Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL27355

Re-Engaging Spinal Reflexes: Toward Multisensory Feedback Integration in Neuroprosthetic Control

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Abstract. Neuroprosthetic devices have evolved significantly over the last two decades. Modern Electromyography (EMG) prostheses and neural EMG prostheses can fully decode the user's intention for basic motor tasks. Bidirectional research has revealed exciting advances, with intraneural stimulation and bionic encoding of tactile and proprioceptive inputs. Thus, even without visual feedback, they can modulate force and other properties of the object they interact with. Clinical trials of neuromusculoskeletal prostheses have shown feasibility for long-term use. This paper applies these ideas: feedback should not be limited to processing artificial sensory signals at the controller level; it should be returned to the spinal reflex pathway to engage intrinsic circuits in low-latency correction, perturbation, and postural stabilization. These frameworks can be illustrated by case studies of intraneural tactile feedback and tendon vibration to understand how users of the prosthesis can restore stability, efficiency, and implement reflex arcs with artificial receptors. Taken together, these findings suggest that the prosthesis can be viewed as an embodied extension of the nervous system rather than a robotic device separated from the body. If neuroprostheses include multimodal sensory feedback and revert to spinal cord level reflexes, these implantable devices have the potential to produce natural motor coordination that remains clinically feasible for daily functioning.

Keywords: Neuroprosthetics, Somatosensory feedback, Proprioception, Spinal reflexes, Embodiment

1. Introduction

The world has made substantial advancements in neuroprosthetic technology in the last twenty years. Current myoelectric / neuromyoelectric systems can now represent user intention reliably and with high fidelity during basic daily tasks involving movement, such as grasping, pinching, and releasing. Nevertheless, while these advances have occurred, functional outcomes to date remain limited by the absence of near-natural somatosensory feedback. For instance, with the absence of somatosensory feedback the user is unable to optimally scale grip-force, leading to uncoordinated use of delayed feedback and reduced embodiment of the device. Recent pioneer studies in bidirectional systems, particularly among amputees receiving intraneural stimulation and real-time encoding of sensory information, have demonstrated the magnitude of imprinting sense-function. Amputees reported even when all visual and audio cues were stripped, their ability to regulate force

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DOI: 10.54254/2755-2721/2025.GL27355

and sensing object properties occurred at the conscious level [1]. In terms of repetitive long-term clinical studies, it was reported that in fully implanted neuromusculoskeletal prosthesis the spontaneous use of the device extended multi-year use without any adverse effects [2].

To remedy these limitations, there is an increasing effort by researchers to consider the contributions of multi-modal sensory feedback. For example, instead of relying solely on vision, natural motor control combines visual, cutaneous, and proprioceptive inputs, much like Bayesian sensory weighting, which assists in maintaining stability and efficiency [3, 4]. Clinical evidence has shown that biomimetic peripheral nerve stimulation can enhance dexterous control of a prosthesis: George et al. demonstrated that peripheral nerve stimulation provided precise scaling of grip and reduced dependency on visual feedback, while D'Anna et al. simultaneously demonstrated tactile and position feedback that allowed the subjects to scale hand aperture under blindfold conditions [5, 6]. There is recent evidence that proprioception plays a vital role, with evidence showing that artificial-spindle and tendon-organ-like signals can provide awareness of limb position and enhance coordination [7]. Together, this evidence provides initial confirmation that multichannel sensory feedback, such as two-point touch and proprioception, is critical in allowing prosthetic function that feels natural and embodied.

As discussed above, the literature supports the notion that multisensory feedback can improve coordination, and we propose a fundamentally novel design: instead of relaying these artificial receptor signals to prosthetic controllers, they would be processed at the spinal cord level. This would allow the prosthesis to influence the muscular reflex arc in the body, leading to the low-delay reflex correction required to restore the naturally occurring motor coordination of the individual. For example, the local static reflex allows our arm to maintain a fixed Angle distal to hold a gradually filled cup. The effectiveness of clinical applications demonstrates the feasibility of neuromusculoskeletal prostheses, and the use of these prostheses produces stable system function that can provide prosthetic solutions for everyone for many years [2]. This reflection-based way of constructing meaning and response does not apply only to the upper limbs. For example, in the segmental cross reflex, the cross-extensor reflex helps to maintain postural stability when one foot is on a spike. This example shows that reflexes are still important in balancing lower limb movements; These reflexes are usually not achieved visually alone and require multisensory input to the spine.

