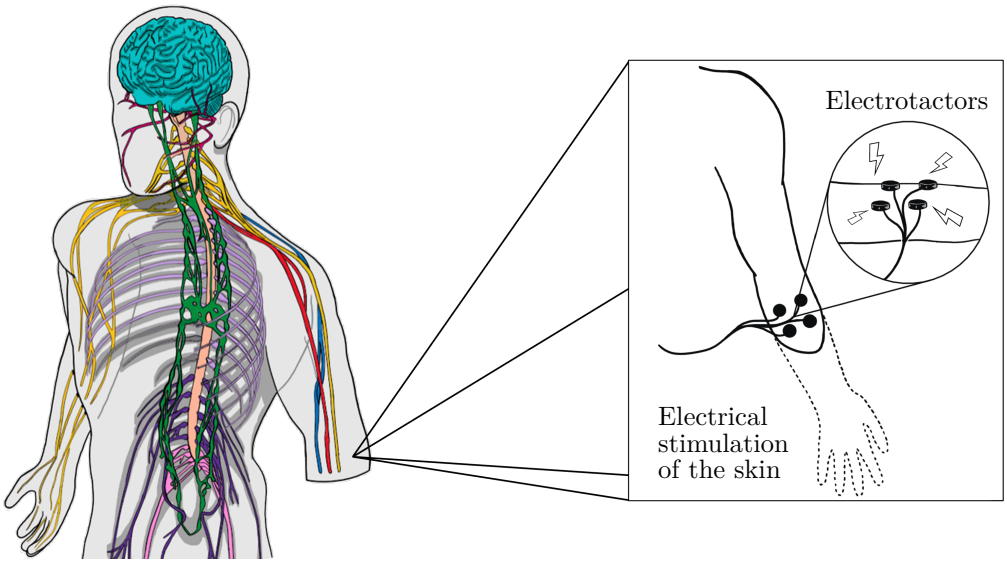

Figure 2.4 Electrotactile stimulation to convey proprioceptive feedback for hand myoelectric prostheses.

Beyond static hand configuration, electrotactile stimulation has also been used to convey dynamic information related to hand movement. Yang *et al.* implemented a 4×4 array of 16 electrodes placed on the volar side of the forearm to generate concurrent square-wave stimulation patterns. Sequentially activating electrodes induced the illusion of a stimulus moving across the skin. As with other sensory substitution strategies involving concurrent stimulation, effective use of this feedback relied strongly on the capacity of the user to learn and interpret complex spatiotemporal patterns to extract the intended information [100].

2.2.4 Auditory stimulation

Auditory stimulation has also been explored as a means of conveying information about the state of a hand prosthesis through sounds modulated in frequency or amplitude. As summarized in Table 2.1, this stimulation method is described as a sensory substitution strategy that leverages the auditory system for its capacity to integrate complex information in real time, enabling the transmission of proprioceptive feedback to the user [101].

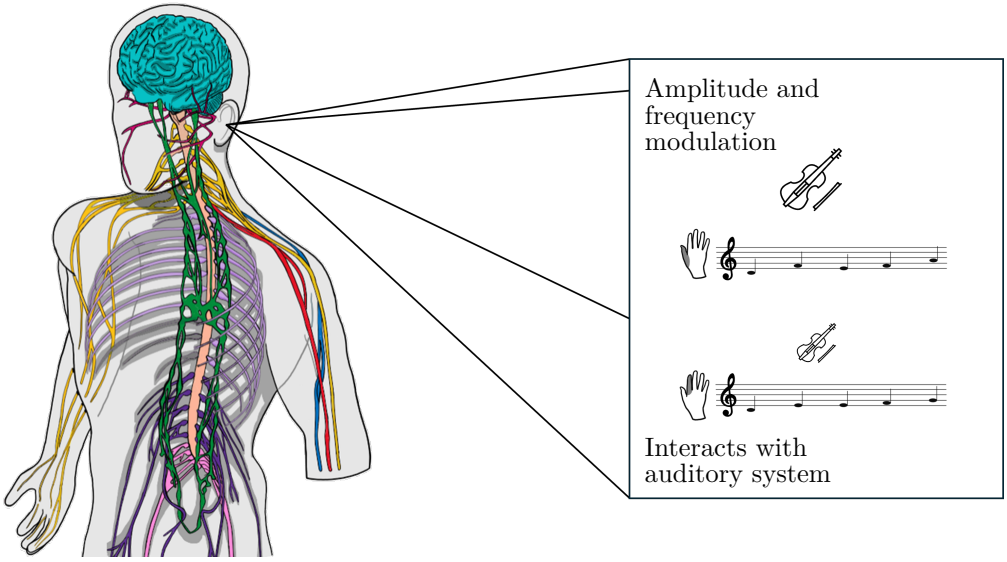

Figure 2.5 Auditory stimulation to convey proprioceptive feedback for hand myoelectric prostheses.

A practical application of auditory stimulation was presented by Gonzalez *et al.*, who encoded distinct prosthetic hand configurations using different major piano triads. These auditory cues allowed users to identify eight hand gestures and resulted in improved efficiency during reach and grasp type tasks, as well as reduced cognitive load associated with task execution [102].

In a related study, Gonzalez-Vargas *et al.* expanded on this approach by mapping sounds

from different instruments to individual digits. In their implementation, cello and violin sounds were respectively associated with thumb and index finger motion during object manipulation tasks [101]. By distributing information across multiple distinct frequency bands, as illustrated in Figure 2.5, continuous proprioceptive feedback related to multiple degrees of freedom could be conveyed simultaneously, which was shown to further improve prosthetic control during manipulation tasks [103].

Despite these promising results, auditory-based feedback is associated with increased cognitive load in everyday use, particularly in situations where auditory attention must be shared during task execution and learning [103]. In addition, the long-term integration of this stimulation method for proprioceptive feedback remains insufficiently explored, and further studies are required to assess the impact of sustained use.

2.2.5 Kinesthetic illusion

Conveying proprioceptive feedback is also achievable by inducing limb motion illusions, commonly referred to as kinesthetic illusions [104]. As illustrated in Figure 2.6, applying a mechanical vibration in the range of approximately 70 to 115 Hz to a tendon, myotendinous junction, or muscle belly can evoke the sensation that a limb is moving, even in the absence of actual motion [105, 106].

This physiological mechanism can be leveraged to artificially evoke homologous proprioceptive feedback, accompanied by tactile sensations at the stimulation site. Although the vibration itself is mainly applied non-invasively, prior work relied on invasive surgical intervention in order to evoke kinesthetic illusions at specific phantom hand joints [19, 54].

Kuiken *et al.* demonstrated that following targeted reinnervation, in which sensory innervation from the hand was redirected to the chest skin, vibration applied at the chest enabled perception of finger joint position in an amputee subject [19]. Building on this concept, Marasco *et al.* elicited 22 distinct motion sensations across six participants with upper limb amputation who had also previously undergone targeted reinnervation, where this time residual motor and sensory nerves were surgically redirected to skin regions proximal to the amputation [54].

Nevertheless, vibration induced kinesthetic illusions remain difficult to elicit consistently across users and experimental conditions [107, 108]. Implantation of vibrating devices at the tendon level has been proposed as a means of improving perceptual integration and reducing erroneous motion sensations [109].

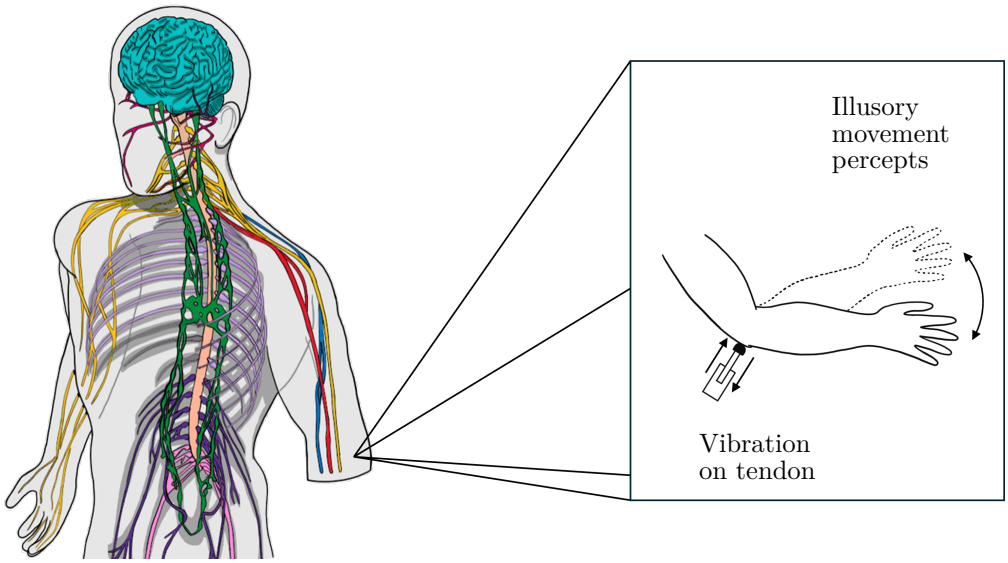

Figure 2.6 Kinesthetic illusion to convey proprioceptive feedback for the upper limbs.

2.2.6 Direct neural stimulation

Direct neural stimulation can be leveraged to convey artificial physiological feedback for myoelectric control by electrically stimulating specific afferent fibers within residual nerves that previously conveyed sensory information from the hand. This invasive stimulation method requires surgical implantation of electrodes to interface directly with preserved peripheral neural pathways [19]. As a prerequisite, afferent pathways proximal to the amputation must remain intact to allow sensations to be perceived in the phantom hand, downstream of the stimulation site [110].

Multiple electrode designs have been developed to support direct neural stimulation. As illustrated in Figure 2.7, commonly used interfaces include Transverse Intrafascicular Multichannel Electrodes (TIME), Longitudinal Intrafascicular Electrodes (LIFE), Utah Slanted Electrode Arrays (USEA), and Flat Interface Nerve Electrodes (FINE) [10]. These devices differ in how deeply they interface with the nerve and in their ability to selectively activate subsets of afferent fibers.

Numerous studies have demonstrated that direct neural stimulation can provide real-time, somatotopically organized sensory feedback to prosthesis users [111]. Although the long-term safety and stability of chronic implantation remain active areas of investigation [112], this approach has been shown to reliably convey meaningful sensory information [10].

Wendelken *et al.* interacted with the residual median and ulnar nerves of upper-limb amputees by implanting USEA approximately 2 cm proximal to the amputation site. They were

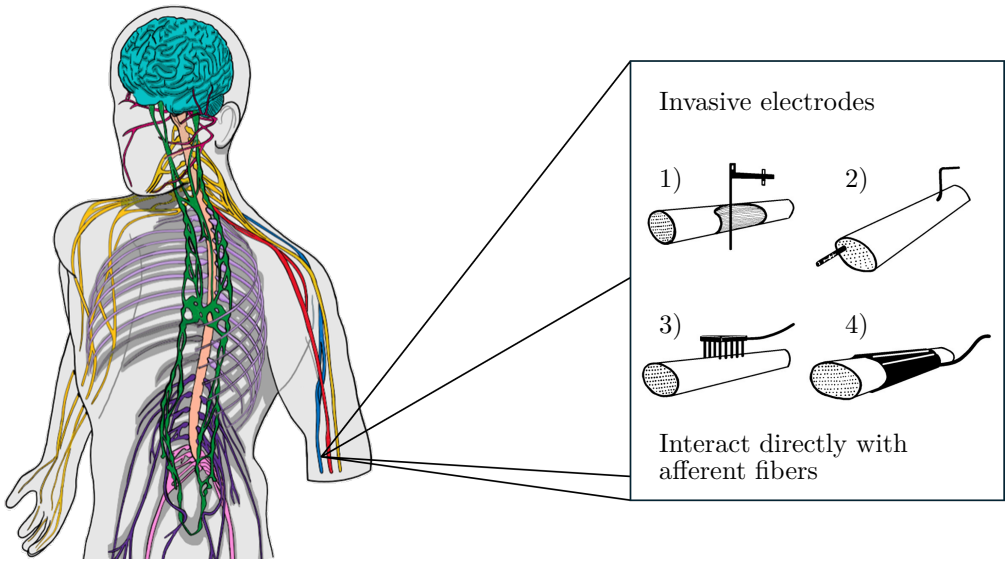

Figure 2.7 Direct neural stimulation to convey proprioceptive feedback for hand myoelectric prostheses, with different types of electrodes: 1) TIME, 2) LIFE, 3) USEA and 4) FINE.

able to evoke a wide range of tactile and proprioceptive sensations felt in the phantom hand, such as finger flexion and extension as well as wrist extension [70]. However, the evoked proprioceptive sensations lacked in consistency and specificity across participants.

This variability reflects a fundamental limitation of artificial proprioceptive feedback, highlighted in Challenge 1 of Section 1.3. Direct neural stimulation is better suited to evoke tactile or mixed-modality sensations [17], because proprioceptive afferents are sparsely distributed within peripheral nerve bundles, making it difficult to selectively activate them, even with current electrode technologies [68, 69]. As a result, the perceived nature of the evoked sensations is described as unfamiliar or non-physiological [41], with users also reporting unintended muscle fiber recruitment [11, 113].

Acknowledging this limitation, researchers have favored the delivery of concurrent stimulation to close the control loop in myoelectric applications. In this context, somatotopically matched tactile feedback is typically prioritized, while proprioceptive information is conveyed using a complementary sensory substitution strategy [114].

D'Anna *et al.* implemented this approach to convey physiological feedback for a robotic hand, using implanted TIME in the medial forearm to evoke sensations of paresthesia through two stimulation channels. These channels respectively evoked tactile feedback localized to the fingers (somatotopic) and proprioceptive information felt in the palm and the wrist (not somatotopic) [17]. In both cases, contact interactions and hand configurations were encoded using an intensity-based scheme, in which the perceived stimulation magnitude was

modulated by varying the delivered electrical charge. For comparison, the same strategy was also implemented using electrotactile stimulation to convey proprioceptive feedback. Under identical encoding conditions, direct neural stimulation resulted in higher proprioceptive acuity and stronger prosthesis embodiment than its non-invasive counterpart. Nevertheless, the adoption of direct neural stimulation for artificial physiological feedback remains hindered by the substantial costs and surgical risks associated with implantation, limiting accessibility for most amputees [71].

2.2.7 Intracortical microstimulation

While all the feedback strategies discussed so far relied on interfacing with the peripheral nervous system to convey proprioceptive information, Intracortical Microstimulation (ICMS) directly interacts with the central nervous system. Implementation of this method requires invasive surgical intervention for the implantation of microelectrodes to electrically stimulate the primary somatosensory cortex, as illustrated in Figure 2.8.

Recent studies have allowed for the identification of multiple cortical regions involved in the encoding of limb position and movement, areas that can be electrically stimulated to evoke sensations of limb movement [115, 116]. Because artificially evoked proprioceptive sensations are often accompanied by tactile sensations, the degree to which ICMS can be considered strictly homologous remains debated. Nevertheless, as summarized in Table 2.1, this stimulation method provides real-time feedback organized in a somatotopic manner, but this comes at the cost of a highly invasive procedure.

ICMS is particularly relevant for individuals with high-level spinal cord injuries where communication between peripheral nerves and the brain is severed [11]. In such cases, direct cortical stimulation offers a unique pathway for restoring sensory feedback in brain–machine interface and neuroprosthetic research aimed at conveying proprioceptive information [117, 118].

While the research literature on ICMS for conveying artificial physiological feedback relies mainly on animal models [117, 119], an increasing number of studies have demonstrated its feasibility in humans [64, 120]. London *et al.* showed that non-human primates could reliably detect the presence of stimulation trains and identify different stimulation frequencies delivered to area 3a of the primary somatosensory cortex, a region associated with proprioceptive processing in the brain [118].

Human ICMS studies enabled further characterization of the perceptual quality of evoked sensations. Most participants report sensations resembling pressure or touch, while explicitly proprioceptive percepts have been described less frequently and are restricted to specific

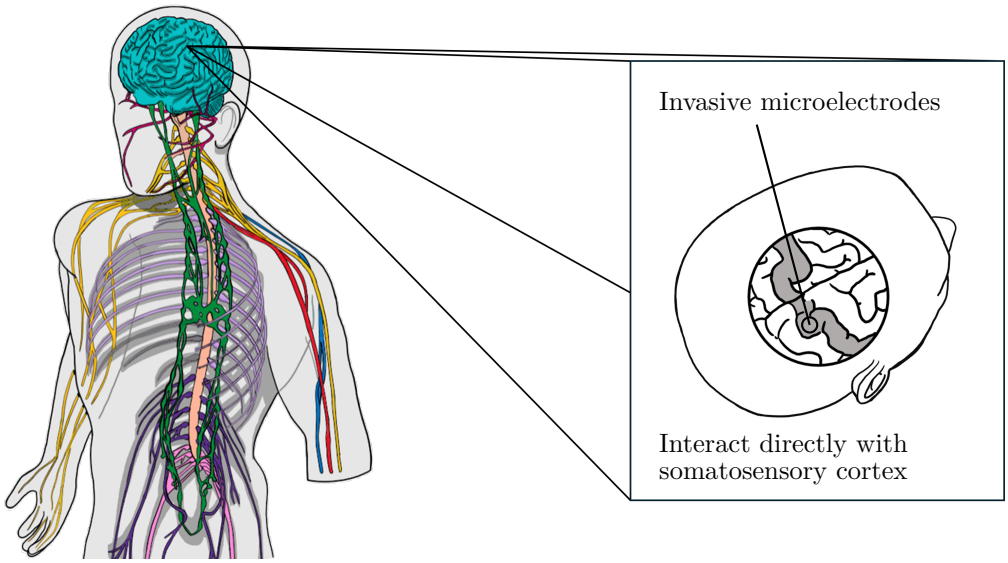

Figure 2.8 Intracortical microstimulation to convey proprioceptive feedback for hand myoelectric prostheses. The shaded grey area of the brain corresponds to the primary somatosensory cortex.

participants [64, 65].

To elicit more naturalistic proprioceptive sensations, Armenta Salas *et al.* implanted two intracortical microelectrode arrays directly within the somatosensory cortex to deliver biphasic, charge-balanced stimulation trains, which required lower stimulation currents than surface cortical stimulation [120]. This approach allowed a tetraplegic participant to consistently report proprioceptive sensations perceived in the contralateral arm.

From a functional perspective, ICMS therefore comes closest to what was previously defined as an optimal strategy for artificial sensory feedback. However, as with other invasive approaches, its widespread applicability remains limited. Many individuals with upper limb amputation don't have access to the resources required for surgical implantation and long-term maintenance, or are unwilling to undergo neurosurgical procedures altogether [121].

2.3 Implementation problem in the current landscape

The literature review presented above makes it possible to assess the current state of the art by evaluating existing proprioceptive restoration strategies for the upper limb according to the criteria of homology, somatotopy, real time operation, and non invasiveness.

Table 2.1: Evaluation of proprioception restoration strategies. H: Homologous, S: Somatotopic, R: Real time and N: Non-invasive. This table is adapted from *A Review of Proprioceptive Feedback Strategies for Upper Limb Myoelectric Prostheses*, by Lecompte *et al.* [42].

Strategies	**H**	**S**	**R**	**N**
Vibrotactile stimulation	☐	☐	☑	☑
Skin stretch	☐	☐	☑	☑
Electrotactile stimulation	☐	☐	☑	☑
Auditory stimulation	☐	☐	☑	☑
Kinesthetic illusion	☑	∼[1]	☑	∼
Direct neural stimulation	∼[2]	☑	☑	☐
Intracortical microstimulation	∼[2]	☑	☑	☐

[1] All reported cases of somatotopic sensation in phantom fingers were preceded by specific invasive surgery.

[2] Only isolated cases reported homologous proprioceptive feedback.

Table 2.1 summarizes how each strategy aligns with these criteria, while the Venn diagram in Figure 2.9 provides a visual representation of the classification of the available methods according to all possible combinations of these properties.

The classification makes two patterns explicitly apparent. All reviewed strategies are capable of real-time operation, yet none satisfies the full set of criteria (HSRN). Furthermore, homologous proprioceptive sensations are seldom reported, and the methods that come closest rely on invasive stimulation, which prevents them from meeting the non invasiveness requirement. Consequently, the current landscape is characterized by a fundamental trade-off, whereby researchers must choose between high-fidelity, invasive approaches (HSR) and lower-fidelity, non-invasive sensory substitution strategies (RN).

As discussed earlier, these limitations stem from the intrinsic constraints of current stimulation technologies. Existing methods have limited capacity to selectively target proprioceptive afferent fibers and reliably evoke proprioceptive sensations [41, 68, 69], an issue that corresponds directly to Challenge 1 identified in Section 1.3. As a result, the development of a non-invasive restoration strategy that satisfies the full set of biomimetic criteria is not currently achievable. Even invasive approaches, which hold theoretical advantages in selectivity and somatotopy, often remain difficult to implement reliably and suffer from challenges related to long-term stability and surgical burden.

Efforts to advance proprioceptive restoration remain ongoing, with recent studies exploring emerging approaches, including myokinetic stimulation [122] and electrical stimulation delivered via regenerative peripheral nerve interfaces [123]. These stimulation methods aim to

address several limitations inherent to the invasive and non-invasive approaches presented earlier.

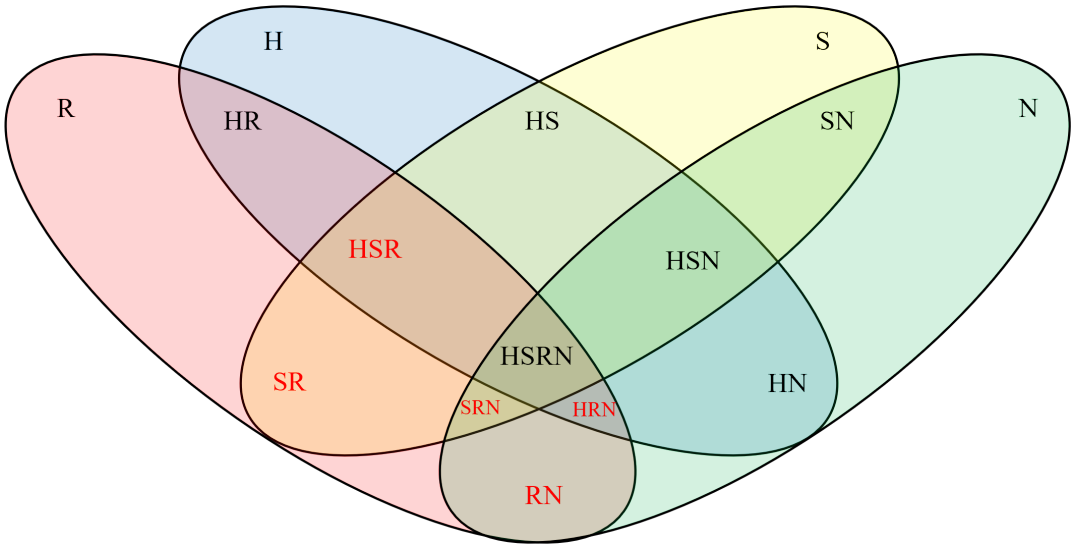

Figure 2.9 Venn diagram illustrating the classification of proprioceptive restoration strategies according to homology (H), somatotopy (S), real time operation (R), and non invasiveness (N). Red labels indicate that at least one documented stimulation method satisfies the combination of criteria corresponding to that region. This image is adapted from *A Review of Proprioceptive Feedback Strategies for Upper Limb Myoelectric Prostheses*, by Lecompte *et al.* [42].

2.4 The case for an alternative framework

We previously introduced the concept of optimal feedback, describing in the research literature what criteria an artificial feedback strategy should meet for users to best interface with their myoelectric prosthetic hand. While establishing this definition was useful to compare different feedback approaches, it is important to recognize that sticking to this definition for the development of artificial proprioceptive feedback raises potential issues.

2.4.1 The issue with biomimicry

The pursuit of a feedback strategy that is simultaneously homologous, somatotopic and real time is based on the prevalent hypothesis, that if we were able to leverage neural and cognitive body mechanisms by closely emulating original biological peripheral inputs, the central nervous system would process the artificial feedback in the same way [15]. This would enable a user to optimally integrate the provided feedback and use it functionally for

closed-loop control [124].

In reality, this hypothesis remains unproven, and the integration of biomimetic feedback is greatly limited by the sensations evoked by available stimulation technologies. The inability of current methods to perfectly and consistently mimic natural proprioception (Challenge 1) could lead to a neurocognitive problem similar to the uncanny valley phenomenon: the inadequate feedback transmitted is incoherent with habitual sensory predictions based on pre-amputation experiences, resulting in an increase in the cognitive load required for interpretation, confusion, discomfort, and even aversion [124–126].

Moreover, even if future technological progress in stimulation methods allows for the exact replication of natural proprioception, it is still not trivial that a biomimetic approach would promote the technological embodiment of artificial limbs. We know that prosthesis users can become proficient at using an artificial limb, akin to how expert tool users would. However, prosthetic limbs are integrated differently in the brain than both a biological hand or a tool. In fact, when investigating the occipitotemporal cortex in prosthesis users, the noticeable dissociation between those three categories (biological hand, tool and prosthesis) increases with their experience in using a prosthetic limb and is consistent whether it is active or purely cosmetic [127]. While users might still experience a myoelectric prosthesis as their own hand (phenomenological embodiment) [15], this use-related brain plasticity suggests that their brain does not, and neural embodiment never really takes place [127]. This is why interfacing a prosthesis by mimicking the biological hand functions might be the wrong approach, while alternative frameworks might be more suited to conveying proprioceptive feedback that is easily integratable and promotes adoption.

2.4.2 Bioinspired approaches

Moving away from the search for a biomimetic feedback strategy opens up new avenues for attempting to mitigate the key issues associated with controlling myoelectric prostheses. An interesting approach, suggested by Makin *et al.*, consists of recycling neural and cognitive mechanisms involved in the sensorimotor loop, taking advantage of an already established and efficient infrastructure for information compression and error-based learning [124]. In this thesis, this type of strategy is referred to as a bioinspired approach, departing from biomimicry by assigning a new role to the resources typically responsible for sensory integration in the hand, rather than replicating their original biological function [44].

While adopting a bioinspired framework may seem less technologically ambitious than a biomimetic framework, it explicitly allows us to consider the current limitations of non-invasive stimulation methods and the neurocognitive processes that determine how the tech-

nology will be integrated by the user. This approach is consistent with the observation that body-powered prostheses are often preferred over more technologically advanced myoelectric prostheses, illustrating that assistive technology design does not need to be highly sophisticated to be functional or have a positive impact on the lives of users. As such, we can promote the integration of an artificial limb without seeking neural embodiment, thereby avoiding the risk of potential adverse effects on maladaptive body representation [124].

The implementation of a bioinspired framework requires that we reconsider existing stimulation methods to identify which ones are best suited to this framework. Close attention must also be devoted to the other subsystems of the feedback architecture, including signal preprocessing and encoding, in order to promote effective integration of the selected stimulation method.

2.5 Transcutaneous electrical nerve stimulation

TENS is particularly interesting for this application case because it enables interaction with specific peripheral nerves via stimulation delivered using superficial electrodes applied on the skin [128]. Although the sensations evoked by TENS are not proprioceptive in nature, the transmission of information does not require surgical intervention. This significantly reduces the risks associated with implantation and positions TENS as a compelling option within a framework that prioritizes user acceptance, usability, and long term adoption.

Unlike electrotactile feedback and other non-invasive approaches presented previously, TENS can evoke sensations that are perceived downstream of the stimulation site, rather than exclusively at the electrode or tactor location. Also, simultaneous stimulation of multiple nerves induces spatially distinct compound sensations with adjustable intensity that correspond to the combination of sensations elicited by each individual stimulation [129]. These properties make TENS stand out as a stimulation method that can provide artificial somatotopic feedback in real time and non-invasively.

Previous work has demonstrated how stimulation of the median and ulnar nerves with TENS (see Figure 2.10) can evoke somatosensory percepts that are felt in specific regions of the phantom hand, allowing for the delivery of somatotopic tactile feedback even when the biological hand is missing [71, 130]. Importantly, the evoked sensations were rarely identified as natural touch. Instead, participants often described the sensation as being akin to paresthesia, reporting tingling, vibration, or pulsation. While this perceptual quality represents a major limitation in a strictly biomimetic framework for tactile feedback, it also presents an opportunity for a bioinspired approach.

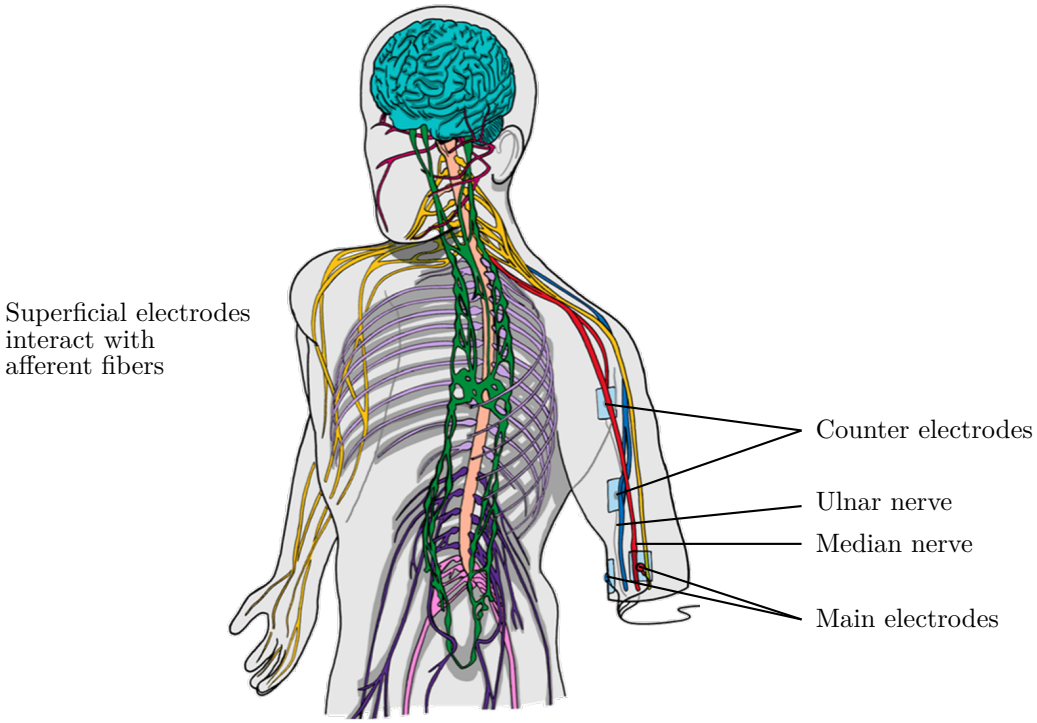

Figure 2.10 Transcutaneous electrical nerve stimulation (TENS) used to convey artificial feedback through non-invasive stimulation of peripheral nerves. Superficial electrodes are applied on the skin to stimulate the median and ulnar nerves non-invasively.

Rather than attempting to compensate for the non-homologous nature of sensations evoked with TENS [131], the approach purposefully accounts for this limitation. It leverages the preserved representation of the biological hand [132] and repurposes existing peripheral neural pathways to convey spatially meaningful information related to the configuration of the myoelectric prosthesis. This stimulation method holds potential to facilitate the interpretation of proprioceptive feedback and the adoption of myoelectric prostheses [45].

2.6 Further considerations for closed-loop control

In order to assess whether the proposed bioinspired approach has an effect on the control performance, reliance on vision, cognitive load, and training period associated with the use of myoelectric hand prostheses, the feedback must be integrated into a closed-loop control system where the commands sent to the hand are generated from EMG signals.

This integration is not trivial, due to the fact that TENS and EMG signals share overlapping frequency bands, with stimulation pulses introducing high-amplitude artifacts in the

recordings that overpower muscle activation signals [133].

To enable real-time myoelectric control with TENS as a stimulation method for artificial feedback, it is necessary to be able to isolate the volitional EMG signal that the user generates endogenously from the artifacts that the feedback introduces exogenously [134]. When electrical stimulation is delivered to the body, the recorded EMG signal can be affected in two ways: 1) the recruitment of motor units causes an exogenous muscle response; 2) the electrical potential delivered by the stimulator, stimulation-related artifacts, contaminates the signal.

The research literature contains several examples of frameworks that enable the separation of volitional EMG from exogenous components of the recorded EMG signal. The prevalent method used is data blanking, an approach that segments the signal to isolate stimulation time windows, most of the time to replace them with the mean value of the signal or even remove the data entirely. Documented approaches have achieved this process using dedicated hardware [135] or using software alone [136].

Several filtering algorithms have also been compared using simulations, with adaptive filtering allowing for the best isolation of volitional EMG during electrical stimulation and comb filters introducing less delay, making them preferable for real-time use [134].

The majority of the approaches investigated focus on use in the context of Functional Electrical Stimulation (FES), which involves different stimulation parameters and signal processing requirements than those used with TENS to elicit muscular activation. Software-based filters have been used in conjunction with hardware blanking, but no purely computational approach capable of real-time suppression of TENS-related artifacts has yet been integrated into practical closed-loop myoelectric control [137]. The integration of such methods could enable stable closed-loop control of artificial limbs while significantly simplifying the overall architecture of the system.

CHAPTER 3 OBJECTIVES

3.1 Research question and hypotheses

As outlined previously, there is a need for a proprioceptive feedback strategy that supports the adoption and long-term use of myoelectric hand prostheses while remaining compatible with user acceptability constraints.

Research question: How can a non-invasive TENS-based proprioceptive feedback strategy be designed and integrated into an EMG-driven closed-loop robotic hand control system to enhance grasping performance, accelerate motor learning, and reduce visual dependence without increasing cognitive load?

This research question is accompanied by three research hypotheses (H):

H1 Proprioceptive artificial feedback based on TENS enables users to discriminate and interpret finger position information.

H2 Proprioceptive artificial feedback based on TENS can be successfully integrated into an EMG-driven closed-loop control framework to enable position control.

H3 Proprioceptive artificial feedback based on TENS improves control accuracy and learning rate, and reduces reliance on vision, without increasing cognitive load during robotic hand grasping tasks.

3.2 Research objectives

This motivates the formulation of the following main objective.

Main objective: Develop a non-invasive proprioceptive feedback strategy for robotic hands based on TENS that conveys finger position and leads to better control accuracy, fast learning, and reduced reliance on vision, without increasing cognitive demands.

To achieve this main objective, the following Specific Objectives (SO) are considered:

SO1 Develop a non-invasive feedback strategy to convey finger position information to a robotic hand user.

SO2 Integrate the developed feedback strategy into an EMG-driven closed-loop control framework to enable position control.

SO3 Validate the effects of the developed feedback strategy on control accuracy, visual reliance, cognitive load, and learning rate during robotic hand grasping tasks.

Figure 3.1 illustrates how the human–machine interface evolves across the specific objectives of this thesis. SO1 focuses on enabling the user to receive proprioceptive feedback from the robotic hand through a non-invasive stimulation method (TENS). SO2 introduces bidirectional interaction by enabling the user to send EMG-based commands to the robotic hand while concurrently receiving stimulation delivered via TENS. Finally, addressing SO3 allows the user to control the robotic hand by modulating EMG-based commands informed by TENS-based proprioceptive feedback.

3.3 Thesis Outline

Chapter 2 already reviewed the relevant literature on proprioceptive feedback strategies for upper-limb myoelectric prostheses. This chapter examined alternative frameworks for artificial limb integration and identified a stimulation method suited to non-invasive proprioceptive feedback: transcutaneous electric nerve stimulation (TENS).

Chapter 4 presents a proof of concept establishing the groundwork for demonstrating the potential of the selected approach in a perceptual task. This contribution addresses SO1 and supports the rationale for pursuing TENS-based somatotopic proprioceptive feedback in closed-loop myoelectric control.

Chapter 5 introduces a methodological framework for suppressing stimulation-related artifacts that arise when combining TENS with EMG-derived commands. This chapter addresses SO2 and allows for concurrent stimulation and command generation. A closed-loop control case study is used to validate the framework, while visual feedback is intentionally preserved throughout the task to avoid confounding effects related to proprioceptive feedback integration, which is investigated in SO3.

Chapter 6 presents the results of a proportional control experiment using the developed feedback strategy to close the sensorimotor loop. This contribution addresses SO3 and evaluates the influence of the feedback on control performance, reliance on vision, cognitive load, and learning rate during the concurrent execution of a visually demanding task.

Chapter 7 offers a discussion on the work carried out throughout the thesis, highlighting both the results obtained and the known limitations of the research to identify areas for

improvement.

Chapter 8 summarizes the main findings and concludes the thesis by outlining future applications of the proposed approach.

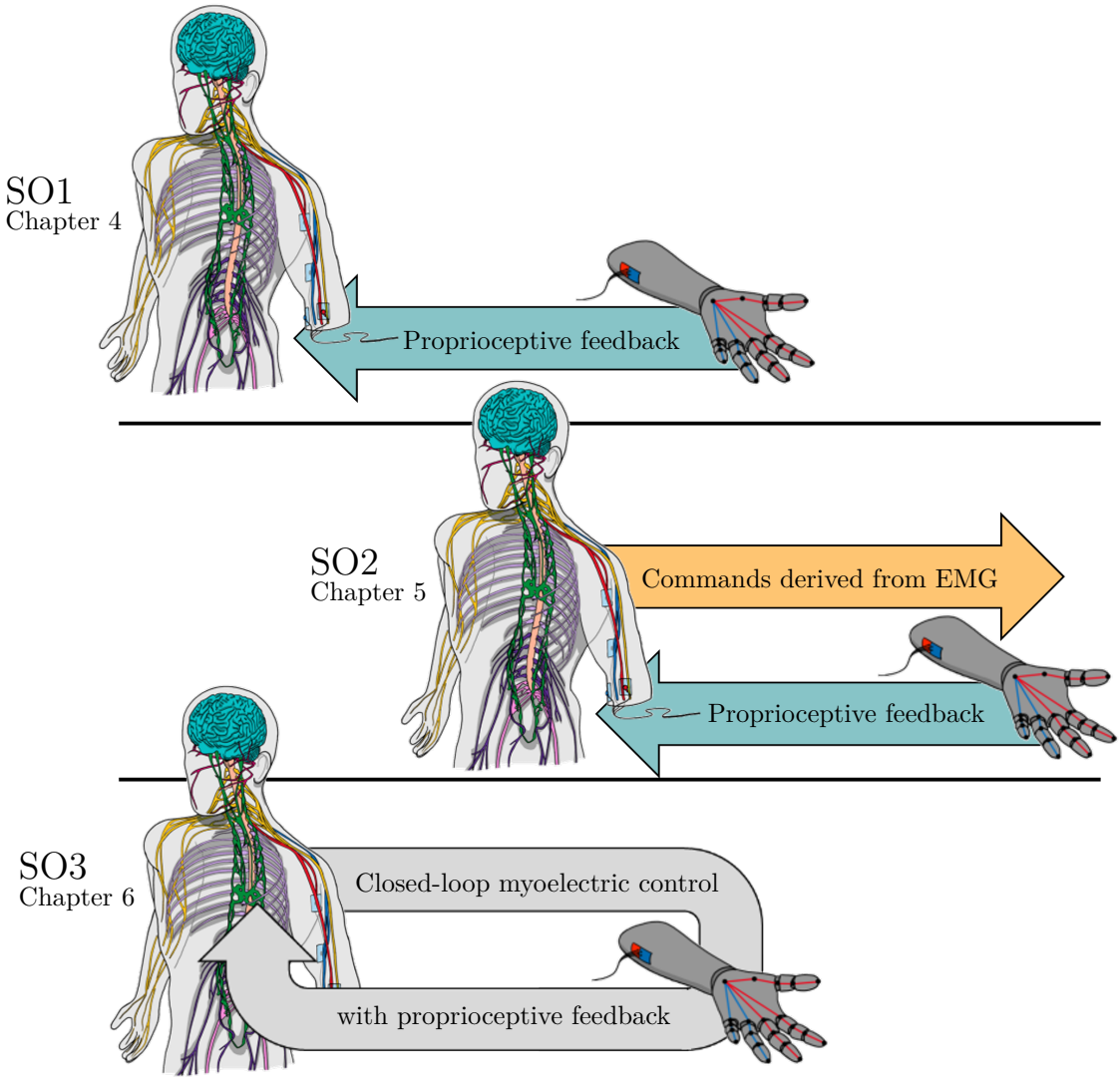

Figure 3.1 Illustration of the relationship (human-machine interface) between the user and the robotic hand across each specific objectives, culminating in closed-loop control.

CHAPTER 4 ARTICLE 1: SOMATOTOPIC NON-INVASIVE PROPRIOCEPTIVE FEEDBACK STRATEGY FOR PROSTHETIC HANDS: A PRELIMINARY STUDY

This contribution acts as a proof of concept for our bioinspired framework and addresses SO1: Develop a non-invasive feedback strategy to convey finger position information to a robotic hand user (See Figure 4.0).

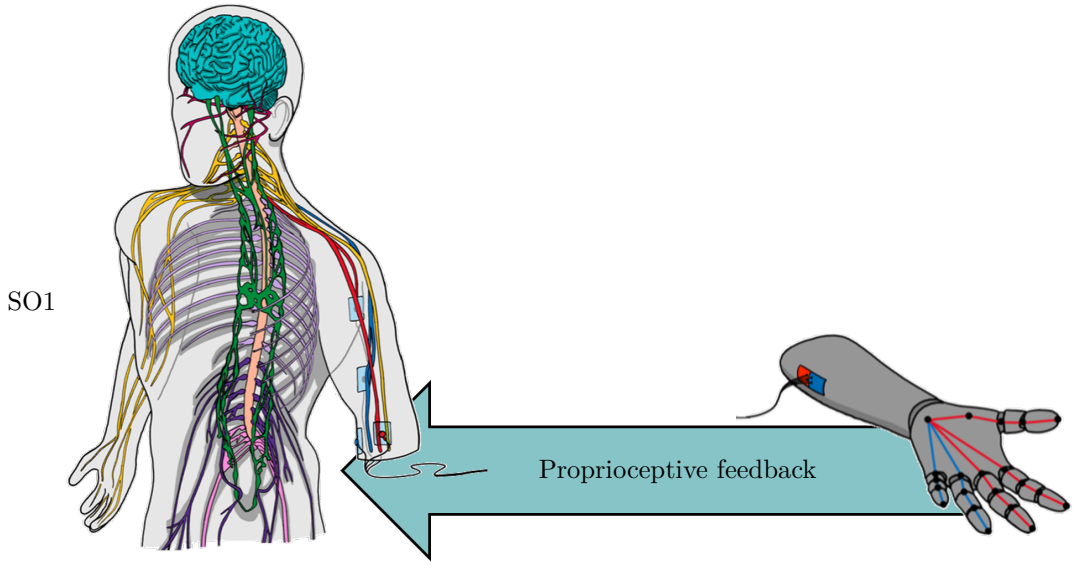

Figure 4.0 Illustration of the relationship (human-machine interface) between the user and the myoelectric prosthesis in this contribution related to SO1.

Somatotopic non-invasive proprioceptive feedback strategy for prosthetic hands: A preliminary study

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Abstract

Objective. Robotic hand prosthesis users often identify the lack of physiological feedback as a major obstacle to seamless integration. Both the low controllability and high cognitive load required to operate these devices generally lead to their rejection. Consequently, experts highlight sensory feedback as a critical missing features of commercial prostheses. Providing feedback that promotes the integration of artificial limbs is often sought through a biomimetic paradigm, limited by the current technological landscape and the absence of neural embodiment in users. As a result, some researchers are now turning to bioinspired approaches, choosing to repurpose existing neural structures and focusing on underlying neurocognitive mechanisms that promote the integration of artificial inputs. *Approach.* Taking a bioinspired approach, this paper describes the first implementation of a somatotopic, non-invasive proprioceptive feedback strategy for hand prosthesis users, developed using a standard sensory restoration architecture, i.e. pre-processing, encoding and stimulation. The main hypothesis investigated is whether a novel use of transcutaneous electrical stimulation can be leveraged to deliver proprioceptive information of the hand to the user. *Main results.* The potential of the proposed strategy was highlighted via experimental validation in conveying specific finger apertures and grasp types related to single and multiple degrees of freedom. Six participants were able to identify apertures conveyed by median and ulnar nerve stimulation with an accuracy of 96.5% ± 2.3% and a response time of 0.04 s ± 0.13 s, as well as grasp types conveyed from concurrent median and ulnar nerve stimulation with an accuracy of 88.3% ± 1.2% and a response time of 0.44 s ± 0.27 s through 5 sets of 10 trials. *Significance.* These results demonstrate the relevance of a somatotopic proprioception feedback strategy for users of prosthetic hands, and the architecture presented in this case study allows for future optimization of the various sub-components.

4.1 Introduction

Transradial amputation is a major amputation of upper-limb involving the removal of the hand and part of the forearm [7]. People who have undergone this surgical procedure experience impairments in their ability to interact with their environment through grasping. The development of robotic prostheses, combined with appropriate training, attempts to provide these individuals with dexterous action capabilities comparable to those available to a person with biological limbs [138]. Myoelectric prostheses occupy an important place in this research, as they enable users to communicate their movement intentions to a robotic prosthesis without the inherent risk of injury associated with the repeated use of body-powered alternatives. However, 40% of users tend to abandon these assistive devices [124], attributing this decision in part to the lack of restoration of sensory pathways, which significantly impedes the execution of voluntary movements [14, 16] due to increased cognitive effort during use [18] and reduced confidence in the prosthesis [15]. Both researchers and users agree that sensory feedback is one of the main missing features of commercial prostheses [10].

The vast majority of current research focusing on the restoration of sensory perception proposes strategies aimed at integrating tactile feedback, i.e. providing awareness of the body's external surface [41]. However, few address the integration of feedback relating to hand posture (proprioceptive perception) [56, 57]. Yet this modality is highly relevant when implemented appropriately, since it improves success rates in movement execution [58] and establishes a sense of agency, a relationship between movement intention and sensory feedback that promotes user acceptance of the technology [61, 62].

Several interesting avenues have been explored to develop proprioceptive feedback strategies, often using sensory substitution techniques or attempting to recreate the physiology involved in somatosensory perceptions through biomimetic approaches. However, limited efforts are being made to develop alternatives that maximize the user's interpretation of the conveyed proprioceptive information, while remaining non-invasive [42]. Adjustments towards such an approach would have the potential to substantially promote the adoption of myoelectric prostheses by minimizing the problems associated with their use, such as high cognitive load and low controllability when performing grasping tasks, especially without the contribution of visual inputs [71, 78].

The aim of this article is to investigate whether a novel strategy involving Transcutaneous Electrical Nerve Stimulation (TENS) has the potential to offer effective proprioceptive feedback. This stimulation method is selected because it allows for interaction with the peripheral nervous system non-invasively via electrodes applied to the skin surface. This framework

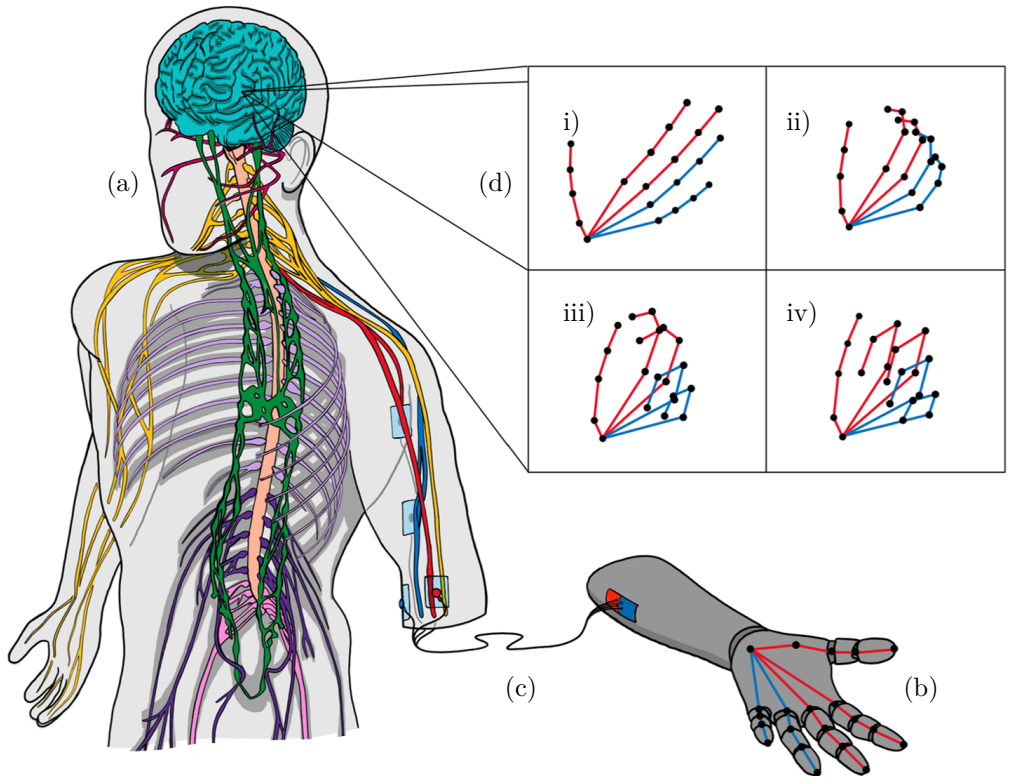


Figure 4.1 Implementation of an elementary proprioceptive feedback strategy for users (a) of hand prosthesis (b), with two concurrent transcutaneous electrical nerve stimulations applied to the median and ulnar nerve (c) to provide proprioceptive information required for real-time identification of grasp types (d). A blue and red color code highlights the relationship between the controlled states of the robotic hand, the transmission channels used for TENS and the grasp type perceived by the user. The grasp types considered in this proof of concept are i) non-prehensile, ii) cylindrical, iii) pinch and iv) oblique palmar. Descriptions of each grasp type are offered in Figure 4.4.

circumvents many of the technical difficulties inherent to the induction of proprioceptive percepts [10] and provides an interesting bioinspired compromise between the concepts of soft and hard embodiment, two complementary alternatives for promoting the integration of artificial limbs introduced in the literature by Makin *et al.* [124].

For this preliminary study, an implementation was carried out to provide a basis for experimental validation and a platform for future development and optimization. Consequently, as depicted in Figure 4.1, stimuli are delivered by concurrent TENS through two transmission channels, the *median* and *ulnar* nerves, jointly responsible for somatosensory perception of the fingers. Participants are then asked to interpret the stimuli and identify the conveyed grasp type among a limited set of options selected on the basis of their significant representation in activities of daily living.

This article discusses the first implementation of a non-invasive approach for delivering somatotopically mapped proprioceptive feedback to hand prosthesis users. Relevant related work is presented in section 4.2, after which section 4.3 describes the methodology used to obtain the results presented in section 4.4 and discussed in section 4.5, which also hints at interesting avenues for further development.

4.2 Background

4.2.1 General architecture of a sensory feedback strategy

A review of the relevant literature reveals a standard architecture (see Figure 4.2) commonly used in the development of sensory restoration strategies [30, 41, 42]. To begin, the preprocessing algorithm retrieves the states that describe the configuration of the robotic hand from the instrumentation, such as encoders or potentiometers. Next, the encoding algorithm packages these states into features, such as Cartesian or angular positions, which are selected to facilitate the user's interpretation. Finally, the encoded signals are transmitted in the form of stimuli to the user. Sensory restoration strategies are generally classified based on the type of stimulation method involved in conveying sensory information.

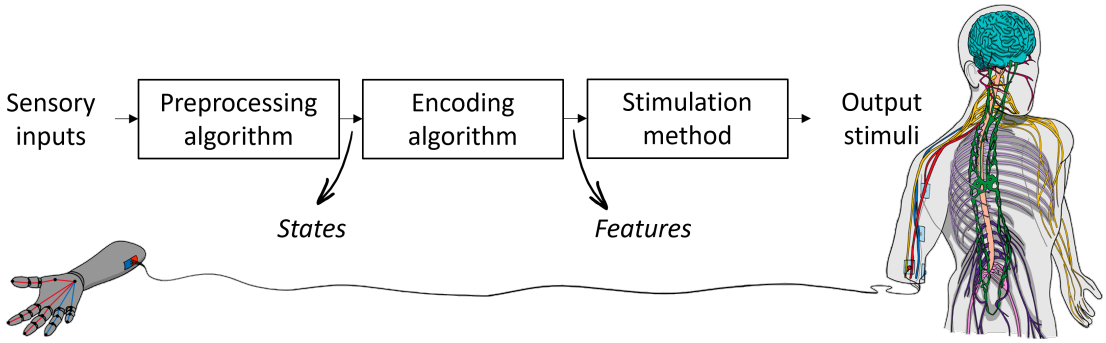


Figure 4.2 Illustration of the standard architecture implemented for sensory feedback restoration. The preprocessing algorithm extracts relevant states describing the robotic hand from the instrumentation. These states are then repackaged by the encoding algorithm for transmission via the selected stimulation method.