In this article, we will survey the responses from multiple senses and the reflexes we obtain through the use of artificial senses, in their contribution to fostering the regulation of movements of neural prosthetics. This response will include basic theories, case studies, as well as current issues and future directions.

2. Theoretical foundations

Human motor control relies on perceiving and integrating different modalities of somatosensory information, with all modalities describing the body and environment differently but complementary. For example, cutaneous receptors that detect surface contact, vibration, and skin stretch include Merkel cells, Meissner corpuscles, Pacinian corpuscles, and Ruffini endings [8-10]. The central nervous system uses cutaneous signals to perceive object texture, object compliance, and object slip, any and all of which are necessary for stable manipulation of objects. Proprioceptors are located in muscles and tendons and provide a continuous flow of feedback regarding body configuration. Muscle spindles respond to stretch and velocity, thus encoding information of muscle spindles respond to stretch and velocity, thereby encoding limb position and movement, while Golgi tendon organs respond to muscle tension and are involved in force regulation. Cutaneous and

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proprioceptive systems provide the foundation for closed-loop control over behavior, and allow voluntary actions to continue being productive when disturbances arise from the environment [11].

The functional significance of these modalities is most pronounced when they are missing. Prosthesis users who use visual information to control the prosthesis, have to actively think of their movement. This results in a slower reaction time, and increased total cognitive load to manage their prosthesis. On the other hand, with the inclusion of artificial tactile and proprioceptive information, participants are able to scale grip forces and assess limb position in real time. As Ernst and Banks nicely captured, Humans integrate visual and haptic information in a statistically optimal way and Kor ding and Wolpert showed, the brain pools multiple streams of uncertain information in a statistically optimal way [3, 4]. In other words, the nervous system considers each modality as a source of information with varying levels of reliability. The highest reliable information has greater weight. For example, if vision is quite accurate, more weight is given to visual input; whereas, in cases where visual input is degraded, more weight is given to proprioceptive and tactile signals. This active dynamic reweighting of sensory information is called Bayesian integration, and it allows the resulting motor output to consist of the most reliable combination of these inputs. Thus, movement becomes more stable, and more efficient, because the brain is saved from making errors by taking advantage of whichever sensory channel provided the most accurate information at that time.

Clinical neuroprosthetics have validated this concept. George and co-workers have even reported in a pioneering case, that “Biomimetic sensory feedback transmitted via peripheral nerve stimulation facilitates dexterous use of a bionic hand” [5]. Likewise, D’Anna and co-workers demonstrated that “A closed-loop hand prosthesis with concurrent intraneural tactile and position feedback” was able to allow subjects to modulate the dynamics of grasp without vision [6]. It is also crucial to point out that proprioceptive restoration has been increasingly recognized as critical. Marasco and de Nooij state, “Proprioception is an important sensory modality that is typically not well incorporated in current neuroprostheses” [7]. Taken together, these findings suggest that being able to restore cutaneously mediated touch and proprioception is not simply an enhancement, but a foundational requirement for prosthetic embodiment. By restoring these modalities, prostheses more closely approach biological effectors that can truly be seamlessly incorporated into an individual's body schema.

The discussion of processing separate somatosensory modalities inevitably raises the question of how these sensory inputs inform the nervous system to produce movement. Voluntary action is not a simple set of afferent and efferent signals as if feedforward, but essentially a closed-loop process whereby cortical signals are influenced by sensory inflow. As Massey, Cunniffe, and Noorani state in Carpenter's Neurophysiology: A Conceptual Approach (6th ed.), descending motor commands are continuously modified by sensory feedback, allowing for real-time corrections [11]. This hierarchy allows the cortical architecture to specify overarching goals while allowing spinal and brainstem circuits ability to provide rapid response variability to perturbations. Scott alludes to this design in his interrogation of Optimal Feedback Control (OFC), noting "Optimal feedback control provides the nervous system with a structure for comprehending how the nervous system controls movement" [10]. In this sense, feedback is selectively weighted, specifically, sensory signals suppress irrelevant responses and amplify cues relevant for the task; hence, errors are corrected only when they threaten the task goal. Therefore, the efficient execution of motor action lies within the interplay of high-level cortical constraints, and low latencies through spinal assemblies.