4.2.2 Applications retrieved from the literature

The use of vibrotactile [79, 80, 85, 86] and electrotactile stimulation [97–99], as well as linear and rotational skin stretch [90, 91, 93, 94], has been widely studied as a means of relaying proprioceptive information to hand prosthesis users. Those strategies are referred to as

sensory substitution techniques, meaning that the evoked sensation does not correspond to the original location or nature, since the information is transmitted through tactile stimuli. Sensory substitution techniques, can promote prosthesis-related embodiment [80, 81] when paired with the necessary learning period. However, this type of feedback is usually non-intuitive, difficult to adapt to concurrent signals [82] and requires a high cognitive load to be correctly interpreted [83].

In contrast, the literature defines an optimal sensory restoration strategy as both homologous and somatotopic, meaning that the restored sensation corresponds to its original modality and is anatomically consistent. The appeal of this approach is that the perfect mimicry of peripheral inputs could facilitate seamless integration by the central nervous system, allowing the artificial limb to directly replace the biological hand [139]. These two characteristics have been shown to enhance the interpretation of transmitted information, provide greater precision in terms of discrimination (acuity) and reduce learning time [45, 71].

Invasive stimulation strategies are often associated with the implementation of homologous and somatotopic feedback. For example, direct neural electrical stimulation is an invasive method that requires surgery to implant an electrode targeting specific fibers of the residual peripheral nerves involved in transmitting sensory feedback from the hand [19, 70]. This approach allows for various sensations to be evoked in specific regions of the hand downstream of the stimulation site [110]. Nevertheless, invasive approaches also come with notable drawbacks and users' reluctance to undergo surgical procedures for the installation or the maintenance of the device [71], as well as their concerns about the stability of the technology through time [72–74] have driven a recent shift in perception restoration research towards the development of non-invasive strategies. However, in both cases, lack of available actuation technologies capable of specifically targeting proprioceptive afferent nerve fibers results in an implementation problem [41, 68, 69]. This renders the development of an optimal biomimetic strategy for the non-invasive restoration of proprioception currently unfeasible and leads researchers to explore alternative solutions, experimenting with feedback mechanisms that fall at intermediate points on the biomimicry spectrum [42, 139]. Further developments could be introduced in the near future to improve on this issue, but a compromise must currently be made to maximize the user's ability to interpret proprioceptive feedback while maintaining a non-invasive approach.

The proposed approach is an alternative framework which draws from previous research conducted in the field of tactile feedback, and considers the use of TENS for the stimulation method. TENS can be used to transmit intuitive artificial feedback, although not proprioceptive in nature, by specifically targeting residual peripheral nerves through stimulation

delivered via non-invasive electrodes applied to the skin [128]. This eliminates the need for surgery, thereby reducing risk and improving user acceptance. Research by D'Anna *et al.* and Shin *et al.* has been instrumental in showing that concurrent stimulation of the ulnar and median nerves induces spatially distinct, compound sensations of adjustable intensity that correspond to the sum of the sensations elicited by the individual stimulation of each nerve [71, 129]. However, unlike electrotactile feedback or any other non-invasive approach, sensations are evoked downstream of the stimulation site and not exclusively *in loco* [63].

In pursuit of a bioinspired somatosensory feedback strategy, the interest here is to take advantage of this non-invasive somatotopic stimulation method, which targets specific regions of the phantom hand while eliminating the need for surgical intervention. While approaching optimal biomimetic feedback, this implementation deliberately departs from hard embodiment frameworks, a term that refers to the leveraging of neural and cognitive body mechanisms by closely emulating their original biological functions, by setting aside the idea of transmitting homologous feedback [124].

Adhering to a hard embodiment framework may prove to be ineffective in promoting integration and may be limited by an inability to fully mimic sensory integration. The implementation of this type of framework with the TENS method, as seen previously in a tactile feedback context, could therefore increase the cognitive load required for use, as well as induce discomfort and even aversion, i.e. the Uncanny Valley phenomenon [124, 126, 140]. This may be attributable to the fact that participants in numerous published studies using TENS to provide tactile feedback have repeatedly reported that the evoked sensations were restricted to specific areas of the hand and were non-homologous. Rather than replicating the original sensory modality, the sensations elicited by TENS more closely resemble paresthesia, i.e. "tingling", "vibration" or "pulsation" [71, 129, 130, 141].

Moreover, relevant evidence obtained through functional MRI data investigating the occipitotemporal cortex suggests that neural embodiment does not occur in prosthesis users and that their brain can always distinguish between a biological hand and an artificial limb [127]. Furthermore, this dissociated categorization of artificial limbs is consistent across different types of prostheses, whether cosmetic or active, and is correlated with a user's level of prosthesis use in activities of daily living [127].

While suggesting that the implementation of perfectly biomimetic proprioceptive feedback may prove futile, this demonstration of use-related plasticity with regards to artificial limbs hints at new opportunities for the design of sensory feedback strategies by removing some of the restrictions imposed by hard embodiment frameworks and making way for alternatives. Based on this assessment, an interesting conceptual approach to the limitations of hard

embodiment frameworks is to introduce elements of soft embodiment and sensory substitution by leveraging mechanisms within existing neural structures to support a different function instead of pursuing biomimicry [124]. The successful integration of these stimulation methods will depend on the implementation of the other subsystems that make up the standard architecture of a feedback strategy, as well as on the synergy between them, ensuring the most effective use of available biological infrastructures.

Providing non-invasive somatotopic proprioceptive feedback via the proper integration of TENS offers an innovative and previously unexplored compromise between soft and hard embodiment frameworks. Additionally, taking advantage of users' maintained representation of the missing hand [132] by repurposing existing neural structures, i.e. median and ulnar nerves, might enable faster learning. Finally, the development of appropriate preprocessing and encoding algorithms could lead to more intuitive and less cognitively demanding control of robotic prostheses.

4.3 Methods

4.3.1 Proprioception as a classification problem

To properly assess the hand's configuration, the prosthesis user must be able to accurately interpret the information conveyed. Since TENS is used to achieve somatotopy, i.e. the evoked sensation corresponds to the original location, the user must integrate information transmitted by two stimulation channels: the median nerve, responsible for relaying the states of the thumb, index and middle fingers, and the ulnar nerve, associated with the ring and little fingers. As illustrated in Figure 4.3, the interpretation required for proprioception feedback can be modeled as a combinatorial classification task, performed by the user, where the inputs are encoded proprioceptive data transmitted by TENS through the median and ulnar nerves, and the outcome is the configuration of the hand.

For the purposes of this case study, the hand configurations are limited to four classes, selected from the literature because they enable 66 % of everyday grasping tasks to be performed [142]. Also, the fingers targeted by each stimulation channel are in a similar arrangement, which lends itself well to the coding strategy and stimulation method discussed in sections 4.3.3 and 4.3.4. The selected grasp types are the non-prehensile grasp, the cylindrical grasp, the pinch grasp and the oblique palmar grasp, as presented in Figure 4.4.

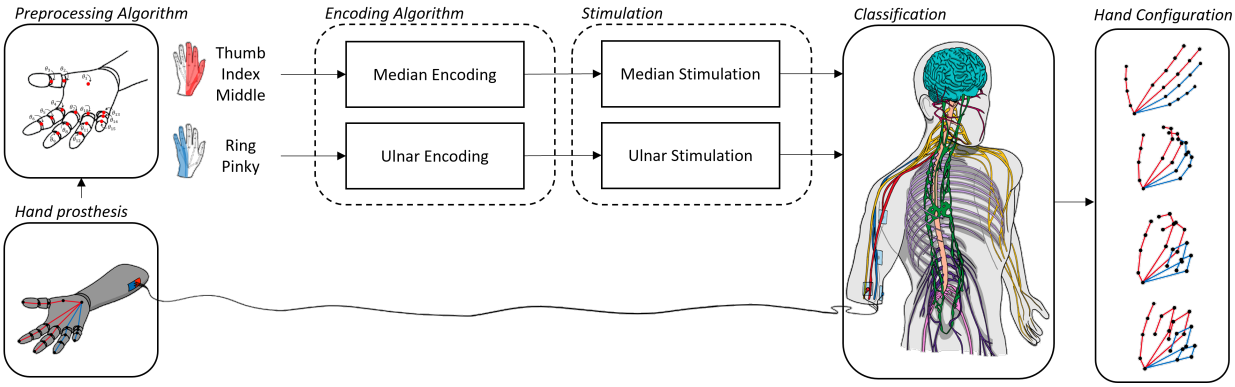


Figure 4.3 Illustration of proprioception feedback as a combinatorial classification performed by the participant. Both the encoding algorithm and the stimulation actuation are modeled by separating the transmission channels for median and ulnar information.

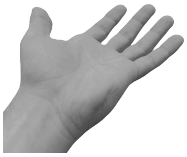
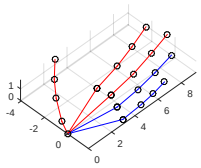
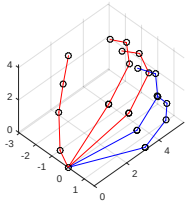
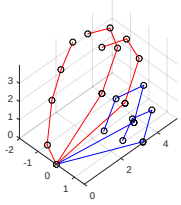
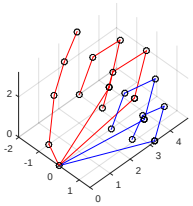
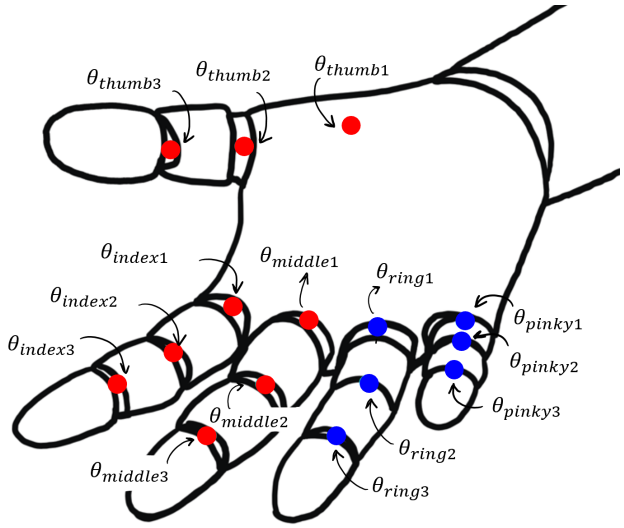
Hand Gesture	Configuration	Grasp type	Description
		Non-prehensile	Reference hand configuration where objects are manipulated without grasping them.
		Cylindrical	Type of grasp where the palm is involved and the thumb is in direct opposition to the other fingers.
		Pinch	Type of grasp where the thumb and two fingertips are used.
		Oblique palmar	Variation of the cylindrical grasp where the palm is involved, but the thumb is adducted.

Figure 4.4 Grasp types selected for their use in activities of daily living.

4.3.2 Preprocessing Algorithm

For this application, the preprocessing algorithm outputs a set of 15 angular positions between each phalanx of the hand, providing the encoding algorithm with information that characterizes the hand's configuration. These dimensionless outputs, presented in Figure 4.5, are selected because they eliminate system specific details related to the physical hardware used and its instrumentation. As a result, the proprioceptive feedback strategy discussed can be generalized to a variety of hardware.



Angle	Description*
θ_{thumb1}	Thumb CMC
θ_{thumb2}	Thumb MCP
θ_{thumb3}	Thumb IP
θ_{index1}	Index finger MCP
θ_{index2}	Index finger PIP
θ_{index3}	Index finger DIP
$\theta_{middle1}$	Middle finger MCP
$\theta_{middle2}$	Middle finger PIP
$\theta_{middle3}$	Middle finger DIP
θ_{ring1}	Ring finger MCP
θ_{ring2}	Ring finger PIP
θ_{ring3}	Ring finger DIP
θ_{pinky1}	Pinky MCP
θ_{pinky2}	Pinky PIP
θ_{pinky3}	Pinky DIP

*CMC: Carpometacarpal joint, MCP: Metacarpophalangeal joint, IP: Interphalangeal joint, PIP: Proximal interphalangeal joint and DIP: Distal interphalangeal joint.

Figure 4.5 Identification of the 15 angular positions outputted from the preprocessing algorithm.

4.3.3 Encoding Algorithm

As mentioned previously, the encoding algorithm must be able to package the angular positions emitted by the preprocessing algorithm in a format that promotes proprioceptive interpretation by the user. Typically, the literature suggests that increasing the number of stimulation channels, and therefore the number of features output by the encoding algorithm, enhances the precision of the information conveyed, but impairs an individual's ability to understand it [45]. The encoding algorithm produces a set of features that constitutes

an alternative to the 15 angular positions provided by the preprocessing algorithm, while offering a compromise between information completeness and interpretability.

Considering the grasp types selected in this proof of concept, it is conceivable to reduce the dimensionality of the feature set to two, i.e. one feature per transmission channel (median and ulnar). Equations 4.1 and 4.2 describe the encoding strategy selected based on piloting results, where features vary inversely with finger aperture, enabling effective classification of the grasp types. The feature transmitted by the median channel f_m is defined as the average of the aperture of the thumb, index finger and middle finger, while the feature transmitted by the ulnar channel f_u is the average of the aperture of the ring and pinky fingers.

Figures 4.6 (a) and 4.6 (b) illustrate the effectiveness of this encoding strategy, which leverages the interdependence between finger apertures to reduce feature set dimensionality while accurately capturing the configurations associated with the grasp types under study. In both figures, f_m and f_u are plotted separately, and a dashed line represents the ideal case of perfectly correlated finger apertures, providing a visual reference for assessing the relationship established by this encoding scheme. Additionally, Figure 4.6 (c) presents a graphical representation of the normalized amplitude of the median and ulnar features relative to the grasp type communicated. The reduced set of features offers sufficient discriminability to differentiate between each of the grasp types when combining the two features, without the need for high resolution, which could lead to interpretation problems for the participant [143].

$$f_m = \frac{\sum \theta_{thumb} + \sum \theta_{index} + \sum \theta_{middle}}{3} \tag{4.1}$$

$$f_u = \frac{\sum \theta_{ring} + \sum \theta_{pinky}}{2} \tag{4.2}$$

where:

$$\sum \theta_{finger} = \theta_{finger1} + \theta_{finger2} + \theta_{finger3}$$
$$finger \in \{thumb, index, middle, ring, pinky\}$$

4.3.4 Stimulation

In the current application, where TENS is used to evoke a somatotopic sensation downstream of the stimulation site, the quality of the feedback depends on the electrodes location and the stimulation parameters. The percepts produced in specific areas of the hand result from

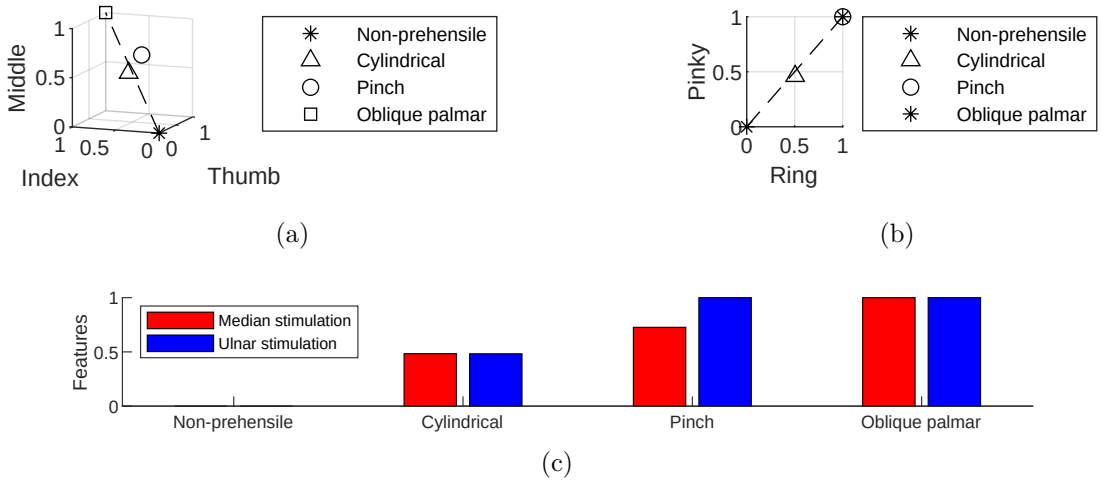


Figure 4.6 Graphical representation of the features, where (a) Distribution of selected grasp types where f_m is represented in a three-dimensional space where the axes are the normalized aperture of the thumb, index finger and middle finger; (b) Distribution of selected grasp types where f_u is represented in a two-dimensional space where the axes are the normalized aperture of the ring and pinky fingers; (c) Normalized amplitudes of the median and ulnar features as a function of the grasp type to be conveyed. Both (a) and (b) feature a dashed line representing the ideal case of perfectly correlated finger apertures

the activation of distinct groups of neurons in the nerve bundles, and are therefore primarily attributable to electrode placement, which depends on the participant's physiology [129]. Furthermore, while the properties of the signal have limited effects in modulating the area of sensation, the delivered electrical charge is proportional to the firing rate of sensory afferents that encode the referred sensation intensity I [71]. An extensive exploratory phase is required to optimize these factors for each participant.

Electrode placement:

The primary purpose of electrode placement is to ensure that the evoked sensations are somatotopic. In this case, the optimal configuration ensures that stimulating the median nerve evokes concurrent sensations in the thumb, index and middle fingers, while stimulating the ulnar nerve evokes concurrent sensations in the ring and pinky fingers. The secondary objective is to minimize, if not eliminate, the perceived intensity of the *in-loco* sensation generated during stimulation.

The methodology applied for electrode placement builds upon the work of D'Anna *et al.* [71] and Vargas *et al.* [130]. Two regions of interest will be investigated: the forearm and the

brachial region between the biceps and triceps muscles, chosen because the median and ulnar nerves are most superficial in these areas. The configurations decribed in these studies, along with the schematic representation illustrated in Figure 4.7, serve as heuristics of sorts in the electrode placement process.

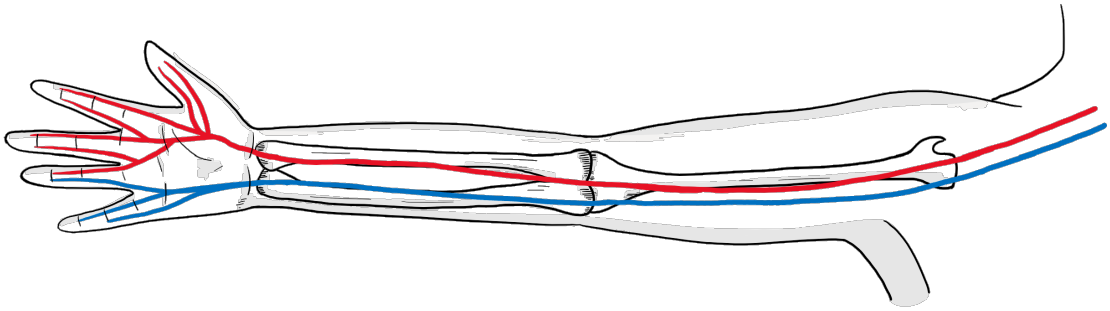


Figure 4.7 Illustration of the spatial organization of the median and ulnar nerves, respectively displayed in red and blue.

Participants are exposed to a short duration stimulus on their right arm. To accurately identify the region of the hand targeted by the neuromodulation, subjects are asked to verbally report the regions where the evoked sensation is located, using a reference drawing of a labeled hand that is presented in front of them. In the event that the participants feel no evoked sensation in their hand, they are asked not to indicate any region of the hand.

For both the median and ulnar nerves, the experimenter begins by identifying the optimal placement of the main electrode, ensuring the elicitation of a precise sensation in the appropriate areas of the hand. To achieve this, a motor point pen (Compex, Chattanooga, TX, USA) and electrotherapy gel are used, while the counter-electrode is positioned proximally over the stimulated nerve. Once the main electrode placement is determined, the experimenter then uses the motor point pen to locate the counter-electrode position that minimizes *in-loco* sensation.

Stimulation parameters:

The established optimal electrode placement is then used to determine the stimulation parameters for each participant. This stage of the methodology aims to identify two relationships, one for each transmission channel, between the intensity of the evoked sensation and the electrical charge delivered via TENS. These participant-specific relationships will be used to determine the administration of electrical charge needed to evoke a sensation with a perceived intensity that corresponds to the features that describe the hand configuration.

The stimulator delivers a charge balanced rectangular-wave biphasic stimulation current, enabling the appropriate amount of charge to be delivered, while minimizing the amount of current supplied as well as the residual electrical charge, thus avoiding the undesired side effects associated with electro-chemical changes [144]. In this context, the amplitude and pulse width of the signal are particularly important, since they directly influence the amount of charge injected, i.e. the product of the two parameters, and consequently the intensity of the perceived sensation [143]. However, the stimulation device featured in this work offers improved electrical charge resolution by modulating the pulse width in relation to the amplitude, which is consequently set at a constant value. The signal frequency was set to 120 Hz and remained at a constant value, since its variation can lead to modulations of the area of the reported sensation [71].

To establish the relationship between electrical charge and evoked sensation intensity for the median and ulnar transmission channels, the experimenter applies multiple stimuli with fixed amplitude and frequency, varying the signal pulse width over a domain ranging from 75 μs to 400 μs with a resolution of 25 μs, ensuring coverage of the full range of specifications associated with the stimulator used. For each stimulation, the participant vocally informs the experimenter of the intensity of the sensation felt, referring to the scale shown in Table 4.1.

4.3.5 Experimental Protocol

To assess viability of the proposed feedback strategy, the experiments must evaluate the participant's ability to discriminate the information conveyed through each stimulation channel, as well as their ability to synthesize this information. Considering these specific requirements, two experiments are selected: an aperture discrimination task and a grasp type classification task.

Table 4.1: Scale used to assess the intensity of the evoked sensation.

Intensity (I)	Quality
0	There is no evoked sensation.
1	The evoked sensation is barely felt.
	...
5	The evoked sensation is precise and of medium intensity.
	...
10	The evoked sensation is precise and of maximum intensity, while remaining below the pain and motor fiber recruitment thresholds.

Before each experiment, the participants undergo a five minute familiarization session in which they learn to associate the neuromodulation with the corresponding aperture or grasp type using a visual display. This training period is chosen to align with other studies, ensuring that the results obtained can be compared with those in the literature [17, 93, 94].

Aperture discrimination task:

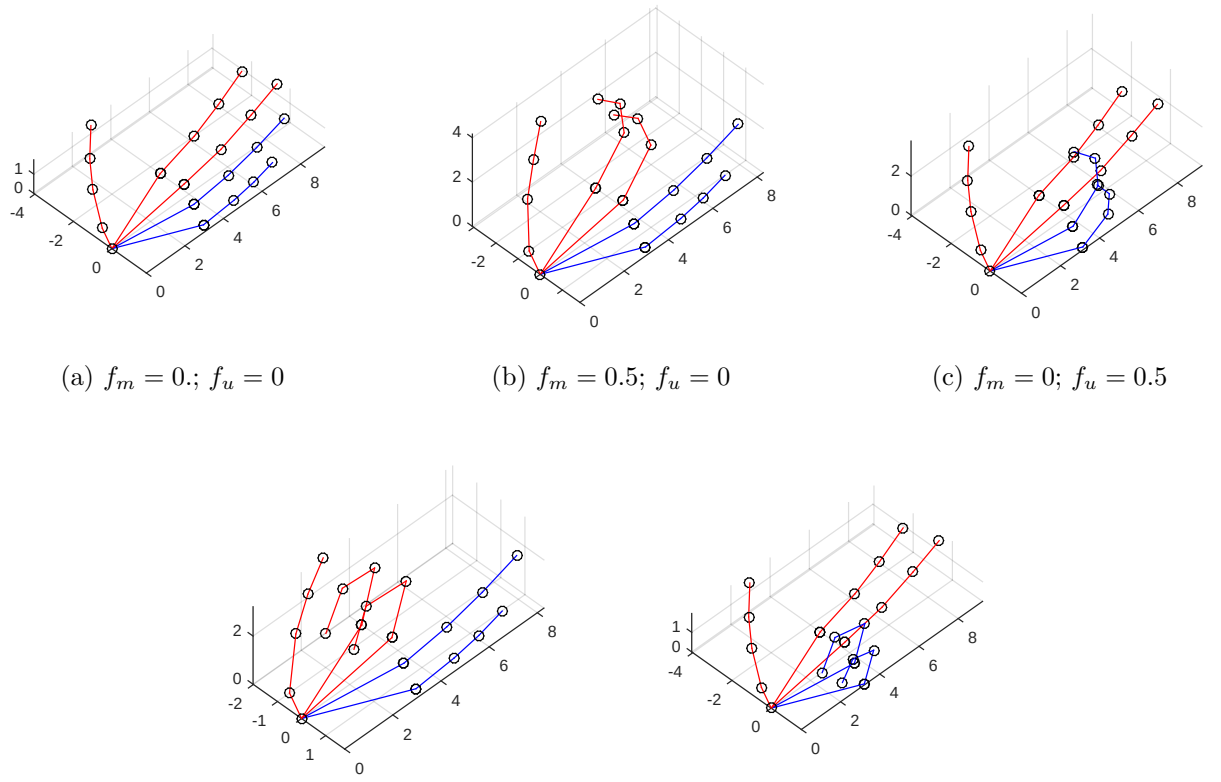
In the first experiment, participants are asked to identify the aperture conveyed through a single transmission channel at a time. The stimulation parameters are defined based on the relationships established in section 4.3.4 to ensure that the electrical charge of the signal evokes a sensation with the appropriate intensity for each participant. The specific sensation intensities corresponding to the grasp types selected for this case study are consistent with Table 4.2 and illustrated in Figure 4.8. The discretization of the felt intensity domain into three levels (0, 5 and 10) is motivated by previous findings from the literature indicating that introducing a fourth level significantly reduces performance in identifying conveyed intensity [71].

Participants undergo five sequences of ten stimulations per transmission channel. During the experiment, they must indicate which aperture is conveyed by interacting with a keyboard, after which stimulation is stopped. For each sequence, stimuli consistent with the values presented in Table 4.2 are administered in a random order. However, these stimuli are interspersed with a return to stimulation corresponding to non prehensile grasping, where the participants must indicate that they are not experiencing neuromodulation. Aperture recognition accuracy and response time are continuously monitored during the experiment.

Table 4.2: Features conveyed in discrimination tasks and corresponding intensity.

Grasp type	f_m^*	f_u^*	I_m^*	I_u^*
Non-prehensile	0	0	0	0
Cylindrical	$0.48 \approx 0.5$	$0.48 \approx 0.5$	5	5
Pinch	$0.73 \approx 0.5$	1	5	10
Oblique palmar	1	1	10	10

*The variables f_m, f_u, I_m and I_u are used respectively to represent the transmitted features (f) and intensity (I) of the evoked sensations through the median nerve and the ulnar nerve.



(a) $f_m = 0.$; $f_u = 0$ (b) $f_m = 0.5$; $f_u = 0$ (c) $f_m = 0$; $f_u = 0.5$

(d) $f_m = 1$; $f_u = 0$ (e) $f_m = 0$; $f_u = 1$

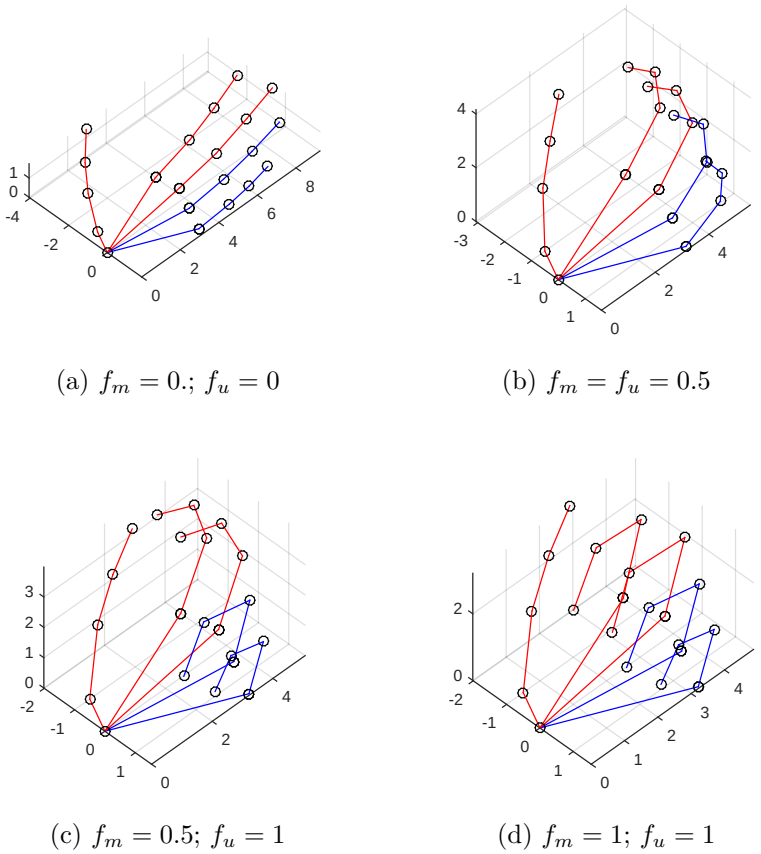
Figure 4.8 Visual representation of the different apertures conveyed during the aperture discrimination task and the value of the features delivered through each stimulation channel.The variables f_m, f_u are used respectively to represent the features (f) transmitted through the median nerve and the ulnar nerve.

Grasp type discrimination task:

In the second experiment, participants are asked to identify the hand configuration corresponding to two concurrent stimuli, defined similarly to the aperture discrimination task (see Table 4.2).

Participants now undergo five sequences of ten stimulations involving both transmission channels. During the experiment, they must indicate which grasp type is conveyed by interacting with a keyboard. For each sequence, concurrent stimuli that are consistent with the values presented in Figure 4.9 are delivered in a random order. Once again, the non prehensile grasping serves as a reference configuration, meaning that each stimulation is interspersed with an absence of stimulation requiring participants to indicate when the are not experiencing neuromodulation. Grasp type classification accuracy and response time are continuously

monitored throughout the experiment.



(a) $f_m = 0.; f_u = 0$ (b) $f_m = f_u = 0.5$

(c) $f_m = 0.5; f_u = 1$ (d) $f_m = 1; f_u = 1$

Figure 4.9 Visual representation of the different apertures conveyed during the grasp type discrimination task and the value of the features delivered through each stimulation channel.

Visual discrimination tasks:

To contextualize the response times recorded during both the aperture discrimination and grasp type discrimination tasks, participants also completed identical tasks using visual stimuli. A four-month interval between sessions was implemented to minimize potential biases. The visual discrimination tasks serve as a reference for evaluating TENS as a stimulation method for conveying proprioceptive information. By comparing the integration time of proprioceptive information via the visual and somatotopic systems, we can assess TENS efficacy while accounting for potential confounding factors, such as the influence of the encoding strategy and the motor response time associated with keyboard interaction. This type of stimulus was selected due to the critical role of visual inputs in constructing an accurate proprioceptive representation of hand configuration during grasping [96]. Minimizing perceptible delays in

transmitting proprioceptive information via somatotopic systems is essential for establishing a sense of agency in closed-loop applications [77, 145].

4.3.6 Experimental setup

The experimental set-up used in both experiments is shown in Figure 4.10. For Experiment 1, the stimulator is the Rehab (Chattanooga, USA), selected for its ability to generate up to four concurrent signals, with stimulation parameters aligned with the literature surrounding the use of TENS for sensory restoration [128,146–148]. The electrodes are Dura-Stick Plus 5 cm repositionable cloth electrodes (Chattanooga, USA), identified in preliminary experiments as minimizing the intensity of *in-loco* evoked sensation compared to smaller alternatives. For Experiment 2, the P24 stimulator (Hasomed GmbH, Germany) is selected because it allows for more flexibility in concurrent stimuli parameters and better implementation than the previous stimulator. Oval repositionable electrodes of dimensions 4 cm $\times$ 6.4 cm are used (Hasomed GmbH, Germany). During both experiments, the participants are visually isolated from the experimenter and wear noise canceling headphones playing white noise in order to avoid any visual or auditory cues that might bias the results.

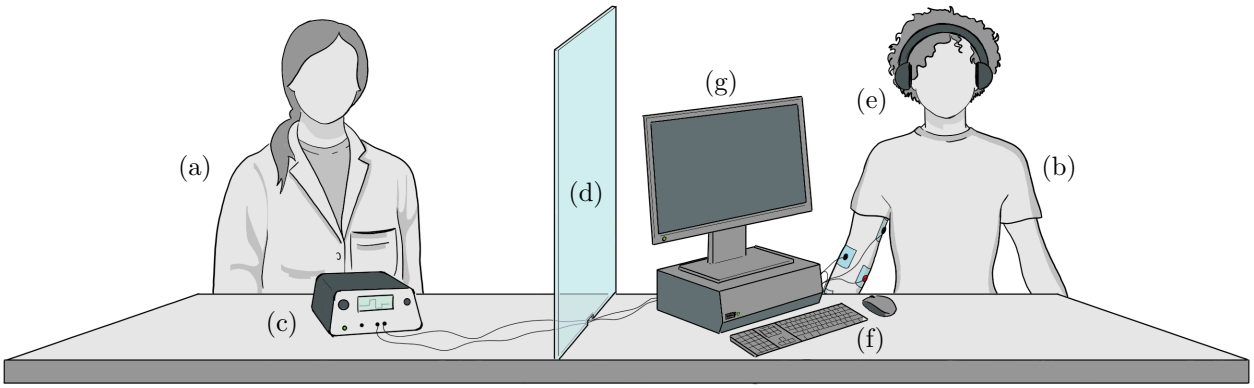


Figure 4.10 Experimental set-up used, including: (a) the experimenter, (b) the participant, (c) the TENS stimulator and electrodes, (d) the visual isolation panel, (e) the auditory isolation headphones, (f) the keyboard with which the participant interacts during the experiment and (g) the visual display used during the familiarization session and the visual discrimination tasks.

4.3.7 Participants

To ensure statistical integrity and consistency with the literature, the experiments will involve six intact subjects (three females, three males) [58, 67, 85, 98, 149, 150]. Participants recruitment adheres to the principles of equity, diversity and inclusion advocated by the Nat-

ural Sciences and Engineering Research Council of Canada (NSERC). Table 4.3 presents the characteristics of the participants included in this study. All participants are over 18 years old and meet the inclusion criteria for safety. Specifically, none have preexisting medical conditions that could pose a risk, such as epilepsy or severe circulatory disorders. Participants also have no known neurological disorders, significant skin conditions, or allergies to electrodes that could be exacerbated by the stimulation. Additionally, individuals who were pregnant or had implanted medical devices (e.g., pacemakers, defibrillators, or other electronic implants) were excluded per the stimulator manufacturer's contraindications.

Table 4.3: Participants characteristics.

	Age	Sex	Wrist circumference	Elbow circumference
P1	23	Female	15.7 cm	23.0 cm
P2	26	Female	16.0 cm	25.7 cm
P3	38	Male	19.8 cm	28.4 cm
P4	26	Male	18.0 cm	29.0 cm
P5	25	Female	15.6 cm	23.9 cm
P6	24	Male	18.0 cm	30.0 cm

4.4 Results

4.4.1 Preliminary experiments

Figure 4.11 presents the results for the preliminary experiments conducted for each of the six participants. The first column illustrates the location of the evoked sensations, as identified by participants during TENS application. These location-specific evoked sensations result from the electrode placement shown in the second column, where the electrodes are marked in red or blue, depending on the nerve they interact with. The third column presents the linear relationship between the intensity of the evoked sensation and the electrical charge transmitted for each stimulation channel, in accordance with the literature [71]. Each dot represents the intensity of the evoked sensation, as perceived by each participant, as a function of the electrical charge applied. The stimulation parameters selected to produce the appropriate values of I_m and I_u, required communicating hand configurations, were identified from the data in the third column of Figure 4.11 and are participant-specific. All six participants reported sensations resembling paresthesia or "tingling," consistent with previous findings in the TENS-based neuromodulation literature. Additionally, some participants described a sensation of "pressure" at higher stimulation intensities [71, 129, 130, 141].

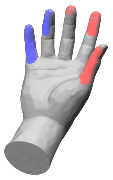
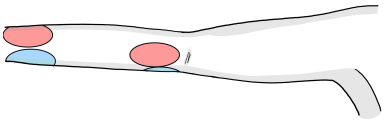
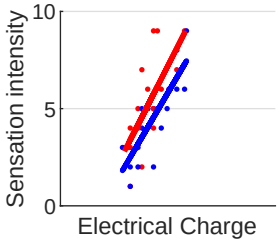
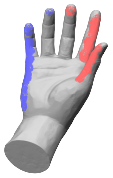
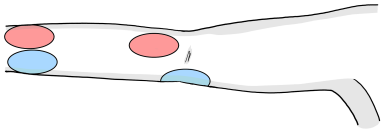
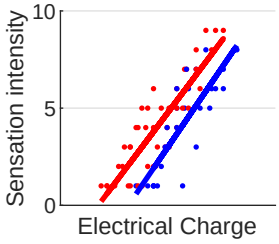
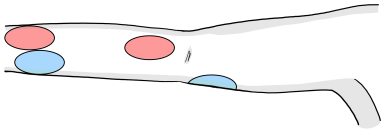
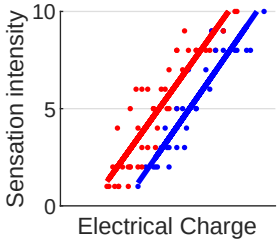
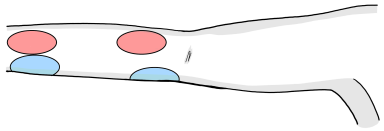
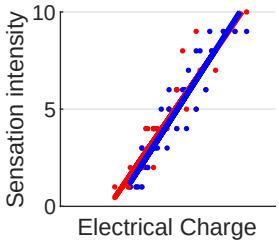
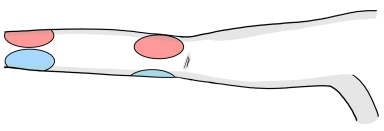
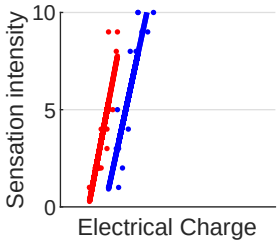
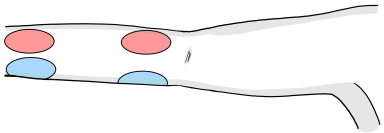
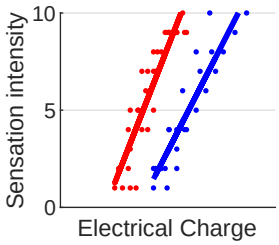
Name	Sensation location	Electrode placement	Sensation intensity
P1			
P2			
P3			
P4			
P5			
P6			

Figure 4.11 Results of the preliminary experiments.

4.4.2 Aperture discrimination task

The results from the aperture discrimination task are presented in Figure 4.12, where median and ulnar stimulation results are shown in red and blue respectively, following the previously established color code. Aside from sub-figures (d) and (e), the figure displays both overall results across participants and inter-participant variability (expressed as mean with standard deviation or median with interquartile range), with individual participant performances being represented by circular markers.

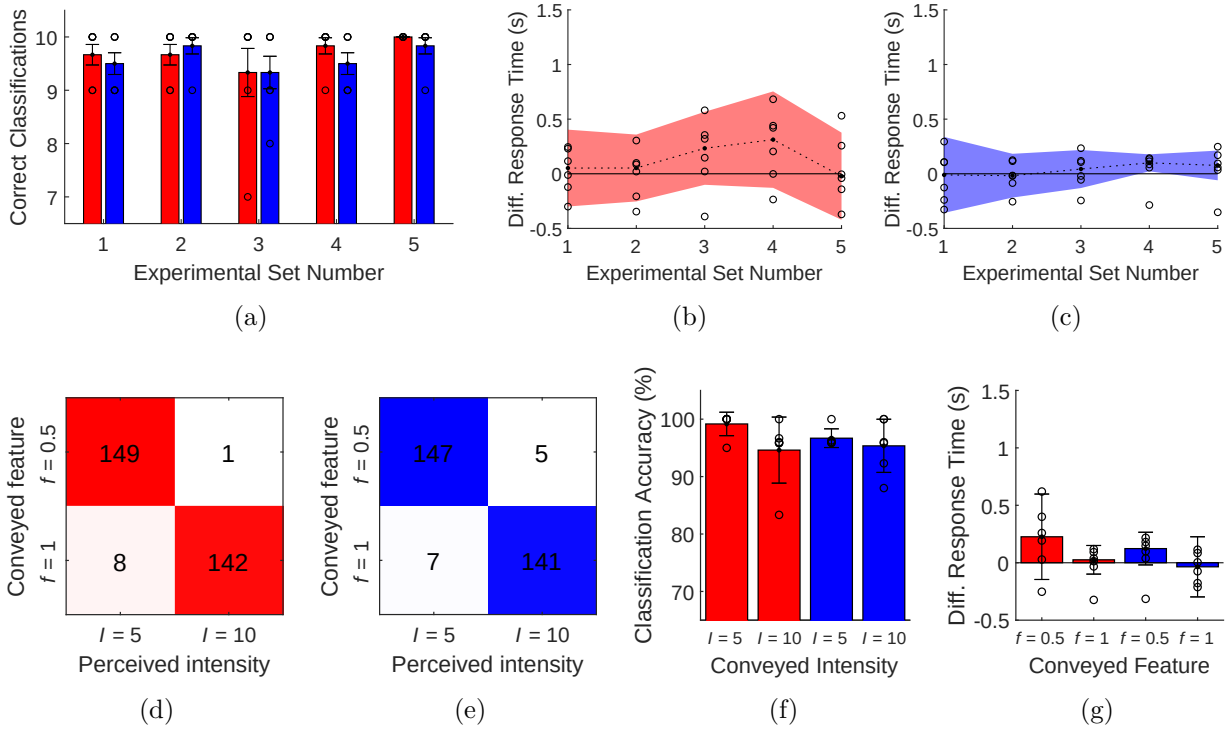


Figure 4.12 Results for aperture discrimination task across six participants, for both the median and ulnar stimulations. Results related to the median and ulnar nerves are shown in red and blue, respectively, with each individual participant's data represented by circular markers. (a) Average aperture classification accuracy and standard deviation across participants through the sets; (b) (c) Median differential response times and interquartile ranges across participants through the sets; (d) (e) Confusion matrix of the conveyed features and the perceived sensation intensities; (f) Average classification accuracy and standard deviation across participants for each conveyed feature; (g) Median response time and interquartile ranges across participants for each conveyed feature.

Aperture classification accuracy:

Figure 4.12 (a) presents the average number of correctly reported classifications and their standard deviation, for 10 trials, across participants for each set. Throughout the five sets, participants were consistently able to identify the apertures conveyed via median and ulnar nerve stimulation. Overall, this is reflected in an average accuracy across participants and sets of 97.0% ± 2.5% for the median nerve stimulation and of 96.0% ± 2.2% for the ulnar nerve stimulation. The confusion matrices shown in Figures 4.12 (d) and 4.12 (e) illustrate participants' overall ability to interpret information transmitted via stimulation, while also suggesting a slightly reduced performance in accurately perceiving the stimulus condition $f = 1$. Figure 4.12 (f) offers further insight, revealing an unusually low classification accuracy for participant P5 when interpreting median nerve stimulation with $f = 1$, achieving only 83.3% accuracy over 5 sets compared to an average of 97.1% ± 2.0% for the other participants. This discrepancy may be attributed to the suboptimal selection of stimulation parameters or participant fatigue due to prolonged TENS exposure. Additionally, participants reported occasional accidental key presses while attempting to respond quickly, which could have contributed to the observed errors.

Response times:

Figures 4.12 (b) and 4.12 (c) present the median differential response times across participants between the aperture discrimination tasks performed using TENS and visual stimuli for each participant (indicated by black hatched lines). The interquartile ranges are represented by the shaded polygonal regions. The overall median differential response time, aggregated across participants and sets, was 0.05 s ± 0.22 s for the median nerve stimulation and 0.04 s ± 0.10 s for the ulnar nerve stimulation. Negative values were occasionally observed in cases where participants responded more quickly with TENS than with visual cues. For both stimulation channels, the differential response time does not appear to introduce perceptible delays. However, it is noteworthy that the differential median response time across participants increases in some of the later sets (Sets 3 and 4), particularly during the median nerve stimulation. This trend may indicate the onset of fatigue or sensory adaptation, a factor that should be minimized to maintain consistent performances [151]. Finally, Figure 4.12 (g) illustrates that differential response times across participants consistently decrease as the magnitude of the conveyed feature increases.

4.4.3 Grasp type discrimination task

Figure 4.13 presents the results from the grasp type discrimination task. To effectively assess how classification performance is affected by simultaneous stimuli and the introduction of multiple features, the analysis is performed similarly to the one described for the aperture discrimination task. Aside from sub-figure 4.13 (c), the figure displays both overall results across participants and inter-participant variability (expressed as mean with standard deviation or median with interquartile range), with individual participant performances being represented by circular markers.

Aperture classification accuracy:

Figure 4.13 (a) illustrates the average number of correct classifications (out of 10 trials) across participants for each set. While participants consistently identified grasp types delivered simultaneously via median and ulnar nerve stimulation, their performance was slightly lower compared to single-stimulus conditions, with an average accuracy across participants and sets of 88.3% ± 1.2%. Beyond the additional class (three grasp types instead of two apertures), the results presented in Figures 4.13 (c) and 4.13 (d) are key to understanding the disparity between performances from the aperture discrimination test and the grasp type discrimination test. Both figures indicate that the primary source of variability in classification accuracy arises when the grasp type 'pinch' is conveyed. This particular grasp type, distinguished as the only condition presenting two distinct features between median and ulnar nerve stimulation ($f_m = 0.5$ and $f_u = 1$), was classified with an average accuracy of 78.1% ± 13.6% across participants. This contrasts with higher average accuracies across participants observed for the 'cylindrical' grasp (90.8% ± 5.5%) and the 'oblique palmar' grasp (97.6% ± 3.7%).

Response times:

Figure 4.13 (b) presents the median differential response times across participants between the grasp type discrimination tasks performed using TENS and visual stimuli for each participant (indicated by black hatched lines). The interquartile ranges are represented by the polygonal regions. The increased complexity of interpreting the hand configurations from concurrent sources of information is reflected in the larger differences in response time for grasp type identification across participants and sets (0.44 s ± 0.27 s), compared to the aperture discrimination task. While a slight increase in average accuracy across participants is observed over the sets, there is a simultaneous decrease in the median differential response

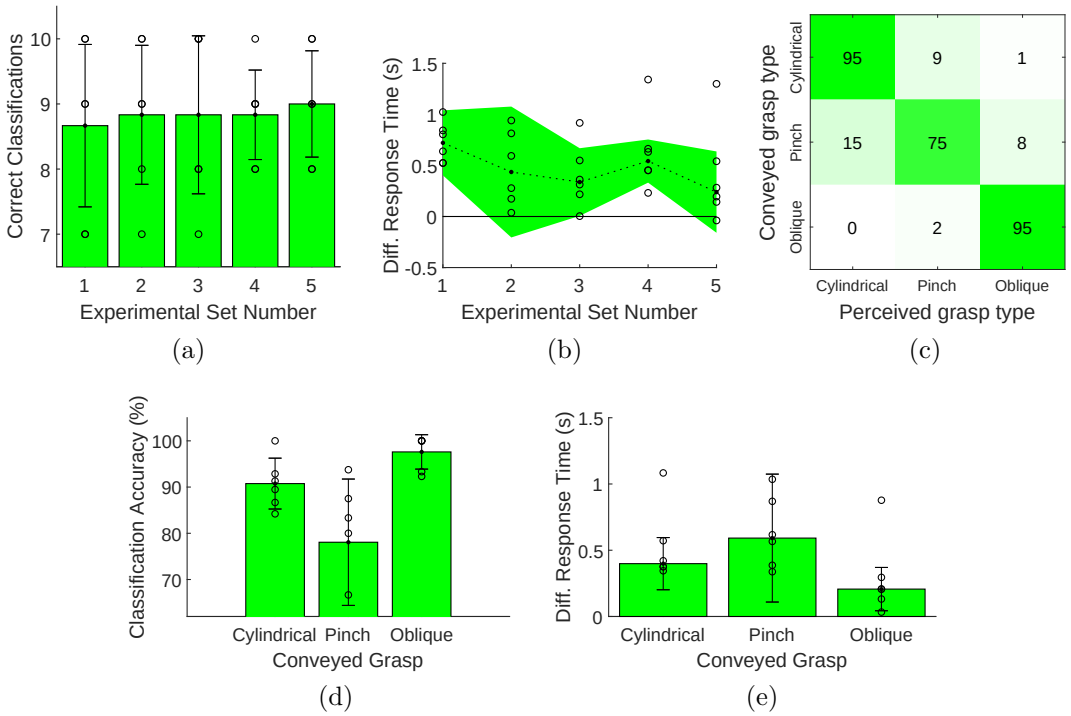


Figure 4.13 Results for grasp type discrimination task across six participants, for concurrent median and ulnar nerve stimulation. Individual participant data are represented by circular markers. (a) Average grasp type classification accuracy and standard deviation through the sets; (b) Median differential response times and interquartile ranges through the sets; (c) Confusion matrix of the conveyed and perceived grasp types; (d) Average classification accuracy and standard deviation across participants for each conveyed grasp type; (e) Median response times and interquartile ranges across participants for each conveyed grasp type.

time across participants, from 0.72 s ± 0.31 s in the first set to 0.24 s ± 0.40 s in the fifth and final set. This suggests that participants became more familiar with the task and increasingly more efficient as the experiment progressed. Notably, one participant responded more quickly with TENS than with visual cues during the fifth set, which explains the negative value observed in the difference between the two conditions. However, a peak in median differential response time is noticeable around the fourth set—similar to what was observed in the aperture discrimination task—which may indicate sensory adaptation related to the nature or modality of the stimulation.

Figure 4.13 (e) demonstrates a significant increase in response times across all conveyed grasp types compared to the single-stimulus aperture discrimination task. This increase is most pronounced for the 'cylindrical' (0.40 s ± 0.20 s) and 'pinch' (0.59 s ± 0.48 s) grasp types. As shown in Figure 4.13 (c), errors involving these two grasp types are the most

frequent, and this difficulty is reflected in the longer time required for classification. In contrast, the 'oblique palmar' grasp type is identified more quickly (0.21 s ± 0.16 s), though response times still do not reach the baseline observed with single-stimulus conditions. This discrepancy may be attributed to fatigue from the increased electrical load delivered during concurrent stimulation [151]. Additionally, potential 'cross-talk' between the median and ulnar nerves, coupled with the heightened cognitive load from classifying three grasp types instead of two apertures in the aperture discrimination task, may contribute to the observed performance differences.

4.5 Discussion

4.5.1 Results analysis

The results from both experiments support the initial hypothesis: the proposed somatotopic stimulation method based on TENS can effectively transmit hand proprioception information. Classification performance remains consistent over time, and response times are comparable to those observed with visual feedback in similar tasks. While classification accuracy may improve with practice, the current sample size does not allow for definitive conclusions regarding learning and familiarization effects. Consequently, it remains unclear whether increased exposure to the feedback would further reduce differential response times between visual and TENS-based conditions. However, the consistency of the results highlights the potential of this approach for both single and concurrent stimulation discrimination tasks.

As a reminder, six participants participated in this study and identified apertures (96.5% ± 2.3% accuracy, 0.04 s ± 0.13 s) and grasp types (88.3% ± 1.2% accuracy, 0.44 s ± 0.27 s) via nerve stimulation across five sets of ten trials. The performance achieved in this study is comparable to, and in some cases surpasses, results reported across a wide range of proprioceptive feedback methods, from non-invasive sensory substitution to invasive techniques. While methodologies and study designs vary, these comparisons provide insight into how the proposed strategy aligns with existing approaches. For instance, Akhtar *et* al. evaluated a passive skin-stretch device for multi-DOF grasp recognition (six grip types), reporting an accuracy of 88.0% with an average classification time of 5.2 s [94]. Vargas *et* al. assessed object recognition with proprioceptive feedback during prosthetic hand position control, using an array of vibrotactors, reporting an accuracy of 85.1% ± 2.2% for recognizing cubes of two different sizes (response time was not disclosed) [85]. Cheng *et* al. explored hand configuration recognition using a vibrotactile belt with different encoding strategies, with participants achieving their highest performance at 79.7% accuracy and an average time re-

quired for identification of 29.4 s using a synergy-based method [152]. Lastly, D'Anna *et* al. investigated remapped proprioceptive feedback delivered via direct neural stimulation, achieving 78% accuracy in an object size identification task using four cylinders of different diameters (response time was not disclosed) [17].

Encoding:

Since this is the first instance of hand proprioception feedback being provided in a non-homologous somatotopic manner, the selection of an encoding strategy was open-ended, with no direct precedents to follow. To address this challenge, inspiration was drawn from another domain where individuals must learn to interpret novel haptic information: *haptic reading*.