In this distributed system, the reflection arc represents the basic building block of coordination. Overextension of muscle spindles induces a pull reflex, while the Golgi tendon organ reflexively regulates force and protects muscles and tendons from overload [11]. Local mechanisms achieve

DOI: 10.54254/2755-2721/2025.GL27355

self-stabilization without conscious involve, as I mentioned before. Simultaneous reflections can be static, so that the arms can all be maintained at a steady Angle when the load is applied in different ways -for example, pouring water into a cup. These examples show that the spinal cord is not a simple relay system, but is capable of supporting the adaptive responses required for higher levels of control. From a prosthetic mechanism perspective, if signals sent by artificial receptors are transmitted back to the spinal cord, then prosthetic devices can return to endogenous reflex pathways that stabilize and coordinate limb movement according to the current environment and the task being performed, which cannot be done by conventional external control algorithms.

3. Case study

3.1. Real-time intraneural tactile feedback with TIMEs

Raspopovic et al. published an important trial for which the investigators implanted Transverse Intrafascicular Multichannel Electrodes (TIMEs) in the median and ulnar nerves of a single 36-year-old transradial amputee [1]. The subject was chosen because the residual musculature of the amputation stump had sufficient residual strength that the sEMG could establish and decode the participant's grasp types and the participant had intact peripheral nerves that could be stimulated with afferent information. They created a prosthetic hand that had force sensors on the index and little fingers so that they functioned as artificial receptors. The information that was read from the sensors was converted into current-controlled biphasic pulse trains, with the amplitude derived from the sensor readout. This allowed for transformation of mechanical input into graded, somatotopically localised touch. Although the sensations typically mapped to the phantom digits (thumb/index, little finger) and were stable during the four weeks that observations were made, and charge levels were all well below any safety thresholds.

Motor commands were decoded using a multi-layer perceptron processing stump sEMG online. This led to a bi-directional closed-loop; voluntary sEMG directed prosthetic movement while sensory events initiated intraneural stimulation. They tested the participant under blindfolded and acoustically blocked conditions to ensure that he was relying on artificial sensations. Over 700 trials, participants were able to modulate quantifiable grip strength, discriminate between two different stiffening’s of objects, and identify and discriminate object shapes. During a week of daily testing, participants significantly improved their performance on the strength-measurement task, increasing their ability to recognize objects from about 67% to >90% accuracy compared with previous prostheses. In placebo trials, subjects did not have the ability to control the prosthesis in the off-stimulus condition, thus consolidating the causal relationship between them. In the speed perturbation, they observed that subjects had the most accurate accuracy at lower driving speeds, suggesting that it was also easy in terms of perceptual grading.

Functional tasks provided additional demonstration of ecological relevance - the participant, using the induced sensation, was able to locate objects on the palm and select appropriate grasps with ~97% accuracy. In stiffness recognition, additional features of stimulation dynamics permitted discrimination of hard, medium, and soft objects. In shape recognition, differential onset times for digits permitted reliable classification of cylinders, spheres, and smaller objects (~88% accuracy). Subjectively, the participant reported localized, graded touch that could be integrated into control without extended training [1].

This case demonstrates that artificial sensors can be used as alternatives to biological receptors to appropriately lift accurate haptic feedback at the neural level. More importantly, the central nervous system immediately receives signals from these receptors, suggesting that the prosthesis acts less

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like a robotic device and more like an embodied effector. In addition to task performance, the participant indicated that he had stable graded tactile sensation, which verifies that the intraneural coding represents preserved somatic sensations. This study demonstrates that artificial force sensors can act as alternative receptors that generate signals at the neural level and are quickly accepted by the CNS, setting the stage for future exploration of spinal reflex integration [1].

3.2. Reflex-level feedback via closed-loop tendon vibration

Sagastegui Alva et al. put forth a spinally anchored feedback paradigm which aims to instantiate prosthetic assistance within natural reflex loops as opposed to controller-level-based heuristics. To accomplish this, Sagastegui Alva et al. used a strap-mounted tactor to delivery vibration to the common wrist flexor tendons at subject-specific optimal frequencies (typically 120-140 Hz, ~0.6-1.3 mm amplitude). The stimulation from the tactor would excite the muscle spindle Ia/II nerve endings which increase α-motoneuron excitability monosynaptically and create reciprocal inhibition of the antagonists. because of that, they used voluntary semG and reflexive inputs to drive the prosthetic limb for movement, which reactivates natural spinal cord circuits [12].