Comparing different haptic alphabets—such as Braille, Fishburne, and Moon—revealed three key principles for defining features that promote interpretability: (1) a limited number of features, (2) high discriminability between features, and (3) reliance on prior knowledge [153–156]. This analysis supports the use of an encoding strategy limited to two degrees of freedom, ensuring physiological congruence for a structured and interpretable proprioceptive feedback mechanism. By maintaining intuitive and distinguishable features based on physiology, this approach enhances the potential for effective integration into somatotopic feedback strategies for hand proprioception.

The set of features selected for this proof of concept could be optimized in the future to offer a maximum of prosthesis control performances while minimizing the cognitive load required to use a prosthetic hand. In particular, exploring alternative encoding schemes, spanning the biomimicry spectrum, could be interesting. Inspiration could be drawn from ProprioStim by Cimolato *et* al. [131], which focuses on developing of a framework to encode proprioception from electroneural and musculoskeletal models. At the other end, dimensionality reduction principles derived from machine learning and offering highly discriminable features without explicit physical meaning could also prove interesting [152].

Stimulation:

For each of the tests carried out, participants P1 and P5 recorded the poorest performances. This disparity can partly be explained by the fact that the range of electrical charge that can be delivered before muscle activation is lower for these participants, who have the smallest arms among the participants (see Table 4.3). As a result, the preliminary tests were unable to reach an intensity I = 10 before the appearance of movements in their hand. The range

of sensations experienced during the two tests was therefore restricted for these participants, which reduces the discriminability of the features and may be the source of a greater number of classification errors [71].

In future work, it would be valuable to explore the effect of varying the stimulation parameters used [14, 143] and electrodes size on the quality of the information transmitted. Additionally, although the present protocol involved brief stimulation bursts, future applications may require prolonged exposure during sustained grasps [157], increasing the risk of perceptual adaptation to neuromodulation. This potential limitation should be carefully considered. Finally, the risk of electromyographic signal contamination due to concurrent TENS application remains a critical challenge for the control of artificial limbs and warrants further attention.

4.5.2 Futures considerations

Transcutaneous electrical nerve stimulation provides a unique opportunity to assess the effectiveness of a somatotopic, non-homologous feedback strategy without the need for invasive intervention. As a versatile platform, it offers valuable insights that can be applied to other stimulation methods, including invasive approaches. A crucial next step is to investigate how this feedback strategy influences controllability and cognitive load when operating a robotic limb. The observed performance improvements with repeated exposure may also suggest underlying neuroplastic mechanisms, which warrant further investigation, particularly in the context of closed-loop control for grasping with an artificial limb. Given the known differences in sensory processing for perception and action [139], adjustments will likely be required when implementing closed-loop control in a grasping task. However, the results from this perceptual study are encouraging and provide a strong foundation for further research. One of the key advantages of our presented approach is its adaptability. The feedback strategy can be tailored to both the user's specific needs, i.e. conveying specific grasp types, and the robotic artificial limb being used, whether it has one or multiple degrees of freedom. Beyond prosthetic applications, this feedback method holds promise for other fields, including rehabilitation, gaming, virtual reality, and teleoperation. Exploring these possibilities could further refine the approach and enhance its impact.

4.6 Conclusion

This study presented the first use of TENS to convey non-invasive somatotopically mapped proprioceptive feedback for the hand, providing both a proof of concept and a preliminary

foundational architecture for future developments in sensory feedback integration. Following a standardized approach, a preprocessing algorithm and an encoding strategy were developed based on the selected stimulation method and the physical system under study—the robotic hand. Six healthy participants completed two tasks: an aperture discrimination task and a grasp type discrimination task. Across five sets of ten trials, they successfully identified apertures conveyed via median and ulnar nerve stimulation with an accuracy of 96.5% ± 2.3% and a response time of 0.04 s ± 0.13 s. Similarly, grasp types transmitted through concurrent stimulation were identified with an accuracy of 88.3% ± 1.2% and a response time of 0.44 s ± 0.27 s. Response times were computed as differential response times relative to those recorded when performing the same tasks with visual inputs, providing a direct comparison of performance across sensory modalities.

Future work on closed-loop control of a robotic hand incorporating this feedback will provide further insight into generalization to prosthetic users with limb-loss and its impact on mitigating common challenges such as low controllability and high cognitive load. Additionally, exploring its integration into other application domains could further establish its relevance in assistive technologies, rehabilitation, and human-computer interaction.

CHAPTER 5 ARTICLE 2: A FRAMEWORK FOR THE INTEGRATION OF NON-INVASIVE AND SOMATOTOPIC PHYSIOLOGICAL FEEDBACK IN MYOELECTRIC ARTIFICIAL LIMBS

This contribution enables for concurrent extraction of motion intent from muscle engagement and stimulation via TENS by addressing SO2: Integrate the developed feedback strategy into an EMG-driven closed-loop control framework to enable position control (See Figure 5.0).

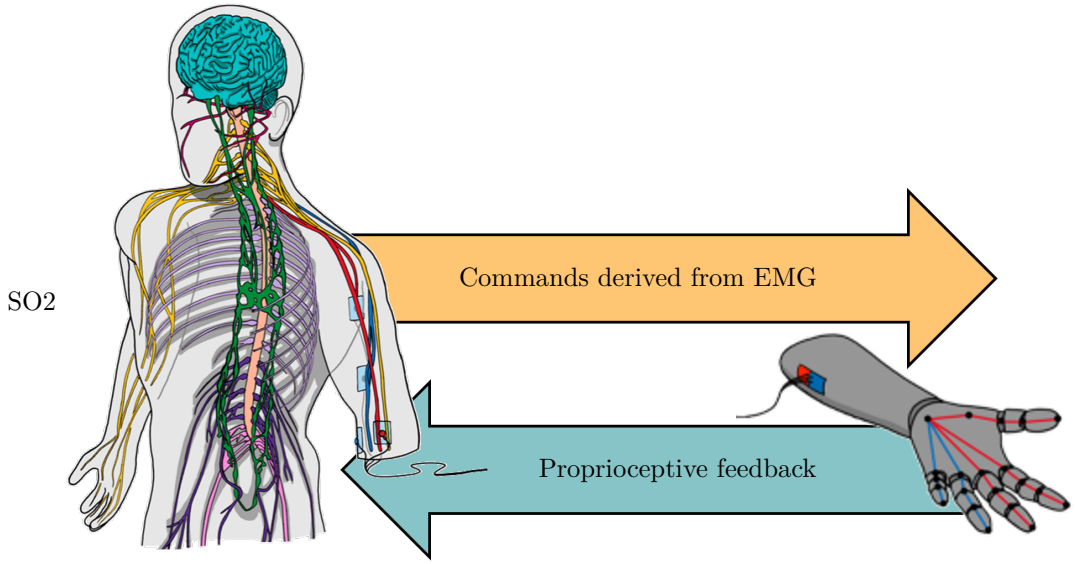


Figure 5.0 Illustration of the relationship (human-machine interface) between the user and the myoelectric prosthesis in this contribution related to SO2.

A Framework for the Integration of Non-Invasive and Somatotopic Physiological Feedback in Myoelectric Artificial Limbs

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Abstract

The lack of physiological feedback in myoelectric artificial limbs contributes to low user adherence. While transcutaneous electrical nerve stimulation (TENS) can provide non-invasive, real-time physiological feedback to users, large stimulation-related artifacts make it difficult to assess its impact on control. These artifacts overpower user movement intention and render surface electromyography unusable for generating commands. In this paper, a methodological framework for providing TENS-based physiological feedback concurrent to proportional control of a robotic hand is put forward and its application is demonstrated via a closed-loop robotic hand control task in which 20 able-bodied participants (10 with TENS feedback) modulated biceps activity to reach a desired hand aperture. After five trials of 60 s, comparisons in control performance and low-frequency envelope power revealed no significant difference between feedback conditions.

5.1 Introduction

Myoelectric robotic prostheses allow users to partially restore motor pathways by translating residual muscle activity into control commands for an artificial limb. Surface electromyography (sEMG) provides a practical interface for this purpose, allowing users to convey movement intentions through muscle activation. Despite major technological developments, prosthesis adoption remains limited. Up to 25% of individuals with upper-limb amputation do not use any prosthesis, and among those who do, fewer than 50% adopt a myoelectric device [12, 13]. The main reasons for declining or abandoning use include the extensive and complex training required for reliable control and the absence of physiological feedback, which is essential for closing the sensorimotor loop [3]. Without tactile and proprioceptive inputs, users experience poor control performance [15], increased reliance on vision [17], and high cognitive effort [18]. These limitations negatively affect performance in real-world scenarios where visual attention is divided or unavailable, and ultimately undermine confidence in the device [15]. Consequently, sensory feedback is identified by researchers and users alike as a key missing feature in current commercial prostheses [10].

Transcutaneous electrical nerve stimulation (TENS) offers a promising, non-invasive means of providing real-time physiological feedback to artificial limb users. It has proven effective in delivering somatotopic physiological sensations through surface electrodes across several perceptual tasks [49, 71, 130]. However, when assessing the potential of this stimulation approach for developing feedback strategies that enhance prosthesis integration and for enabling closed-loop control, a major implementation challenge arises. Since both sEMG and TENS occupy overlapping frequency bands, the stimulation pulses introduce large artifacts in the recorded sEMG [133]. In a closed-loop configuration using TENS as the feedback modality, it is crucial to preserve the volitional EMG signal (endogenously generated) while rejecting the stimulation artifacts (exogenous). Effective artifact suppression allows simultaneous acquisition of volitional EMG and delivery of sensory feedback, enabling users to control the artificial limb in real time without the stimulation signal overpowering the underlying neural activity [134].

To isolate the volitional EMG signal, data blanking was explored in both hardware and software strategies. Early hardware-based approaches include the "sample and hold" amplifier developed by Babb *et al.*, which eliminates stimulus artifacts by storing the mean value of the signal and maintaining it during the stimulation period [135]. Among software-based methods, Dosen *et al.* used time-division multiplexing, performing the stimulation and recording in dedicated, non-overlapping time windows [158]. Hartmann *et al.* applied artifact blanking, in which data segments affected by stimulation are removed or replaced.

This approach restored classification performance to near artifact-free levels in closed-loop myoelectric prosthesis control using electrotactile feedback [136].

Hambly *et al.* evaluated the effectiveness of several filtering approaches in removing electrical stimulation artifacts, including high-pass, adaptive, and comb filters, through simulation and found that adaptive and comb filters best estimated volitional muscle activity during electrical stimulation. The comb filter introduced less delay, making it preferable for real-time use, and combining it with blanking or interpolation techniques was recommended for continuous decoding of volitional EMG under stimulation [134]. Frigo *et al.* applied a comb filter, with and without blanking, to remove stimulus-correlated components [159]. Pilkar *et al.* implemented a related strategy by combining notch filters at the stimulation frequency and its harmonics with empirical mode decomposition to enhance artifact suppression [160]. Despite these advances, Yu *et al.* noted that most artifact suppression techniques have not yet been integrated into practical methodological frameworks for closed-loop prosthetic control and therefore proposed a hybrid approach combining hardware blanking with software filtering to support real-time implementation [137]. Existing filtering approaches have therefore focused on functional electrical stimulation (FES) or on TENS systems that rely on hardware blanking for practical implementation.

Building on these findings, it is crucial to consider the composition of the sEMG signal during electrical stimulation. Outside of the volitional EMG, a stimulation pulse can introduce two additional components into the recording, both interfering with the reliable extraction of motor intent for control. These distinct sources of exogenous signal contamination are often grouped under the term artifact in the broader literature. The first is the M-wave, which is the exogenous muscle response produced when motor units are recruited by the stimulus. The second is the stimulation artifact, which is the unwanted electrical potential delivered by the stimulator. In FES, these components overlap in both time and frequency, and isolating volitional EMG requires suppressing the stimulation artifact and the evoked M-wave. In contrast, TENS is applied below motor threshold. As a result, TENS does not elicit an M-wave and the only exogenous contamination present in the recording is the stimulation artifact. This difference reduces the complexity of separating volitional EMG from stimulation-related noise. We hypothesize that a purely computational filtering approach, eliminating the need for hardware blanking, robustly suppresses TENS stimulation artifacts. This could enable stable closed-loop artificial limb control while significantly streamlining system architecture.

In what follows, we present a software-based filtering framework that enables real-time removal of stimulation-related artifacts during TENS, allowing simultaneous sEMG-based control and delivery of physiological feedback. We demonstrate the potential of this framework in

a closed-loop robotic hand control task in which participants modulated their biceps activity to reach targeted hand apertures.

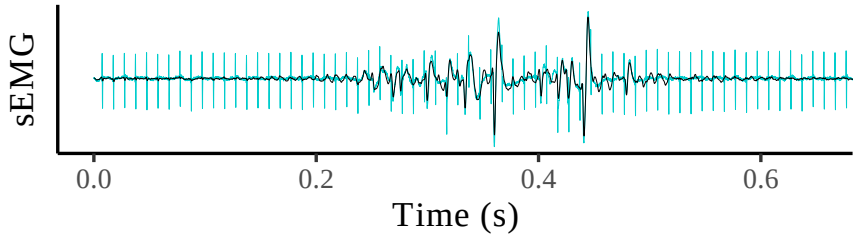
5.2 Methods

5.2.1 Signal Processing and Artifact Suppression

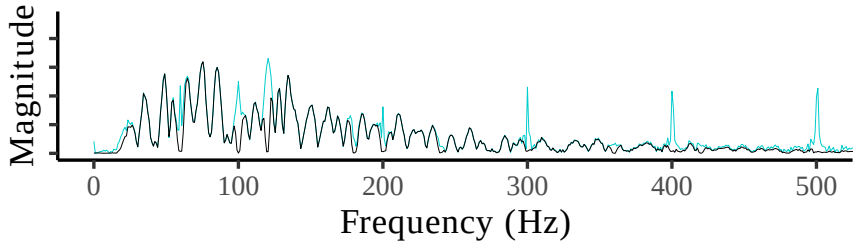
To extract the user's movement intention during simultaneous sEMG acquisition and TENS delivery, the raw bipolar EMG signal was processed through a cascaded filtering pipeline designed to suppress stimulation artifacts while preserving volitional muscle activity. First, a fourth-order Butterworth band-pass filter (20-500 Hz) retained physiological EMG components and attenuated low-frequency motion artifacts and high-frequency noise. To remove periodic interference, as illustrated in Fig. 5.1, a set of narrow second-order Butterworth band-stop filters was applied at 60 Hz, at the TENS stimulation frequency, and their harmonics (stopband width ± 2 Hz). After this stage, the signal was rectified and low-pass filtered at 5 Hz using a fourth-order Butterworth filter to obtain a smooth envelope suitable for real-time proportional control of the robotic hand.

5.2.2 Participants

Twenty able-bodied adult volunteers were recruited and randomly assigned to either a control group receiving no additional feedback (-TENS: 5 females, 5 males; age = 27.2 ± 9.3 years), or a group receiving TENS-based artificial feedback (+TENS: 5 females, 5 males; mean age = 26.7 ± 5.0 years). Participants reported no neurological or medical conditions that could affect safe participation, and had no dermatological issues that could be exacerbated by electrodes or stimulation. Additional exclusion criteria included implanted or external electronic medical devices, and pregnancy (as the safety of the Hasomed P24 during pregnancy has not been established). All participants selected for the study provided written informed consent, and demonstrated sufficient prosthesis control performance (motor control) and adequate sensory perception (in the +TENS group with TENS), during preliminary assessments.



(a)



(b)

Figure 5.1 Effect of the filtering pipeline on sEMG recorded for one muscle contraction during TENS delivery. For both subfigures, the raw sEMG and artifact-suppressed sEMG signals are respectively in cyan and black. (a) Temporal sEMG trace before and after artifact suppression. Periodic stimulation pulses dominate the raw signal and obscure volitional muscle activity. The filtered output preserves physiological EMG while eliminating stimulation-induced transients. (b) Frequency-domain representation of the raw and filtered signals. Narrowband components at the stimulation frequency and its harmonics are strongly attenuated, while the broadband sEMG content is preserved.

5.2.3 Closed-Loop Control

The closed-loop evaluation was performed using an aperture control task in which participants modulated their biceps activity to repeatedly grasp a cylindrical object during each trial (Fig. 5.2). The goal of this experiment was to assess the effectiveness of the artifact suppression pipeline under realistic closed-loop conditions rather than to evaluate motor-learning or sensory feedback integration. For this reason, all trials were carried out with visual feedback available. Each participant completed five 60 s trials. Throughout each trial, participants were instructed to prioritize accurate grasps by minimizing grasping force, mimicking the handling of a fragile object. The cylinder diameter was set to 50% of the hand's maximum aperture to increase sensitivity to control errors and to avoid ceiling effects in performance measures. All fingers except the thumb moved together, and the aperture of the middle finger was recorded as the control output. A cutout at the middle finger's contact point allowed aperture measurement even during overshoot and provided a clear visual reference

for the target aperture. Performance for each participant was quantified as the absolute error between the measured aperture and the target aperture, averaged across all grasp repetitions within each trial.

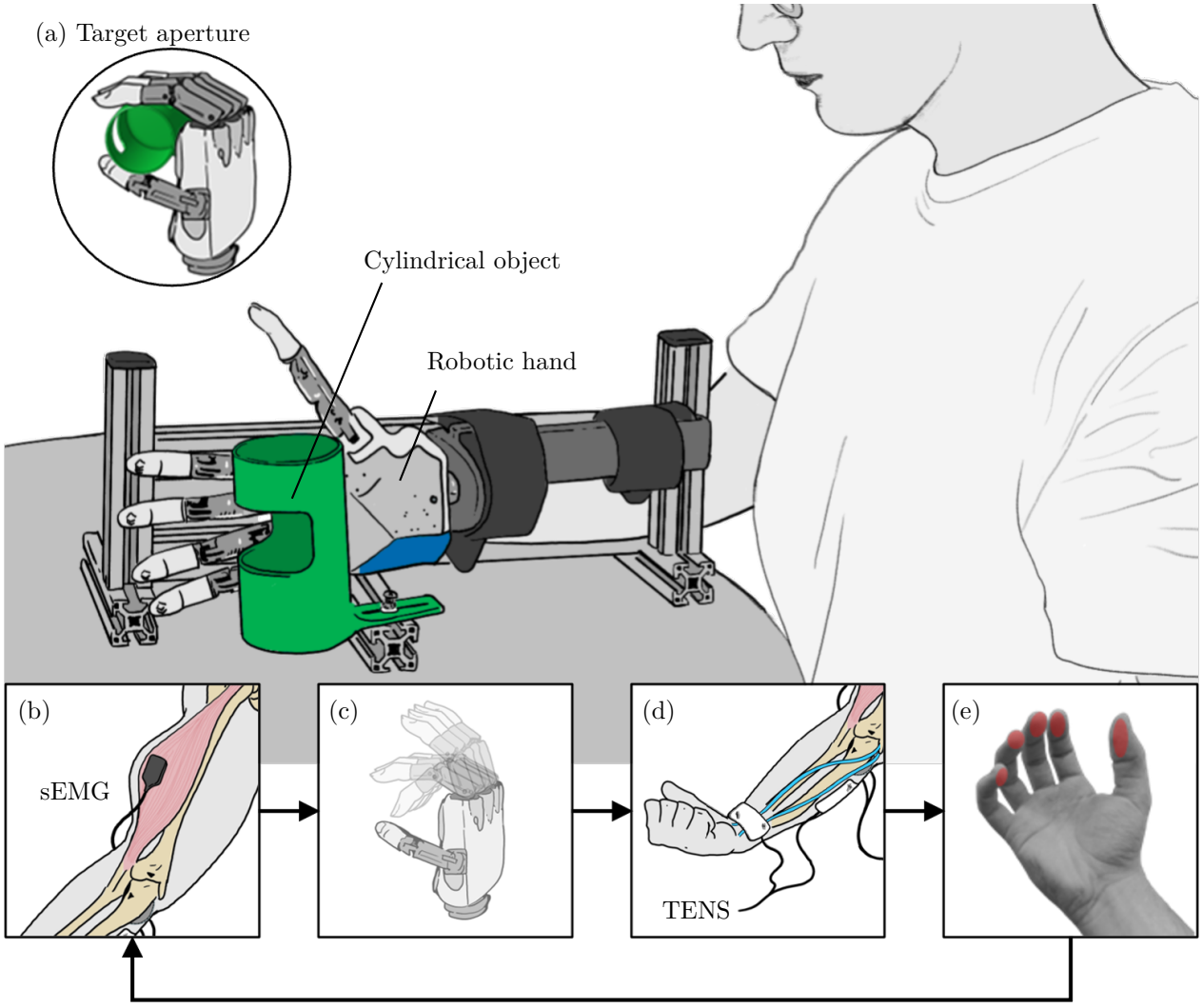


Figure 5.2 Overview of the closed-loop robotic hand control task performed to demonstrate the stimulation-related artifact removal. (a) Participants modulated their biceps activity to minimize the error between the outer diameter of a cylindrical object (reference aperture) and the robotic hand aperture. (b) sEMG signals were processed into motor commands. (c) The motor commands were delivered to the embedded low-level PID controller that actuated the hand. (d) In addition to visual feedback, participants in the +TENS group received artificial proprioceptive feedback. (e) This artificial feedback, generated from real-time position sensor readouts, evoked somatotopically appropriate sensations in all fingers concurrently.

Robotic Hand

A self-contained robotic hand (IH2 Azzurra, Prensilia, Italy) equipped with integrated position sensors, actuators, and an internal PID controller for low-level position control was used. The robotic hand was mounted on an aluminum support rather than on the participant's limb to limit muscle fatigue, given the hand's mass and the duration of the experimental protocol. The participant's biological right hand was placed beside the device and concealed from view.

Command generation

The robotic hand commands were computed from a single differential sEMG signal recorded with a Bagnoli sensor (Delsys, USA) connected to a Bagnoli-4 EMG system. Acquisition was performed using custom multithreaded Python software (3.12) built around the NI-DAQmx API and a NI-9239 module housed in a cDAQ-9171 chassis (National Instruments, USA). One bipolar sEMG channel was placed over the right biceps brachii. Following established recommendations [9], the sensor was positioned on the muscle belly at the midpoint between the acromion and the cubital fossa and aligned with the muscle fibers (Fig. 6.2. (b)). A reference electrode was placed on the olecranon. All electrode sites were cleaned with alcohol before placement to ensure low impedance at the skin-electrode interface. The sEMG signal was sampled at 25 kHz and processed through the previously described signal processing algorithm (subsection 5.2.1) to extract the envelope. For control, the envelope was normalized following a short calibration performed in the absence of stimulation, even for +TENS participants, and mapped linearly to an aperture setpoint for the robotic hand controller. This allowed participants to proportionally modulate hand aperture through their muscle activation (Fig. 6.2. (c)). The command signal was transmitted to the hand at a downsampled frequency of 100 Hz.

TENS Feedback

Finger positions from the robotic hand's integrated sensors were streamed in real time to the custom Python software to extract joint angle measurements for each finger. These measurements provided a continuous representation of the hand configuration. The multidimensional sensor data were reduced to a single scalar metric that varied linearly with hand aperture. This encoding scheme preserved task-relevant information while keeping the feedback intuitive and consistent with commonly used approaches in closed-loop prosthesis control [17, 89].

For the +TENS group, encoded proprioceptive information was conveyed through TENS. A programmable stimulator (P24, Hasomed GmbH, Germany) delivered charge-balanced, rectangular-wave biphasic currents to ensure net-zero injected charge and minimize electrochemical side effects at the electrode–skin interface [144].

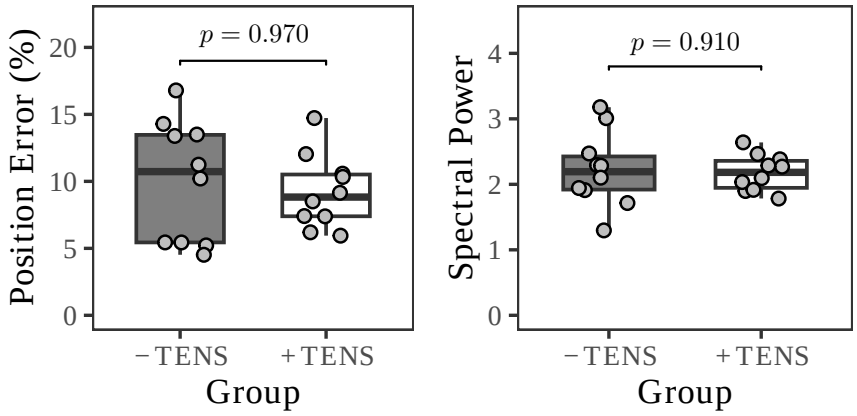
Stimulation electrodes were placed on the right forearm. The active electrode was positioned at the volar wrist, and the return electrode was placed on the ventral upper forearm adjacent to the ulna at the cubital tunnel (Fig. 6.2. (d)). These locations were selected because the median and ulnar nerves travel superficially in this region, which supports activation of their distal receptive fields while limiting unintended recruitment of proximal fibers [161]. Participants verbally reported the projected location of evoked sensations to confirm that percepts were stable and involved all fingers simultaneously (Fig. 6.2. (e)). A single stimulation channel was used to recruit both nerves. Large-area electrodes (PALS 5 cm × 9 cm, Axelgaard, USA) were used to distribute current and reduce current density [162].

To align with psychophysical limits, where discrimination performance significantly degrades beyond three intensity levels [71], hand aperture feedback was discretized into three levels, corresponding to 25%, 50%, and 75% of maximum closure. This provided adequate resolution for task-relevant feedback while maintaining perceptual reliability. Stimulation parameters were individualized to balance discriminability, comfort, and safety. Intensity was modulated by varying pulse width at a fixed frequency (100 Hz) and constant current amplitude. Three non-overlapping pulse width values were selected at a fixed current amplitude to encode the discretized aperture levels. Final parameter choices were confirmed in passive perception tests and in short preliminary closed-loop trials to ensure that the three levels remained discriminable during movement.

5.3 Results

To determine whether stimulation-related artifacts affected closed-loop proportional control performances, we compared both the control error and the frequency content of the sEMG-derived command signals between feedback condition groups. Statistical comparisons used median values computed across all five 60 s trials for every participant, with trials consisting of multiple grasps. Fig. 5.3. (a) illustrates the absolute position error relative to maximum aperture for each participant (circular markers), computed as the absolute error relative to the maximum aperture. Control accuracy did not differ significantly between groups (two-sided Wilcoxon Rank-Sum Test, $U = 51$, $p = 0.970$), indicating that stimulation did not impair voluntary aperture regulation during the task. We then examined whether stimulation introduced envelope distortions that bypassed the filtering pipeline. Since the power of the

normalized EMG envelope is predominantly concentrated below 5 Hz, we quantified power between 0 and 5 Hz, which captures the slow variations that drive the proportional command signal. Any residual stimulation artifact would appear as increased energy or a shifted baseline in this band. As shown in Fig. 5.3. (b), envelope power did not differ significantly between feedback conditions (two-sided Wilcoxon Rank-Sum Test, $U = 52$, $p = 0.910$). These findings suggest that stimulation did not noticeably alter the low-frequency structure of the envelope within the bandwidth relevant to the control. Overall, the findings indicate that the proposed framework allows TENS-based feedback to be delivered without compromising the sEMG command signal or proportional control accuracy.



(a) (b)

Figure 5.3 Control performance and sEMG-derived command signal stability. (a) Median absolute position error across participants (-TENS, median: 10.70 % (IQR: 8.03 %); +TENS, median: 8.83 % (IQR: 3.12 %)). (b) Low frequency envelope power (0–5 Hz) of the sEMG-derived command signal (-TENS, median: 2.19 (IQR: 0.51); +TENS, median: 2.18 (IQR: 0.41)). The proposed filtering method enables TENS-based feedback without degrading the command signal or proportional control performance.

5.4 Conclusion

This work demonstrated that real-time software filtering can enable proportional sEMG control of a robotic hand during TENS, allowing physiological feedback to be delivered without disrupting the extraction of the volitional EMG signal used for commands. Ten participants using TENS-based feedback achieved control accuracy comparable to the matched control group without TENS feedback, and the low frequency power of the EMG envelope was also similar across groups. These findings validate our hypothesis that software-only filtering can suppress stimulation artifacts to a sufficient level for robust closed-loop artificial limb con-

trol, eliminating the need for specialized artifact-removal hardware. This framework provides a practical foundation for future studies involving non-invasive physiological feedback and artificial limb integration.

CHAPTER 6 ARTICLE 3: NON-INVASIVE SOMATOTOPIC PROPRIOCEPTIVE FEEDBACK FOR CLOSED-LOOP ROBOTIC HAND POSITION CONTROL

This contribution closes the loop on myoelectric control and addresses SO3: Validate the effects of the developed feedback strategy on control accuracy, visual reliance, cognitive load, and learning rate during robotic hand grasping tasks (See Figure 6.0).

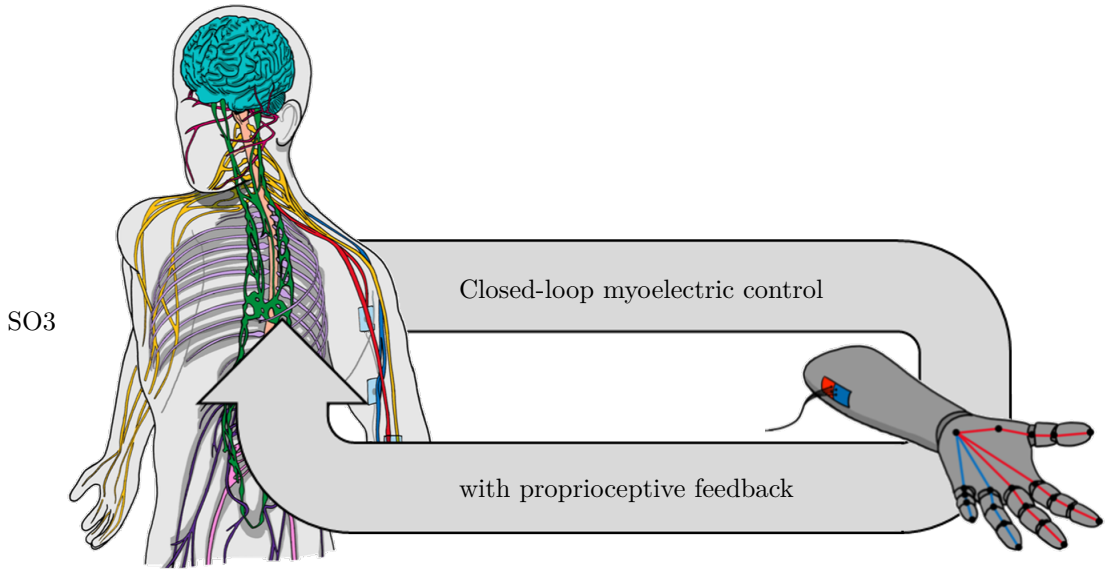


Figure 6.0 Illustration of the relationship (human-machine interface) between the user and the myoelectric prosthesis in this contribution related to SO3.

Non-Invasive Somatotopic Proprioceptive Feedback for Closed-Loop Robotic Hand Position Control

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Abstract

Objective: Current robotic prostheses developed for individuals with transradial amputation often lack physiological feedback, particularly proprioceptive information, which limits control precision and increases reliance on vision. *Approach:* This study investigates the effect of introducing non-invasive somatotopic proprioceptive feedback using transcutaneous electrical nerve stimulation (TENS) on robotic hand position control. Twenty healthy participants were divided into two groups: one receiving TENS-based feedback and one without feedback. Participants performed an aperture control task under visual and non-visual conditions, with some trials including a concurrent Stroop task to assess cognitive load. We hypothesized that providing non-invasive somatotopic proprioceptive feedback via TENS mitigates key control and integration challenges, leading to improved accuracy, faster learning, and reduced reliance on vision, without increasing cognitive demands. Under visual deprivation, participants receiving TENS feedback achieved significantly smaller aperture control errors than those without feedback, both under alternating visual conditions ($p < 0.001$) and under prolonged visual deprivation conditions ($p = 0.017$). From the very first trial, TENS-based feedback enabled control accuracy comparable to that with visual input. Under dual-task conditions, the +TENS group maintained high cognitive and motor performance, indicating efficient integration of the artificial feedback. *Significance:* These findings highlight the potential of noninvasive somatotopic proprioceptive feedback delivered through TENS to provide physiologically meaningful information and support future strategies for restoring proprioceptive function in prosthetic hand users.

6.1 Introduction

The upper limbs play a central role in activities of daily living, providing the ability to reach, grasp, and manipulate objects in the environment. These coordinated actions are fundamental to functional independence and underlie many aspects of human interaction. For individuals with transradial amputation, a major upper limb amputation involving removal of the hand and part of the forearm [7], prosthetic hands can be used to restore dexterous action capabilities approaching those of an intact biological hand [138]. In particular, myoelectric robotic prostheses attempt to restore function by artificially reestablishing motor pathways: movement intentions are decoded from electrical activity in residual limb muscles and transmitted to the device, which then executes the intended motion [163].

Despite significant technological advances, prosthesis adoption remains limited. Between 10% and 25% of individuals with upper-limb amputation do not use any prosthesis, and among those who do, only 37.5% to 45% adopt a myoelectric device [12, 13]. Those who decline or discontinue use often cite the long and complex training required for reliable control and to the absence of physiological feedback [15]. Effective motor control is not achieved through efferent commands alone but relies on physiological feedback, particularly tactile and proprioceptive information, to close the sensorimotor loop [3]. Without restored sensory pathways, voluntary movements become difficult to execute and result in poor control performance [14–16], leading to overreliance on vision [17] and increased cognitive effort [18], both of which can limit performance in real-world scenarios where visual attention is divided or unavailable, and therefore undermine confidence in the device [15]. Accordingly, researchers and users alike identify sensory feedback as one of the most critical missing features of commercial prostheses [10].

Restoring sensory feedback through artificial methods has emerged as a central focus in research on prosthetic limbs, offering a path to alleviate persistent limitations of current devices. Efforts have largely concentrated on tactile feedback, recreating surface-level sensations to improve awareness of contact and interaction with objects [41]. By contrast, the restoration of proprioceptive feedback has received less emphasis [56, 57], despite its critical role in motor control, largely because artificially evoking reliable proprioceptive cues remains challenging [33]. Proprioception not only improves movement accuracy and efficiency [58] but also reinforces the sense of agency by aligning motor intention with sensory consequences, a key factor in user acceptance and long-term integration of prosthetic technology [61, 62].

Artificial sensory feedback strategies can be broadly positioned along a biomimicry spectrum, with sensory substitution at one end and biomimetic approaches at the other. Vibrotac-

tile [79,80,85,86] and electrotactile stimulation [97–99], along with linear and rotational skin stretch [90,91,93,94], have been widely studied as sensory substitution methods for relaying proprioceptive information relevant to prosthetic control. These techniques transmit information through tactile surrogates, producing sensations that differ in location or modality from the biological input. Sensory substitution can promote prosthesis-related embodiment [80,81] after sufficient training, but it remains non-intuitive, cognitively demanding and difficult to integrate with concurrent sensory channels [82, 83]. In contrast, biomimetic strategies aim for homology and somatotopy, restoring sensations in their original modality and anatomical location. By closely replicating peripheral inputs, this approach is theorized to facilitate seamless integration by the central nervous system, allowing the prosthesis to approximate the role of the biological hand [44]. Homologous and somatotopic feedback has been shown to improve discrimination acuity, enhance information processing, and reduce training demands [45, 71]. To date, such strategies have been implemented primarily through invasive electrical stimulation of peripheral nerves using implanted electrodes [19,70]. While effective, these approaches face significant barriers, including surgical risks, concerns over long-term stability, and user reluctance [71–74]. As a result, recent research has turned toward non-invasive alternatives. Two persistent constraints limit biomimetic approaches, regardless of whether stimulation is invasive or non-invasive; neural embodiment remains problematic, as neuroimaging shows that the brain consistently categorizes prostheses as distinct from biological limbs; this dissociation is observed across cosmetic and active devices and increases with prosthesis use in activities of daily living, suggesting that full embodiment may remain unattainable even with perfect mimicry [164]. Implementation is also constrained, and the difficulty is especially pronounced for proprioception. Current stimulation technologies, from surface and percutaneous systems to implanted extraneural or intraneural electrodes, cannot selectively and reliably recruit proprioceptive afferents, creating a fundamental barrier to truly biomimetic restoration of this submodality [41,68,69].

To address the limitations of both ends of the biomimicry spectrum, the present study explores a feedback strategy positioned at an intermediate point. We leverage transcutaneous electrical nerve stimulation (TENS) to deliver feedback that combines somatotopic mapping and proprioceptive encoding about hand aperture through non-invasive stimulation of residual peripheral nerves [128]. This application of TENS offers a compromise between substitution and biomimicry by capitalizing on the preserved neural representation of the biological hand [132, 165] while avoiding the surgical risks of invasive methods, thereby improving safety and user acceptance. While TENS has previously been explored to evoke tactile sensations conveying contact-related information [45, 71, 130], and to provide proprioceptive sensations in perceptual discrimination tasks [49], it has not yet been implemented

to convey somatotopic proprioceptive information in a closed-loop control paradigm, where continuous real-time sensorimotor integration is required. We hypothesized that providing non-invasive somatotopic aperture feedback mitigates key control and integration challenges, leading to better control accuracy, faster learning, and reduced reliance on vision, without increasing cognitive demands.

The present study evaluates this hypothesis through an experimental paradigm designed to probe both motor control and cognitive demand when operating a robotic hand with and without artificial physiological feedback. It constitutes the first demonstration of closed-loop robotic hand control using non-invasive TENS-based somatotopic proprioceptive feedback. Participants performed a position control task requiring them to modulate hand aperture in order to grasp a fragile object of fixed diameter. Control performance was assessed under varying sensory conditions, including trials with and without visual feedback, and in some cases while participants simultaneously engaged in a secondary cognitively demanding task. This design enabled us to quantify the effect of the proposed feedback strategy on grasp accuracy, reliance on vision, and cognitive load, thereby providing a comprehensive assessment of its potential to inform prosthesis usability.

6.2 Methods

6.2.1 Experimental Design and Procedures

The experiment was designed to test the hypothesis that providing non-invasive somatotopic aperture feedback would mitigate critical control and integration challenges, leading to better control accuracy, faster learning, and reduced reliance on vision, without increasing cognitive demands.

Design overview and Participants

Twenty participants were randomly assigned to one of two groups, distinguished by the sensory feedback modalities available during the experiment. Group -TENS performed the experimental tasks with and without visual feedback according to the block structure, while Group +TENS performed the tasks under the same visual conditions but received additional somatosensory feedback via TENS. This design enabled isolation of the specific contribution of the developed physiological feedback and facilitated direct comparison of its impact on control performance, cognitive load, and retention relative to visual feedback alone.

Experimental Tasks

The primary task was an aperture control exercise in which participants, for the duration of each trial, repeatedly closed the robotic hand through muscle engagement to grasp a cylindrical object and then reopened it. Participants were instructed to prioritize accurate and stable grasps (closing the hand just enough to securely contact the object) rather than simply maximizing the number of grasps. The object was presented as fragile, requiring the hand to close tangentially to its surface: insufficient closure resulted in failure to grasp, whereas excessive closure would theoretically break the object. The cylinder diameter was fixed at 50% of the hand's maximum aperture to increase sensitivity to control errors while avoiding ceiling effects in statistical analyses. Primary task performance for each participant was calculated as the absolute aperture error, compared to the desired aperture of 50%, and averaged across all grasp repetitions for that trial. Although rigid, the object featured a cutout at the middle finger's contact point, which enabled monitoring of aperture even during overshoot. This design provided a clear visual reference for the aperture setpoint while avoiding potential confounds associated with deformable objects. During the task, all fingers except the thumb moved together, but only the middle finger's aperture was recorded to quantify performance. The task remained constant across all trials, while the surrounding experimental conditions varied.

The secondary task was a computerized Stroop test used to assess cognitive load. This paradigm was selected for its strong visual interference effects and its ability to reveal changes in task automaticity. It also reflects real-world situations where prosthesis users must divide visual attention while performing concurrent motor tasks [166]. Color words (red, green, yellow, or blue) were displayed every 1.5 s in either congruent or incongruent font colors, and participants were instructed to vocally report the font color as quickly and accurately as possible. Vocal responses were recorded and analyzed offline using automated speech recognition (Vosk Speech Recognition Toolkit) with manual verification to extract response times and accuracy [167]. To ensure balanced effort across the primary and secondary tasks, participants were instructed that their performance would be scored equally on the quality of grasps and on Stroop test accuracy.

Experimental Procedure

The experiment consisted of 20 consecutive trials of 60 seconds each, organized into four blocks (Figure 6.1). Two Cognitive Assessment Blocks (trials 1–2 and 13–14) required concurrent execution of a primary motor task and a cognitively demanding secondary task to evaluate cognitive load during hand control and potential learning effects. The Alternating

Feedback Block (trials 3–12) involved the primary task under alternating visual and no-visual feedback conditions to assess how repeated exposure to restricted feedback modalities influenced control performance over time. In the final Prolonged Visual Deprivation Block (trials 15–20), participants performed one trial of the primary task with visual feedback, followed by five consecutive trials without visual feedback to assess retention of control performance in the absence of vision.

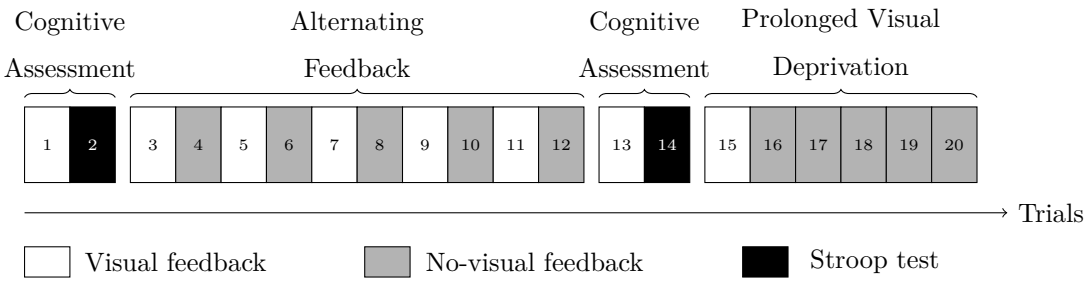

Figure 6.1 Schematic representation of the experimental timeline. Participants completed 20 trials divided into four blocks. Cognitive Assessment Blocks (trials 1–2 and 13–14) combined the primary motor task with a Stroop test to evaluate cognitive load at the start of the experiment and after repeated exposure to feedback and training. The Alternating Feedback Block (trials 3–12) required execution of the primary task under alternating visual and no-visual feedback conditions to assess adaptation. Finally, the prolonged Visual Deprivation Block (trials 15–20) evaluated control performance in the absence of visual feedback. Each block was initiated with a trial including visual feedback.

6.2.2 Experimental Setup

The experimental setup was structured as a closed-loop control system (Figure 6.2). The aperture setpoint (θ_{ref}) corresponded to the hand aperture required to grasp the fragile cylindrical object without breaking it. Participants acted as high-level controllers, generating motor commands through biceps activation to minimize the error between the actual hand aperture and θ_{ref}. Perception of this error relied on the available feedback modalities, which varied according to group and trial (visual, TENS or visual and TENS). To ensure that only the intended feedback modalities were used, participants were isolated from other sensory cues. Noise-canceling headphones playing white noise were used for acoustic isolation, foam squares placed under the setup isolated the participant from vibration, and when required, participants were visually isolated.

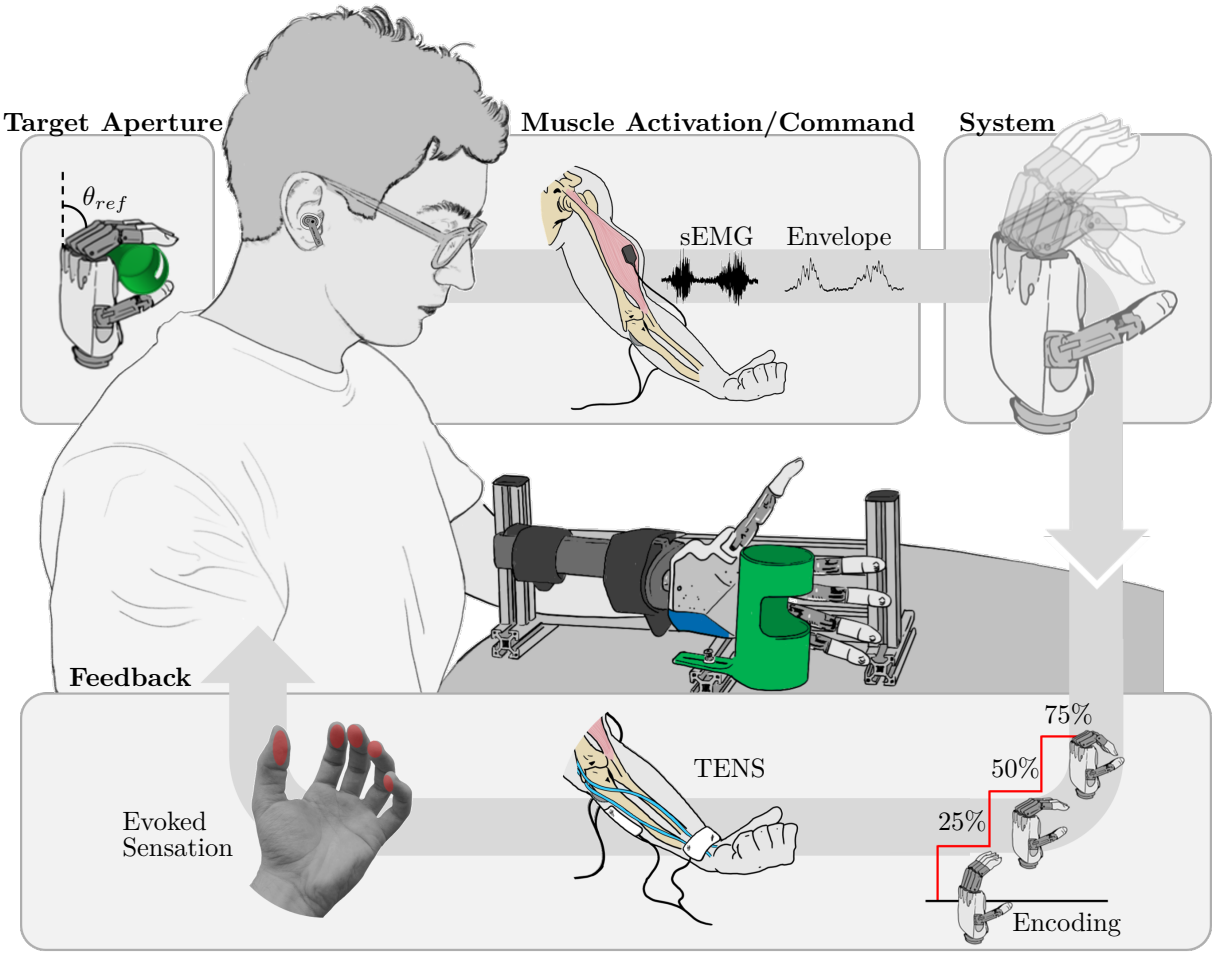

Figure 6.2 Overview of the closed-loop experimental setup. Participants acted as the high-level aperture controller of the robotic hand, executing the grasping task by minimizing the perceived error between the cylindrical object's outer diameter (reference aperture, θ_{ref}) and the actual hand aperture. sEMG signals recorded from the biceps were processed into motor commands and delivered to the embedded low-level PID controller for the hand's actuators. Participants in the –TENS group received only visual feedback of hand aperture, whereas participants in the +TENS group received additional proprioceptive feedback via TENS applied simultaneously to the median and ulnar nerves. This artificial feedback, generated from real-time position sensor readouts, evoked somatotopically appropriate sensations referred to the fingers. To ensure that only the intended feedback modalities were available, participants were acoustically, vibrationally, and, when required, visually isolated from external cues.

Muscle Activation and Command

The robotic hand was driven using a single differential sEMG channel (Bagnoli-4 EMG system, Delsys, USA) acquired through a custom multithreaded Python (3.12) software developed around NI-DAQmx (NI-9239 and cDAQ-9171, National Instruments, USA). One bipolar sEMG channel was recorded from the biceps brachii using a Bagnoli sensor (Delsys, USA) with a fixed inter-electrode distance. In line with established recommendations [9], the sensor was positioned over the muscle belly at the midpoint between the acromion and the cubital fossa, aligned with the fiber direction. A reference electrode was placed over the olecranon. To ensure low impedance and signal quality, the skin at all electrode sites was cleaned with alcohol prior to placement.

Data were sampled at 25 kHz and processed through a cascaded filter pipeline designed to extract the volitional EMG signal. A 4th-order Butterworth band-pass filter (20 to 500 Hz) reduced broadband noise, and a series of 2nd-order notch filters with ± 2 Hz stopbands were applied at 60 Hz and its harmonics to suppress power line interference. The signal was then rectified and low-pass filtered at 5 Hz to extract the EMG envelope. For control, the EMG envelope was linearly mapped to an aperture setpoint for the robotic hand's low-level controller and transmitted at 100 Hz, enabling participants to proportionally modulate the hand aperture through their muscle activity. The introduction of TENS-based feedback required additional filtering to suppress stimulation-related artifacts, which would otherwise overpower voluntary EMG potentials and bias the command signal [17]. An additional set of 2nd-order Butterworth notch filters (±2 Hz stopbands) was implemented at the TENS stimulation frequency (100 Hz) and its harmonics to suppress stimulation-related artifacts while preserving the integrity of the volitional EMG signal.

System (Robotic Hand)

The controlled system was a self-contained robotic hand (IH2 Azzurra, Prensilia, Italy) equipped with position sensors, actuators, and an internal low-level position controller. The hand was mounted following approaches similar to Ajoudani *et al.* [168] and Schone *et al.* [140]. However, to account for the experimental design (tasks, duration) and the hand's mass, it was mounted on an aluminum support rather than attached to the participant's forearm, thereby minimizing muscular fatigue. The participant's biological right hand was positioned beside the robotic hand and concealed from view, following approaches used to promote integration of artificial limbs [169].

Feedback

The feedback strategy was developed according to the standard architecture outlined in Lecompte *et al.*, consisting of three main stages: preprocessing, encoding, and stimulation [42]. The robotic hand was equipped with five position sensors that monitor finger movements in real time. These signals were processed via a custom Python (3.12) software to extract aperture measurements for each finger, thereby providing the encoding algorithm with a continuous representation of the hand's configuration.

Because the study focused on cylindrical grasps, hand aperture was chosen as the primary feature to represent hand configuration. The encoding scheme reduced the multidimensional sensor data to a single degree of freedom that varied linearly with aperture. This reduction preserved the task-relevant information while keeping the feedback intuitive, consistent with previous approaches (e.g., D'Anna *et al.* [17]; Vargas *et al.* [89]). The encoded proprioceptive information was conveyed through TENS. A programmable stimulator (P24, Hasomed GmbH, Germany) delivered charge-balanced, rectangular-wave biphasic currents to ensure net-zero injected charge and minimize electrochemical side effects at the electrode–skin interface [144].

Electrodes were positioned on the right forearm following a protocol adapted from D'Anna *et al.* [71], consistent with the approach used in our earlier study [49]. The active electrode was placed at the volar wrist near the hand, while the counter electrode was positioned on the ventral upper forearm near the cubital tunnel and adjacent to the ulna. These sites were selected because the median and ulnar nerves run superficially, enabling activation of their distal receptive fields while limiting unintended recruitment of proximal fibers (e.g., muscle contractions or nociceptive fibers) [161]. Participants verbally reported the location of evoked sensations to confirm that they were consistently perceived across all fingers simultaneously. A single stimulation channel was sufficient to concurrently recruit both nerves. Large-area electrodes (PALS 5 cm $\times$ 9 cm, Axelgaard, USA) were used to lower current density at the skin interface, thereby minimizing local cutaneous sensations, improving overall comfort, and helping to slow the onset of sensory adaptation [50, 162, 170].

Previous psychophysical studies and preliminary piloting demonstrated that participants can reliably discriminate up to three distinct levels of TENS intensity, while performance deteriorates when a fourth level is introduced [71]. Accordingly, hand aperture was discretized into a three-level step function (25%, 50%, and 75% of maximum closure). This provided sufficient resolution to convey task-relevant aperture information while maintaining perceptual reliability.

Stimulation parameters were optimized individually to balance discriminability, comfort, and safety. Perceived intensity scales with injected charge (the product of amplitude and pulse width) [71, 143], while frequency primarily affects sensation quality. Because the stimulator provided finer resolution for pulse-width modulation, amplitude was held constant within a comfortable range (2.0–5.0 mA depending on sensitivity), frequency was fixed at 100 Hz, and pulse width was varied to encode intensity. During a psychophysical calibration, participants received brief trains of stimulation while pulse width was incremented from 25 to 800 μs in 25 μs steps. The upper limit tested was reduced as needed to avoid discomfort, ensuring that only comfortable and safe intensities were explored. After each train, they verbally reported sensation intensity and quality (e.g., tingling, pressure, discomfort). From these data, three non-overlapping pulse-width settings were selected to encode the discretized aperture levels. Final parameter choices, detailed in Table 6.1, were validated both in passive perception trials and in preliminary closed-loop control to ensure discriminability under dynamic task conditions.