The study demonstrates how reflex activation can be individualized and captured into closed-loop control. In practice, acceleration and vibration are incorporated into a type of task in the context of a practice task in specific loops, amputs showed improved stability in force output and reduced grip strength, while experiencing less variability and unexpected object sliding compared to closed-loop practices using only external vibrations without performing a specific task.

Conceptually, the significance of this work lies in two points. First, it demonstrated that it was possible to resend artificial sensory signals to the spinal reflex pathway, Second, it underscores that reflex-level integration enhances embodiment: instead of feeling like an autonomous robotic tool, the prosthesis becomes an extension of the neuromuscular system. This aligns directly with our thesis that neuroprosthetic design should restore the hierarchical logic of natural control, where cortical planning coexists with spinal reflex stabilization.

4. Challenges and future directions

Despite impressive advances in neuroprosthetic design, significant challenges remain before these systems can achieve robust clinical translation. Perhaps the most pressing issues arise at the interface between artificial devices and biological tissue. Intraneural electrodes, epineural cuffs, and other chronically implanted interfaces promise high-fidelity recording and stimulation, yet their long-term performance is threatened by fibrosis, scarring, and electrode migration. These tissue responses not only diminish signal quality over time but also heighten the risk of infection, ultimately jeopardizing the usability of the device. In some experiments, the implanted microelectrodes caused a reactive glial sheath and a rise in impedance at 1 kHz prior to stabilization, a pattern that affected unit stability and signal-to-noise ratio. Solving these problems requires innovation in materials. One solution is to use conductive polymer coatings such as PEDOT, which enlarge the effective interface area and reduce the impedance at low frequencies. It can also be used for flexible film arrays to reduce micromotion, and regenerative peripheral nerve interfaces (RPNIs) to couple nerves to autogenous muscle grafts, which are stable "bioamplifiers". In human studies, RPNIs can achieve reliable control of prosthetic fingers over a period of months [13].

Besides physical barriers, ethical and regulatory issues also represent a significant challenge to researchers. The most natural form of feedback is necessarily expressed with intraneural electrodes, dorsal root ganglion stimulation, or spinal cord stimulation, but all of these entail invasive

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procedures, causing substantial risk for infection, long-term neurological consequences, and significant risk for fibrosis. As a result of the risks presented in invasive experiments, invasive work faces more regulatory scrutiny and more hurdles to get approved [14]. In contrast, feedback that is non-invasive (i.e., electrotactile or vibration-tactile) can be safer and easier to endorse, but this is bandwidth-limited, and in most cases doesn't reproduce the natural tactile experience. This ultimately poses a dilemma: to get a good tactile experience, one has to go invasive, while the safety of a non-invasive procedure disregards the prosthetic performance.

Future work will be balance is balanced between these two-type experiment. For now, there are some invasive interfaces, for example microelectrode arrays that can sit subdermally or minimally invasive peripheral nerve methods, that may provide an intermediate risk trade-off. Beyond the technical trade-offs, ethical considerations are paramount. Patients must have paramount autonomy, meaning that invasive patients must not have a dis-incentive for the patient from refusing or withdrawing from invasive options at any time during the process. Additionally, equitable access should take center stage to ensure advanced neuroprostheses are not exclusively available to privileged few [15].

5. Conclusion

There is no doubt that from the theory of restoring feeling to people who have lost limbs, it is now possible to experiment. Emerging artificial receptors and biomimetic feedback systems have shown that tactile and proprioceptive signals can mimic natural afferents and engage spinal and motor cortical pathways. This integration allows the prosthesis to regulate its own strength, stiffness, and coordination-less like a tool and more like a true extension of the body. To fully realize this vision in the future, we will need to achieve stable, long-term neural interfaces and validate reproducible neural signals. Again, safety, ethical, and material concerns must be addressed if this is to go well. The ultimate goal is to produce a prosthetic limb that can not only obey commands, but also feel, adapt and self-regulate like a biological limb.

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