Table 6.1: Stimulation parameters selected to modulate the intensity of the evoked sensation for each +TENS participants, based on the aperture conveyed. I is the current in mA while pw is the pulse-width in μs. For apertures between 0% and 25%, there was no stimulation.

	Parameter	P6	P7	P8	P10	P13	P16	P18	P20	P23	P24	Mean ± Std
Aperture	I	4.0	4.0	4.0	3.0	2.0	5.0	3.0	4.0	5.0	3.0	3.7 ± 0.9
$[25\%, 50\%[$		300	400	300	250	325	275	350	400	200	300	310 ± 57
$[50\%, 75\%[$	pw	450	550	500	500	425	400	450	600	500	500	488 ± 54
$[75\%, 100\%[$		650	750	650	750	500	525	650	800	800	700	678 ± 94

6.2.3 Participants

Twenty healthy volunteers were recruited and randomly assigned to either the -TENS control group (5 females, 5 males; age = 27.2 ± 9.3 years), or the +TENS group (5 females, 5 males; age = 26.7 ± 5.0 years). All participants were over 18 years of age, reported no neurological or medical conditions that could compromise safe participation, and had no dermatological issues that could be aggravated by electrodes or stimulation. Additional exclusion criteria included implanted or external electronic medical devices, pregnancy (as the safety of the Hasomed P24 during pregnancy has not been established), and color vision deficiencies that prevented reliable discrimination of red, green, yellow, and blue (required for Stroop testing). Participants selected for the study demonstrated sufficient prosthesis control performance (muscle capacity), adequate sensory perception with TENS (in the +TENS group), and proper cognitive performance (in a standalone Stroop test), during baseline assessments.

6.2.4 Statistical Analysis

Data was processed using Matlab (R2024b, The MathWorks, Natick, USA). All statistical analyses were performed in RStudio (R 4.5.1). All data were tested for normality using the Shapiro-Wilk test, independence using the Durbin-Watson statistic, and homoscedasticity using Levene's test. Since all assumptions were met, two-way mixed-design ANOVAs were used to evaluate the effects of feedback condition on group performance. For post-hoc analyses and for detailed comparisons between groups, performance was reported as median across participants with interquartile range (IQR) values in parentheses. All paired and unpaired comparisons throughout the analyses were conducted using two-sided Wilcoxon Signed-Rank and Wilcoxon Rank-Sum tests respectively. The results for the statistical tests, as well as the relevant metrics are reported alongside the corresponding figures and tables. Unless otherwise stated, a statistical level of significance of $\alpha = 0.05$ was used. Where appropriate, Šidák correction was applied to account for multiple comparisons. Tukey's IQR rule was used to indicate outliers in plots showing group performance.

6.3 Results

6.3.1 Baseline performances

Before conducting the main analyses, baseline performance was evaluated to ensure that the –TENS and +TENS groups did not differ systematically in their initial proficiency to perform either task. Baseline values were derived from trial 1 of the experimental design (primary task only) and from a standalone Stroop test (secondary task only) performed during preliminary assessments. No significant differences were observed in primary task absolute position error (–TENS: 9.8% (9.2%); +TENS: 8.1% (7.1%); $U = 69$, $p = 0.162$) or in Stroop accuracy (–TENS: 98.8% (8.1%); +TENS: 97.5% (2.5%); $U = 47$, $p = 0.839$). These findings suggest that both groups started the experiment with comparable baseline performance levels on both the primary and the secondary tasks.

6.3.2 Preliminary analysis

To evaluate the effect of TENS-based proprioceptive feedback on grasp accuracy, visual feedback reliance, and task learning from a comprehensive overall view, a linear mixed-effect model was fit to primary task performance data, excluding trials including the secondary task. In this model, TENS feedback condition, visual feedback condition and trial number were defined as fixed effects, whereas inter-individual differences were defined as random

effects.

Table 6.2: Parameter estimates from the linear mixed-effects model fit on aperture control error from all single-task trials. Variance with standard deviation is reported for the random effect of inter-participant variability. Coefficient estimates with standard deviations (95% confidence intervals) and corresponding p-values are reported for the fixed effects of TENS feedback (+TENS vs. -TENS), visual feedback (present vs. absent), trial number, and for the interactions between TENS feedback condition and the latter two fixed effects.

Random Effect	Variance	Fixed Effects	Coeff. Estimate (%)	p
Participants	18.82 ± 4.34	Intercept	22.65 ± 1.85	< 0.001
		Visual Feedback	-13.48 ± 0.96	< 0.001
		Trial Number	0.12 ± 0.08	0.146
		TENS Feedback	-7.32 ± 2.61	0.007
		Trial Number × TENS Feedback	-0.03 ± 0.12	0.834
		Visual × TENS Feedback	6.06 ± 1.36	< 0.001

As shown in Table 6.2, the addition of visual feedback significantly reduced error by 13.48% ($p < 0.001$), confirming that participants relied heavily on vision for device control. Importantly, the +TENS group exhibited a significantly lower control error than the –TENS group (–7.32%, $p = 0.007$), suggesting a performance advantage associated with the introduction of artificial proprioceptive feedback. The significant interaction between visual feedback condition and the presence of TENS feedback (6.06%, $p < 0.001$) further indicates that although visual input benefited all participants, those receiving TENS relied on it less for task completion, as they already performed better than the -TENS group in its absence. Trial repetition did not significantly affect performance, either as a main effect ($p = 0.146$) or in interaction with TENS ($p = 0.834$), suggesting that learning effects were minimal in the absence of supplemental cognitive load. The model estimates a baseline position control error of 22.65% ($p < 0.001$), corresponding to the –TENS group performing without visual feedback at the start of the experiment. These preliminary findings provide a foundation for the block-specific analyses that follow.

6.3.3 Alternating Feedback Block

The Alternating Feedback block was designed to familiarize participants with the control paradigm while systematically alternating between trials with and without visual feedback. This sequence enabled the evaluation of participants' ability to control the robotic hand under varying sensory conditions. Specifically, it allowed us to assess (i) whether participants could achieve reliable aperture control without relying solely on visual input, (ii) how repeated

exposure to the task influenced control, and (iii) whether the integration of artificial feedback contributed to improved performance in the absence of visual cues. Statistical analysis results are presented at Table 6.3.

Table 6.3: Results of two-way mixed-design ANOVAs investigating the effects of TENS feedback (–TENS vs. +TENS) and trial number on primary task performance during the Alternating Feedback Block under visual (trials {3, 5, 7, 9, 11}) and no-visual feedback conditions (trials {4, 6, 8, 10, 12}). Aperture control error is defined as the absolute deviation from the desired reference aperture ($\theta_{ref} = 50\%$). Reported values are degrees of freedom (df), mean square error (MSE), F-statistic, p-value (p), and effect size (η^2).

Effect	Visual Feedback					No-Visual Feedback				
	df	MSE	F	p	η^2	df	MSE	F	p	η^2
TENS Feedback	18	0.007	0.522	0.479	0.021	18	0.019	7.325	0.014	0.173
Trial Number	72	0.001	0.485	0.747	0.007	72	0.004	1.610	0.181	0.042
TENS Feedback × Trial	72	0.001	0.804	0.526	0.011	72	0.004	0.493	0.741	0.013

Figure 6.3 displays an overview of the position error per group when participants were allowed versus deprived of visual feedback. During trials where visual feedback was available, no significant improvements in control performance were observed over time in either group ($p = 0.747$) (see Figure 6.3 (a)). Additionally, the introduction of TENS-based artificial feedback did not alter overall performance ($p = 0.479$), as evidenced by comparable median aperture errors across groups (-TENS: 10.7% (8.3%); +TENS: 8.8% (3.1%)) (see Figure 6.3 (b)).

When visual feedback was removed, no significant variation in control performance was observed over time within either group ($p = 0.181$) (see Figure 6.3 (c)). However, the +TENS group demonstrated significantly better overall performance compared to the -TENS group under visual isolation, ($p = 0.014$), with a Šidák-corrected level of significance of $\alpha = 0.025$, with median control errors of 13.1% (1.4%) and 24.5% (10.6%), respectively (see Figure 6.3 (d)). These results highlight two key observations. First, participants in the -TENS group were unable to improve their control accuracy without visual feedback, suggesting that proprioceptive awareness of muscle activation alone was insufficient for precise aperture control. Second, participants in the +TENS group maintained control performance under visual isolation that was comparable to their performance with visual feedback (initial trial without visual feedback: 10.5% (5.5%); initial trial with visual feedback: 9.1% (4.0%)), with no significant difference between conditions ($W = 10$, $p = 0.084$, Signed-Rank Test). This indicates that TENS-based artificial feedback could effectively substitute for visual input in supporting accurate motor control.

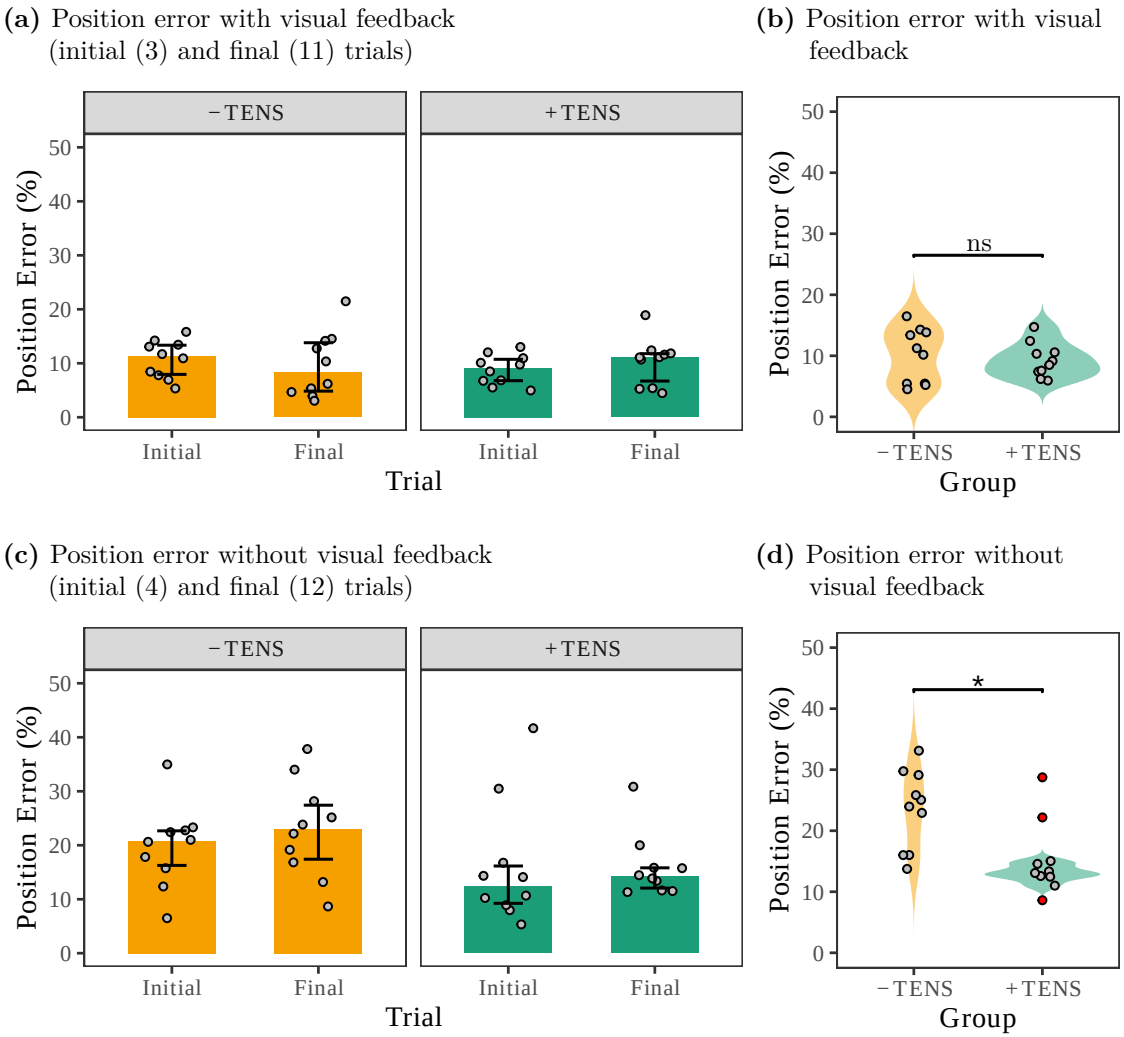

Figure 6.3 Overview of experimental results for primary task execution in the Alternating Feedback Block. **(a)** Absolute position error with visual feedback across participants for initial (3) and final (11) trials. **(b)** Absolute position error with visual feedback across participants and trials ({3, 5, 7, 9, 11}). **(c)** Absolute position error without visual feedback through initial (4) and final (12) trials. **(d)** Absolute position error with visual feedback across participants and trials ({4, 6, 8, 10, 12}). Bar plots represent group medians, error bars show interquartile ranges (25% and 75%) and single circular grey markers show individual participants with red markers highlighting outliers. Asterisks denote significance as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ and ns when not significant.

6.3.4 Prolonged Visual Deprivation Block

The Prolonged Visual Deprivation Block was designed to evaluate participants' ability to maintain accurate motor control across multiple consecutive trials without visual input. Building on the insights gained from the Alternating Feedback Block, this sequence allows us to assess (i) whether performance could be sustained under prolonged visual isolation, (ii) how repeated exposure to non-visual conditions influenced control consistency, and (iii) whether artificial feedback contributed to maintaining precision in the absence of visual cues, reinforcing its potential to reduce reliance on visual feedback in prosthetic control. Statistical analysis results are presented at Table 6.4.

Table 6.4: Results of the two-way mixed-design ANOVAs investigating the effects of TENS feedback (–TENS vs. +TENS) and trial number (trial 16 to trial 20) on primary task performance during the Prolonged Visual Deprivation Block. Aperture control error is defined as the absolute deviation from the desired reference aperture ($\theta_{ref} = 50\%$). Reported values are degrees of freedom (df), mean square error (MSE), F-statistic, p-value (p), and effect size (η^2).

Effect	df	MSE	F	p	η^2
TENS Feedback	18	0.030	4.980	0.039	0.164
Trial Number	72	0.003	1.848	0.129	0.029
TENS Feedback × Trial	72	0.003	1.018	0.404	0.016

Echoing previous results for the Alternating Feedback Block, the +TENS group demonstrated significantly better overall control performance compared to the -TENS group under visual isolation ($p = 0.039$), with median position errors across participants and trials of 15.6% (10.7%) and 26.5% (8.9%), respectively (see Figure 6.4 (b)). This indicates that the beneficial effect due to the addition of TENS feedback persist even under prolonged visual deprivation. However, even though no significant variation in control performance was observed over time ($p = 0.129$), the final trial in the +TENS group showed a noticeable increase in median error across participants, rising from 13.9% (6.4%) in trial 16 to 18.3% (15.2%) in trial 20. This increase was accompanied by the emergence of two distinct clusters in the distribution of position errors for each +TENS participant (silhouette score = 0.695; Figure 6.4 (a)). These clusters (centered around 10.79% and 27.48%; identified by K-means clustering) appear to align with the discrete modulation levels used in the feedback encoding, specifically, ± 25% from the aperture setpoint. This pattern was not observed in earlier trials or in conditions where visual feedback was intermittently available, suggesting that prolonged exposure to the artificial feedback may lead to sensory adaptation when visual cues are consistently absent. When asked throughout this block, all +TENS participants consistently reported

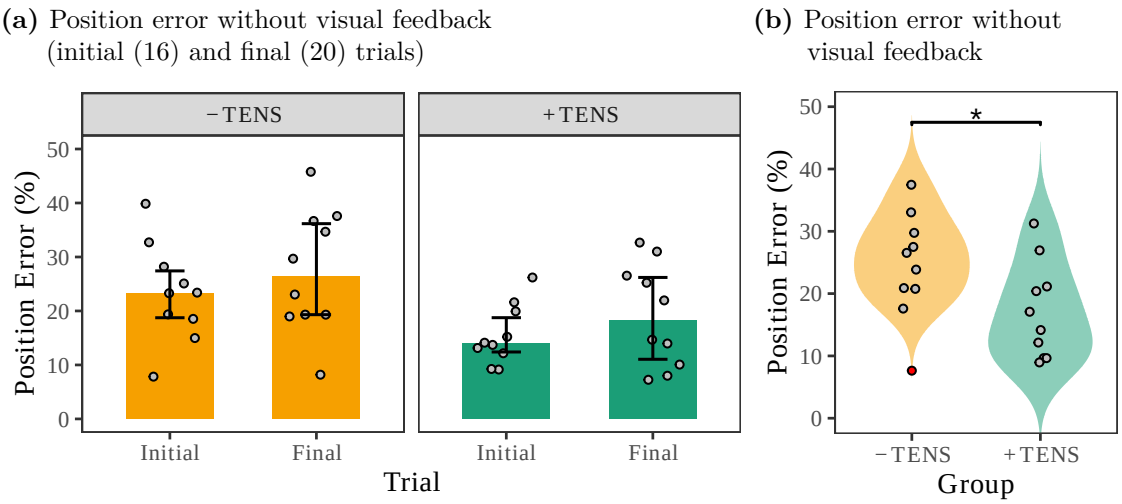

Figure 6.4 Overview of experimental results for primary task execution in the Prolonged Visual Deprivation Block. **(a)** Absolute position error with visual feedback across participants through initial (16) and final (20) trials. **(b)** Absolute position error with visual feedback across participants and trials ({16, 17, 18, 19, 20}). Bar plots represent group medians, error bars show interquartile ranges (25% and 75%) and single circular grey markers show individual participants with red markers highlighting outliers. Asterisks denote significance as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ and ns when not significant.

perceiving two distinct variations in sensation intensity prior to disengaging their biceps to open the hand. This systematic error observed in some participants does not necessarily reflect a failure to integrate the feedback. Rather, it points to potential limitations in the selection of the stimulation parameters or the delivery method, which did not account for stimulus habituation over time [50]. Since stimulation was intermittent throughout the trials, the attenuation did not follow the continuous exponential decay reported under constant stimulation paradigms [50], but remained consistent with adaptive desensitization of the afferent populations. The effect's reversibility after short rest periods between trials further supports its interpretation as physiological sensory adaptation.

6.3.5 Cognitive Assessment Block

The Cognitive Assessment Block was designed to evaluate whether repeated exposure to robotic hand control (during the Alternating Feedback Block) modulated the cognitive load typically associated with prosthetic use. In trials 2 and 14, participants performed the primary grasping task without visual feedback while concurrently engaging in a cognitively demanding secondary task (Stroop test). Improved performance under these conditions would suggest that the proprioceptive feedback did not increase cognitive burden, highlighting its

potential for functional integration in daily life [166].

To ensure that any differences in primary task performance under dual-task conditions were not confounded by participants neglecting the secondary task, we analyzed Stroop task accuracy during trials 2 and 14 of the Cognitive Assessment Block. A two-way mixed-design ANOVA revealed no significant main effect of feedback condition (–TENS vs. +TENS; $F(1, 18) = 0.35$, $p = 0.560$) or interaction between feedback and trials ($F(1.73, 31.12) = 0.05$, $p = 0.929$). This shows that the addition of TENS feedback does not worsen performance on the Stroop task, but also, does not provide any straightforward cognitive benefit, as no strong overall improvement in primary task was observed under this dual-task. Additionally, the number of grasps performed during the cognitive assessment blocks did not differ significantly between groups ($W = 58.5$, $p = 0.54$), suggesting that participants in the +TENS group (20.8 grasps (9.6 grasps)) did not improve performance by reducing grasp frequency compared to the –TENS group (18.25 grasps (10.0 grasps)).

We next examined whether artificial feedback influenced the ability of the participants to control the prosthesis under cognitive load, conducting a two-way mixed-design ANOVA on primary task performance during the Cognitive Assessment Block. This design accounts for repeated measurements within participants over time, allowing us to assess both the overall impact of artificial feedback and its interaction with temporal changes in performance. As shown in Table 6.5, there were no significant main effects of feedback condition ($p = 0.301$) or trial repetition ($p = 0.281$), nor a significant interaction between the two factors ($p = 0.971$). These results suggest that TENS-based feedback did not significantly enhance grasping performance under dual-task conditions when visual input was removed and attentional resources were divided, providing no clear support for our initial hypothesis at this stage.

Table 6.5: Results of two-way mixed-design ANOVAs investigating the effects of TENS feedback (–TENS vs. +TENS) and trial number (trial 2 vs. trial 14) on primary task performance under cognitive load (Stroop test). Aperture control error is defined as the absolute deviation from the desired reference aperture ($\theta_{ref} = 50\%$). The Corrected Error Metric is defined as the absolute deviation from the perceived functional target. Reported values are degrees of freedom (df), mean square error (MSE), F-statistic, p-value (p), and effect size (η^2).

Effect	Original Aperture Error					Corrected Error Metric				
	df	MSE	F	p	η^2	df	MSE	F	p	η^2
TENS Feedback	18	0.02	1.14	0.301	0.059	18	0.01	9.48	0.006	0.345
Trial Number	18	0.01	1.24	0.281	0.065	18	0.01	1.64	0.216	0.084
TENS Feedback × Trial	18	0.01	0.00	0.971	< 0.01	18	0.01	5.33	0.033	0.228

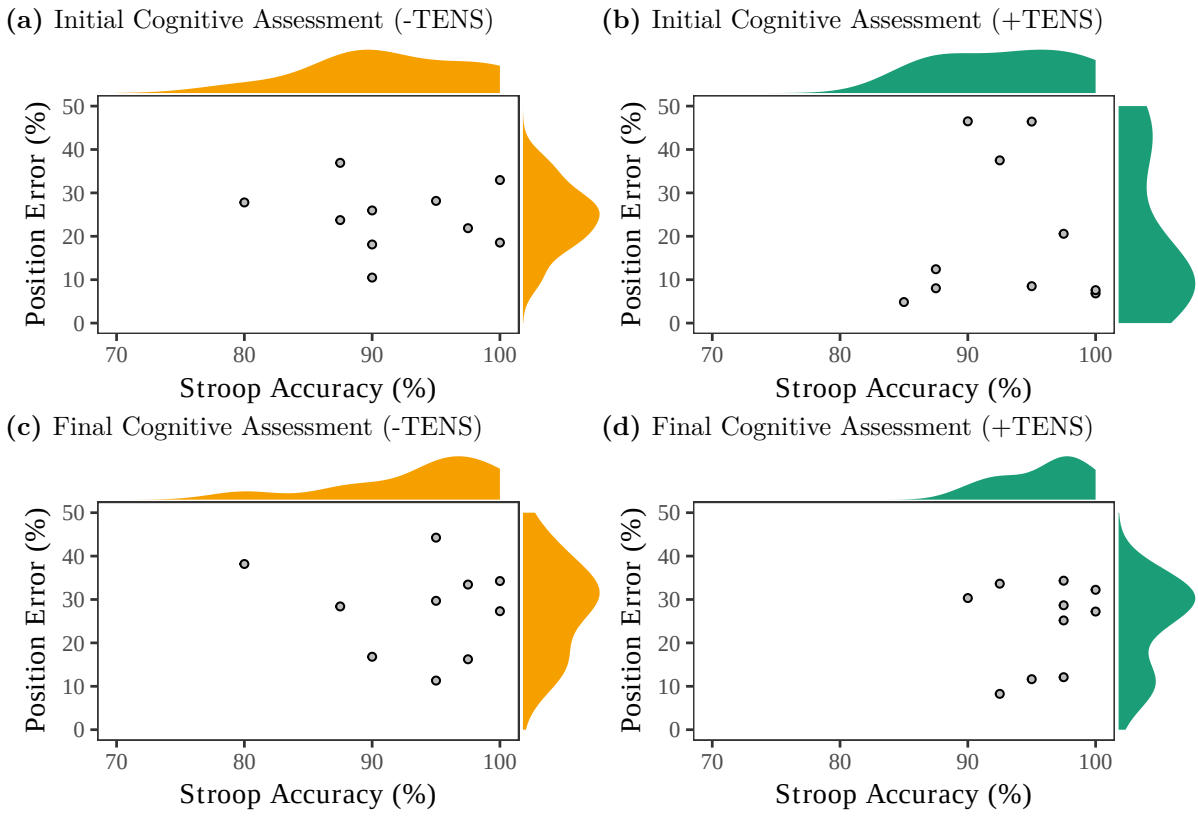

Figure 6.5 Overview of experimental results for primary and secondary task execution in the Cognitive Assessment Blocks. **(a)** Absolute position error and Stroop test accuracy for participants in group -TENS for trial 2. **(b)** Absolute position error and stroop test accuracy for participants in group +TENS for trial 2. **(c)** Absolute position error and stroop test accuracy for participants in group -TENS for trial 14. **(d)** Absolute position error and stroop test accuracy for participants in group +TENS for trial 14. Single circular grey markers show individual participants.

In order to further explore why the results were not coherent with our hypothesis, primary task performances were plotted against secondary task accuracies in Figure 6.5, separated by group (+TENS vs. –TENS) and trial repetition (initial vs. final assessment). This bivariate representation, complemented by density plots, highlights a notable clustering pattern among +TENS participants, especially in trial 14 (silhouette score = 0.775; Figure 6.5 (d)): one subset of participants maintained low aperture errors, while another exhibited substantially poorer control despite the repeated exposure to the artificial feedback. These two clusters were centered around 11.56% and 28.28% respectively, as identified by K-means clustering. While unimodality could not be firmly rejected statistically through Hartigan's dip test (p = 0.071), the low enough p-value and the plot in Figure 6.5 (d) suggest a tendency towards bimodality, which is especially plausible given the sample size (n = 10 per condition) and

the nature of the experimental paradigm.

Similar performance patterns were observed in the last trial of the Prolonged Visual Deprivation Block, where aperture control errors aligned with the discrete modulation levels used in feedback encoding (± 25% from the aperture setpoint). Once again, rather than indicating a failure among a subset of +TENS participants to integrate feedback, this systematic error may reflect alternative mechanisms such as inappropriate calibration step (stimulation parameters selection), sensory adaptation [50], or even attentional limitations affecting perception of low-intensity stimuli [44]. These factors could have led some participants aiming at a shifted functional target, resulting in consistent but inaccurate control.

To assess more accurately how participants integrated the feedback modality, we extended our analysis beyond conventional performance metrics. While minimizing aperture control error relative to the θ_{ref} captures participants' ability to achieve the intended motor goal, it does not account for cases where the perceived target, shaped by the feedback strategy, differs from the intended one. To address this, we introduced a corrected performance metric: the absolute deviation from the perceived functional target. This target was defined as the nearest lower stimulation-associated aperture level, selected from the fixed encoding thresholds of 25%, 50%, and 75%. By anchoring performance to the participant's likely perceptual reference, this metric provides a more nuanced and behaviorally realistic estimate of control accuracy.

Using the corrected performance metric, we repeated the two-way mixed-design ANOVA to reassess the effects of feedback condition and trial repetition on primary task performance under cognitive load (Table 6.5). This refined analysis revealed a significant main effect of TENS-feedback condition ($F(1, 18) = 9.48$, $p = 0.006$), indicating that participants in the +TENS group performed significantly better when performance was evaluated relative to their perceived functional target. Crucially, a significant interaction between feedback condition and trial repetition ($F(1, 18) = 5.33$, $p = 0.033$) suggests that the benefits of artificial feedback became more pronounced over time, highlighting a learning or adaptation effect specific to the +TENS group. Importantly, this improvement in primary task performance did not come at the expense of secondary task execution. Stroop accuracy improved significantly over time in both groups ($F(1.73, 31.12) = 8.12$, $p = 0.002$), with final trial performance approaching ceiling levels (–TENS: 95.0% (6.25%); +TENS: 97.5% (4.38%)). Notably, these final scores were statistically indistinguishable from baseline performance recorded in the absence of any concurrent motor task (–TENS: $W = 19$, $p = 0.444$; +TENS: $W = 29$, $p = 0.124$). The ability of the +TENS group to maintain such high levels of cognitive performance while simultaneously improving in sensorimotor control underscores the robust-

ness of the artificial feedback strategy and its potential to support multitasking in complex environments.

6.4 Discussion

The present study demonstrates that providing non-invasive somatotopic proprioceptive feedback through transcutaneous electrical nerve stimulation (TENS) can effectively address critical control and integration challenges in robotic hand operation in healthy participants. Consistent with our hypothesis, the artificial feedback improved aperture control accuracy and reduced reliance on vision, enabling rapid integration and concurrent execution of cognitively demanding visual tasks.

Participants receiving TENS-based feedback achieved significantly higher hand aperture control accuracy than those without feedback, both during alternating visual conditions ($p < 0.001$) and under prolonged visual deprivation ($p = 0.017$). The performance advantage emerged immediately and persisted across trials, suggesting that participants were able to integrate the artificial feedback with minimal exposure or training, highlighting its functional utility. This improvement confirms that proprioceptive awareness of muscle activation alone is insufficient for precise aperture control, and that the addition of somatotopic feedback provides the necessary state information to sustain accurate performance, consistent with the findings of Vargas et al. [89]. Importantly, feedback integration occurred without detrimental effects when vision was available, indicating that natural and artificial feedback channels can coexist and complement each other during multimodal control. Finally, under dual-task conditions, participants with TENS feedback maintained high cognitive performance while improving aperture control, indicating that the addition of feedback did not increase cognitive load to an unmanageable level. This robust and cognitively efficient integration suggests that this approach to proprioceptive feedback can support multitasking in complex environments.

6.4.1 Positioning our approach within the literature

This study extends the existing proprioceptive feedback research landscape by demonstrating that key functional benefits, including improved control accuracy and independence from vision can be achieved without surgical intervention. It also extends the non-invasive literature by isolating visual contributions, assessing cognitive compatibility during demanding visual tasks, and identifying adaptation outcomes that can inform future feedback design.

Earlier non-invasive studies have shown that feedback can enhance control performance but it often does at the expense of speed, stimulation comfort, or general intuitiveness. Witteveen *et*

al. compared how vibrotactile and electrotactile feedback would affect virtual hand aperture control in both healthy participants and amputees. Although both modalities significantly reduced mean absolute position error ($p = 0.001$ and $p = 0.003$, respectively), they were also associated with longer task durations ($p < 0.001$) and, in some cases, discomfort from electrotactile stimuli. In contrast, in the present study, the number of completed cycles per trial did not differ between visual and non-visual conditions for the participants exposed to the feedback (Wilcoxon signed-rank test, $W = 588.5$, $p = 0.60$). This suggests that while the somatotopic TENS feedback required additional cognitive resources, it was efficiently integrated within the existing control strategy, allowing participants to sustain precision without a corresponding increase in task duration.

The work by Vargas *et al.* offers the most direct comparison to the present study. In their closed-loop experiment, seven neurologically intact participants with no prior experience in prosthesis control operated a prosthetic finger using EMG to generate position commands, similar to the control paradigm used here. Participants received non-invasive vibrotactile feedback conveying information about finger aperture. The introduction of feedback significantly improved task performance when evaluated through a binary accuracy metric, where success was defined as maintaining the aperture within ±5 degrees of the target. However, the feedback did not significantly reduce aperture error. In contrast, the somatotopic TENS feedback proposed in the present study produced a clear and statistically significant reduction in aperture error, suggesting that physiologically congruent feedback delivered through TENS provides a more precise and interpretable proprioceptive signal than vibrotactile cues.

Invasive stimulation methods have allowed for near-natural proprioceptive feedback through direct neural interfaces. For instance, D'Anna *et al.* reported joint-angle reproduction errors of about 9 degrees and motion-detection thresholds comparable to those of intact limbs. Likewise, Marasco *et al.* showed that vibration-induced kinesthetic illusions enhance prosthetic grip accuracy even without visual input, underscoring the central role of movement sensation in motor control. Yet these approaches require surgical implantation or targeted reinnervation, which limits clinical adoption, raises concerns about long-term stability, and increases maintenance demands. The present findings in healthy participants demonstrate that non-invasive somatotopic TENS can reproduce several of the functional advantages described in invasive studies, such as improved control accuracy, reduced visual dependence, and low cognitive load. Although implanted interfaces provide greater spatial selectivity and more precise modulation of afferent recruitment, our approach offers a practical, low-risk complement that captures key functional principles while remaining accessible and deployable with commercially available devices. Extending this work to amputee users will be essential to assess its clinical viability and to determine how non-invasive proprioceptive feedback can

support functional prosthetic control.

6.4.2 Limitations and future work

While the present study establishes the feasibility and efficacy of providing somatotopic proprioceptive feedback through non-invasive TENS, several methodological and translational aspects warrant further investigation. The findings reported should be interpreted in light of the limited cohort of twenty neurologically intact participants divided equally across feedback (+TENS) and control (–TENS) groups. The sample size was sufficient for statistical validation, yet expanding it would improve robustness and ensure broader generalizability of the findings. Importantly, although similar somatotopic sensations have been reported in individuals with upper-limb amputation [71, 128–130], the present data do not capture the variability expected in amputee users. Future work should therefore include participants with upper-limb amputation to confirm the functional relevance and real-world applicability of the feedback strategy.

The sEMG-based position commands used in this study provided stable and easily integrated control, but alternative command schemes could further improve intuitiveness and adaptability. Velocity-based control or discrete grasp-type selection, as explored in previous work [54, 89], may enable smoother transitions and more natural interactions in activities of daily living. Future research should also consider alternative muscle sources for command generation, depending on the mechanical configuration of the prosthesis. If the robotic hand is no longer fixed, signals from the biceps may be suboptimal, as this muscle group would be recruited to support the weight of the prosthesis. In such cases, proximal muscles could provide more stable motor commands during active reaching or object manipulation. If these avenues are pursued, particular attention should be given to classification- and signal-processing-induced delays, which can influence control stability and user perception [71]. Quantifying and minimizing these latencies will be essential for future closed-loop implementations.

Although the current setup with a fixed robotic hand was appropriate for testing feedback integration under controlled conditions, the results observed here may not directly translate to scenarios involving full-arm motion or load-bearing tasks. Future work should examine scenarios in which participants actively move and support the weight of the artificial limb, conditions that would better approximate daily prosthesis use, promote the development of bodily agency, and engage the muscle groups naturally recruited for reach and grasp tasks [13]. When movement is introduced, changes in wrist posture and muscle co-activation may influence both sEMG decoding and the perceived quality (intensity and location) of the

evoked sensations [161]. While the relatively large electrode size and configuration used in this study may help mitigate some of these effects when conveying a single feature, scaling the feedback to higher degrees of freedom to accommodate more complex grasp types will require more precise spatial mapping to target specific regions of the hand. As the number of stimulation sites increases, mechanical strain at the skin–electrode interface during movement may further distort perception or induce cross-talk between adjacent regions, thereby reducing feedback specificity.

The feedback paradigm used here conveyed information about hand aperture in a cylindrical grasp, corresponding to a single degree of freedom. Although even one-dimensional proprioceptive feedback with three-level encoding substantially improved control accuracy, this discretization inevitably limited the continuity of the perceived motion and may have contributed to the clustered performance patterns observed under prolonged exposure to TENS. The three-level scheme was selected based on prior literature and empirical observations to ensure reliable discrimination and participant comfort, but future work should explore richer encoding strategies capable of conveying multiple grasp types or continuous multi-joint movements, without compromising discriminability. Our previous findings [49] demonstrated that two stimulation channels targeting the median and ulnar nerves can provide accurate and distinct somatotopic cues to represent up to four grasp types. Extending this perceptual framework to the present closed-loop paradigm will require longitudinal evaluation and the development of comprehensive training protocols that promote stable, long-term interpretation of multiple concurrent feedback signals.

Sensory adaptation represents another important challenge for implementing artificial feedback in daily use. Following repeated or constant stimulation, the human nervous system naturally reduces its response magnitude over time, prioritizing the processing of novel inputs [50, 171]. Although adaptation is a positive and biologically efficient mechanism that prevents sensory overload, it poses a limitation for prosthetic feedback applications, where maintaining consistent perception is essential. Previous studies involving electrotactile stimulation have suggested that intermittent stimulation patterns can mitigate adaptation by allowing partial recovery of perceptual sensitivity between bursts [84]. The time constant of perceptual decay has been shown to scale with stimulation intensity [84,172], suggesting that dynamic control of stimulation parameters may preserve perceptual constancy. In the vibrotactile domain, multi-tactor arrays have similarly been proposed to enhance spatial resolution and reduce desensitization by alternating activation patterns [85]. In the present study, alternating visual feedback conditions (Alternating Feedback Block) may have contributed to limiting adaptation, as visual information provided an external reference for participants to recalibrate perceived stimulation intensity relative to actual hand aperture. This grounding

across feedback modalities likely helped maintain perceptual stability across trials by reinforcing the correspondence between proprioceptive and visual cues. Short breaks were also introduced between experimental blocks in an attempt to mitigate adaptation effects. However, this approach was not sufficient to prevent progressive attenuation of perceived intensity during long-term exposure to repeated stimuli (Prolonged Visual Deprivation Block). This limitation highlights the need for more adaptive stimulation strategies that can maintain perceptual stability in continuous tasks, where users perform natural, uninterrupted movements. Future work could address this issue by modulating stimulation frequency rather than amplitude to encode aperture information while preserving a constant perceived intensity. This approach could also enhance discrimination between aperture stages, especially in dual-task contexts where attentional resources are divided. Additionally, dynamically adjusting stimulation parameters over time, informed by individual adaptation profiles [50, 143], may further improve the long-term reliability and perceptual naturalness of TENS-based feedback.

The present findings highlight that cognitive effort plays a key role in how users interpret and exploit artificial sensory feedback. Even under dual-task conditions, participants efficiently integrated somatotopic proprioceptive cues, suggesting that feedback delivered through natural perceptual channels imposes minimal attentional demand. However, as shown previously [71], perceptual discrimination declines when feedback resolution exceeds natural limits (around three distinct intensity levels), making higher complexity counterproductive. Notably, participants continued to detect changes in stimulation even when overall intensity perception diminished due to adaptation or divided attention. Their ability to control the hand toward shifted targets indicates preserved sensitivity to relative rather than absolute changes, supporting future exploration of encoding strategies based on frequency modulation or temporal patterning to enhance robustness and reduce cognitive load during long-term use.

6.5 Conclusion

This study leveraged transcutaneous electrical nerve stimulation (TENS) to deliver somatotopic proprioceptive feedback about hand aperture through non-invasive stimulation of peripheral nerves, offering a pragmatic compromise between sensory substitution and biomimicry. The approach shows potential to help mitigate critical control and integration challenges in robotic hand operation while avoiding the surgical risks and long-term complications associated with invasive methods.

Through an experimental design that alternated visual feedback availability and included cognitively demanding dual-task conditions, participants receiving somatotopic TENS feedback

consistently achieved higher aperture control accuracy, even in the absence of vision. This immediate and sustained performance advantage supported our hypothesis that artificial proprioceptive cues can effectively substitute for visual monitoring. Furthermore, participants in the feedback group maintained strong cognitive performance while improving sensorimotor control, demonstrating that the strategy can be integrated efficiently without overloading attentional resources.

These findings highlight the potential of non-invasive, somatotopic stimulation to provide physiologically meaningful proprioceptive feedback and to inform future strategies for the restoration of proprioceptive function in prosthetic hand users. Future work will focus on extending this approach to multiple degrees of freedom, refining stimulation encoding for long-term stability, and validating its functional impact in amputee populations.

CHAPTER 7 GENERAL DISCUSSION

This thesis focused on alleviating several key issues that limit the adoption of myoelectric prostheses by improving how users interact with their artificial limb through the restoration of closed-loop control. The main objective was to develop a non-invasive proprioceptive feedback strategy for robotic hands based on TENS that conveys finger position and leads to better control accuracy, reduced reliance on vision, and fast learning, without increasing cognitive demands. To reach this main objective, a series of specific objectives were defined, each one constituting a necessary step leading to the implementation and evaluation of the strategy. The present chapter synthesizes and interprets the experimental findings in the context of the thesis objectives.

7.1 Perceptual capabilities and limitations of TENS-based artificial proprioceptive feedback

Section 2.4 from the literature review presented in Chapter 2 observed that a biomimetic approach to restoring somatosensory perception, often considered optimal in the research literature, remains largely heuristic. Therefore, it is more reflective of what artificial feedback should look like instead of being experimentally validated. Such approaches are largely inaccessible given the constraints of currently available stimulation technologies, which is especially true with non-invasive methods, and the way prosthetic limbs are represented in the brain. These insights motivated the selection of an alternative, bioinspired framework that circumvents the limitations of strictly reproducing biological feedback, centered around TENS as the stimulation method.

Article 1, presented in Chapter 4, validated the first hypothesis (H1) and demonstrated how the selected bioinspired approach can be implemented to convey proprioceptive information to a robotic hand user. The TENS electrodes were positioned in a pattern that allowed for independent stimulation of the median and ulnar nerves, evoking sensations that were felt respectively in the thumb, index, and middle fingers, and in the ring and little fingers. By modulating the injected electrical charge transmitted through each stimulation channel, it was possible to communicate up to three levels of fingers aperture and four distinct hand configurations. These configurations were selected for their coherence with the implemented encoding strategy and for their prevalence in activities of daily living involving both grasping and object interaction. To our knowledge, the work in this chapter constitutes the first implementation of a somatotopic, non-invasive proprioceptive feedback strategy for the hand

using TENS.

In order to evaluate whether the proposed method could transmit artificial proprioceptive feedback, a proof of concept was conducted, with participants performing a strictly perceptual task. During the experiment, participants received information transmitted by stimulation and had to identify the corresponding hand configuration. Performance was evaluated based on whether the proprioceptive information was classified correctly and the time required to complete the identification. The results obtained from six able-bodied participants indicated that the proposed strategy is adequate for transmitting proprioceptive information for hand configurations involving both one and two degrees of freedom. This is particularly relevant in the context of future myoelectric prosthesis design, as the proposed feedback strategy may be implemented with robotic hands that support finger aperture and low-dimensional grasp type control. This flexibility may enable proprioceptive feedback to be tailored to user-specific needs in activities of daily living, for example by allowing users to select functionally relevant grasp types.

The limitations of this study related to both the data analysis and experimental design. In terms of analysis, the study was based on a limited number of participants and did not include quantitative statistical analyses, which limits the extent of the conclusions that can be drawn at this stage. From a study design perspective, feedback was introduced as part of a strictly perceptual task, which means that no conclusions can be drawn about its impact in a closed-loop motor control context. In addition, although this is not specific to this study, the lack of standardization in the structure of the experimental protocols identified in the literature limits direct comparisons with similar work [110].

That being said, these methodological choices were consistent with the requirements for specific objective SO1. Including a larger number of participants or conducting more in-depth statistical analyses would not enable us to infer whether the observed results, both in terms of classification accuracy and response times, would translate into improved closed-loop control.

Now that a proof of concept for the proposed bioinspired approach had been established, we were ready for the next step in this thesis, which was to introduce this foundational architecture into a closed-loop control framework. This transition to a more realistic application enabled the evaluation of whether the proposed feedback can positively influence motor control performance and contribute to improved integration of myoelectric prostheses.

7.2 Closed-loop control implications of TENS-based artificial proprioception in EMG-driven systems

As discussed in Section 2.6, closing the loop to allow for myoelectric control required the generation of reliable motor commands from EMG signals acquired while users were exposed to physiological feedback delivered via TENS. This introduced a critical challenge due to the presence of stimulation-related artifacts overpowering the volitional EMG signal in the recordings.

Article 2, presented in Chapter 5, addressed this issue by introducing a methodological framework that validated the second hypothesis (H2). It featured the first implementation of a software-based artifact suppression filter designed to isolate volitional EMG for myoelectric control while allowing concurrent exposure to TENS-based feedback.

A cascaded filtering chain consisting of a band-pass filter followed by a set of narrow band-stop filters was designed to preserve the physiological components of the EMG signal while suppressing periodic interference from the electrical grid and TENS stimulation. The processed signal was then rectified and low-pass filtered to extract the envelope used to generate commands for the robotic hand.

In order to validate that the extracted envelope was suitable for proportional real-time control of a robotic hand, an experimental study was conducted in which participants were asked to control the opening of the hand through voluntary muscle activation. At this stage, the analysis was not aimed at determining whether the introduction of artificial physiological feedback improved the interaction with the prosthesis, but rather at assessing whether the established methodological framework constituted an adequate platform for a subsequent evaluation. Consequently, participants performed the control task with visual feedback.

The results obtained from two groups of ten able-bodied participants, with and without TENS stimulation, indicated that the presence of stimulation does not significantly affect the frequency content of the EMG envelope used to generate the command sent to the robotic hand, nor does it affect control performance. These results demonstrate that the proposed artifact suppression method preserves relevant motor information in the presence of stimulation, supporting the relevance of the methodological framework put forward. From a system design perspective, this suggests that closed-loop control of myoelectric hand prostheses may be achieved while streamlining the required architecture, since no dedicated or specialized hardware is needed for the suppression of stimulation-related artifacts.

A limitation is that the proposed framework has only been validated under conditions where physiological feedback was delivered using a single TENS channel. Although this was ade-

quate to address SO2, the case study selected is limited in terms of generalizing the results to more complex feedback strategies that may require more channels to convey richer proprioceptive information.

Despite this, all the necessary elements were in place to effectively close the myoelectric control loop and evaluate the influence of the proposed approach on control accuracy, reliance on vision, cognitive load, and the required learning period.

7.3 Functional impact of TENS-based artificial proprioceptive feedback on motor performance, visual reliance, learning, and cognitive load

Article 3, presented in Chapter 6, validated the third hypothesis (H3). It reported an experimental study in which participants completed multiple trials involving a grasping task under distinct conditions. These conditions included the presence or absence of visual feedback and, in some trials, the concurrent execution of a cognitively demanding visual secondary task.

To enable proportional position control of the robotic hand, the myoelectric control loop was closed using insights gained from SO1 and SO2. Motor commands were derived from muscle activation measured via sEMG and processed to remove stimulation-related artifacts. Proprioceptive physiological feedback was administered via a single stimulation channel, evoking somatotopic sensations with an intensity proportional to hand aperture across all five fingers.

Half of the twenty able-bodied participants who took part in the study received artificial feedback delivered via TENS during the execution of the trials, allowing for a direct comparison of performance between groups. Both under alternating visual conditions and during prolonged visual deprivation, participants receiving TENS-based feedback achieved significantly smaller aperture control errors than those without. Also, from the beginning of the experiment, TENS-based feedback enabled control accuracy comparable to what was observed with visual feedback. Finally, under dual-task conditions, participants receiving artificial feedback exhibited high levels of both cognitive and motor performance. From a user perspective, these findings emphasize how difficult it can be to accurately control a myoelectric prosthesis in the absence of adequate proprioceptive feedback, particularly when vision is absent. By offering a non-invasive option to reliably close the myoelectric control loop, the proposed approach may help users build confidence in their device. It may also enable them to assess whether myoelectric prostheses align with their needs and preferences for performing activities of daily living, without the additional barriers and risks associated with invasive surgical interventions.

Although SO3 was successfully addressed, the study conducted in Article 3 was not without limitations. To begin with, the use of a fixed robotic hand may have influenced how participants interacted with the device, potentially affecting the sense of agency as well as the generation of motor commands from sEMG, given that no muscle contraction was required to physically move the hand.

Furthermore, complementing the participant group by involving individuals with transradial amputation would have been a step forward in strengthening the generalizability of the results to the intended end users [173]. Although previous studies indicate that sensations evoked by TENS are comparable in nature and specificity between able-bodied individuals and amputees [71, 128, 129], the results of the closed-loop control experiments may not fully translate to the target population. In addition, the subjective experience of potential users could not be assessed, even though such feedback could provide valuable insights for improving the design of artificial feedback strategies and the integration of myoelectric devices [174].

Beyond these methodological considerations, sensory adaptation emerged as the primary translational limitation of the proposed feedback strategy. Signs of sensory adaptation were observed over the course of the experimental sequence, which may affect the long-term effectiveness of the proposed feedback strategy. Addressing this limitation will require greater emphasis on monitoring perceptual sensitivity over time, and on the design of the encoding and stimulation methods to explicitly account for this phenomenon. This could be achieved via optimized temporal delivery patterns or adaptive stimulation strategies involving dynamic modulation of stimulation parameters [50]. Another potential translational limitation is that the feedback was limited to three discrete intensity levels, which may constrain the usefulness of proportional control in real-world applications. Further closed-loop evaluations involving activities of daily living and end users will be necessary to determine the practical impact of this discretization and to inform strategies for mitigating its effects.

CHAPTER 8 GENERAL CONCLUSION

8.1 Summary of works

The idea for the present research work was sparked by an initial interest in research related to human–machine interaction and biomechatronics. Myoelectric prostheses emerged as a particularly compelling application, given their ability to allow users to communicate with a robotic system through their peripheral nervous system.

A closer examination of the literature revealed that, despite their technological sophistication, myoelectric prostheses remain less widely adopted by users than might be expected. In several contexts, they are even discarded in favor of body-powered devices, which rely on considerably simpler mechanical designs. This observation suggests that design considerations extending beyond raw engineering performance play a critical role in the adoption and long-term use of artificial limbs.

The use of a myoelectric prosthesis raises issues that are consistent with well-established principles of robotic control. In what is effectively an open-loop system, the absence of feedback beyond vision inherently limits precision and robustness, which in turn translates into reduced user confidence in the device. As a result, users must continuously monitor the artificial limb visually to ensure correct motion, which increases the cognitive load associated with myoelectric prosthesis operation, particularly during activities of daily living that demand divided or sustained visual attention.

In order to enable closed-loop control of a myoelectric hand prosthesis, with command, action, and feel, the research investigation shifted toward the reliable restoration of proprioceptive feedback. The literature review conducted as part of this thesis provided an opportunity to become familiar with the physiological and anatomical mechanisms underlying proprioceptive perception, as well as with the way afferent information contributes to limb state estimation. This process also clarified the standard functional architecture required to provide artificial feedback and highlighted two recurring challenges. First, reliably evoking proprioceptive percepts through artificial stimulation remains difficult. Second, there is an increasing interest in non-invasive feedback approaches, motivated by considerations related to safety, long-term stability, and user acceptance.

These challenges are further exacerbated by the fact that no stimulation method reported in the literature enables the direct evocation of proprioceptive sensations in a non-invasive manner. Faced with this limitation, inspiration was drawn from other contexts in which

stimuli are used to convey information. In particular, principles of associative learning, whereby novel sensory inputs acquire meaning through experience, informed the development of the proposed encoding paradigm. However, identifying an effective and interpretable stimulation method remained a critical step. It is at this stage that a bioinspired approach became central to the thesis, leading to the identification of TENS as a viable solution.

Repurposing existing peripheral neural pathways to convey spatially meaningful proprioceptive information enabled the progressive reshaping of the interaction between users and a robotic hand, thereby achieving the research objectives of this thesis.

As a first step, the perceptual validity of the proposed strategy was established (SO1), as participants were able to reliably discriminate and interpret finger position information delivered non-invasively through TENS, supporting H1.

Subsequent work allowed for the developed artificial proprioceptive feedback to be successfully integrated within an EMG-driven closed-loop control framework (SO2). The bidirectional interface enabled the generation of reliable motor commands from muscle activation for robotic hand position regulation, thereby supporting H2.

Finally, functional evaluation during grasping tasks confirmed the practical benefits of the approach (SO3). The addition of TENS-based proprioceptive feedback improved control accuracy, accelerated learning, reduced reliance on vision, and did not increase cognitive load, supporting H3.

Collectively, these findings provide a positive answer to the research question. A non-invasive TENS-based proprioceptive feedback strategy can be designed and integrated into an EMG-driven robotic hand control system to enhance grasping performance, facilitate motor learning, and reduce visual dependence without compromising cognitive usability constraints.

8.2 Future research

The work documented in this thesis establishes an initial implementation of a bioinspired, non-invasive proprioceptive feedback strategy centered around TENS. As such, it provides a foundation upon which further developments can be built.

Future work may focus on extending the proposed approach to multiple degrees of freedom for artificial feedback, refining encoding schemes and stimulation delivery methods to support long-term stability and mitigate sensory adaptation, and evaluating translational relevance in amputee populations during clinically oriented studies.

Beyond these immediate extensions, further investigation of alternative bioinspired approaches

is of interest. This includes exploring other stimulation methods, conveying different sensory modalities, and extending the framework to functional prosthetic designs that depart from the conventional representation of a biological hand.

Finally, integrating the proposed approach into other application domains could further enhance its relevance. Potential avenues include assistive technologies beyond upper-limb prosthetics, rehabilitation systems, and broader human–machine interaction contexts, where non-invasive sensory feedback may support motor learning, embodiment, and user engagement.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this thesis, the author used ChatGPT (GPT-5.2) solely as a language assistance tool to improve clarity and conciseness. The author reviewed and edited all content as necessary and assumes full responsibility for the final manuscript.

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