Proceedings of ICBioMed 2026 Symposium: Biomedical Engineering and Smart Medicine
DOI: 10.54254/2753-8818/2026.HZ35341

Neuro-Aligned Tactile Feedback for Upper Limb Prostheses: A Neuroanatomical Review and Evaluation Framework

Xinbi Luo

College of Medicine and Biological Information Engineering, Northeastern University, Shenyang, China

regina_0430@outlook.com

Abstract. Upper limb prostheses fail to deliver complete tactile sensation, so most users depend on visual guidance and excessively adjust their grasping movements. The core research focus has shifted from integrating sensory feedback to selecting optimal stimulation strategies for generating tactile perception that is functional, anatomically consistent and neurophysiologically natural. This paper presents a PRISMA-informed scoping review of recent tactile feedback published from January 1, 2020, to May 31, 2026, then integrates classic anatomy and neuroprosthetic papers to build a compact evaluation framework. The initial search retrieved 136 records from PubMed. After removing 4 duplicate entries, 132 unique articles were screened by title and abstract. A total of 20 full-text articles were evaluated, among which 16 studies were finally included. Another eight landmark studies were manually retrieved from Google Scholar, Web of Science and IEEE Xplore to supplement the analysis of cortical mapping, mechanoreceptors, proprioception, motor unit recruitment and interface evolution. The synthesis shows that the strongest studies do not optimize stimulus intensity alone. They align stimulation site, encoding rule, and evaluation metrics with the upper limb afferent route from cutaneous receptors to somatotopic hand area (S1) and with the motor route that stabilizes grasp through corticospinal drive and residual muscle recruitment. On the basis of the synthesis, this work proposes a neuroanatomical mechanism diagram and a three-part evaluation criterion covering perceptual realism, functional utility, and neural congruence. The proposed framework provides a practical evaluation scaffold for selecting tactile feedback strategies in future bionic limb studies.

Keywords: upper limb prosthesis, tactile feedback, neurostimulation, EEG, somatosensory evoked potentials

1. Introduction

Advanced prosthetic hands can open, close, and coordinate several grasp patterns, yet many users still operate them with limited touch. Without reliable feedback, users monitor force visually, contact is delayed, and embodiment remains weak [1-3]. The key question is therefore not whether feedback can be added, but which stimulation strategy can provide practical and natural touch. This criterion should follow hand anatomy. Cutaneous signals travel through the median, ulnar, and radial nerves,

DOI: 10.54254/2753-8818/2026.HZ35341

pass the dorsal column pathway, and reach the somatotopic hand area of S1 [4-7]. If artificial signals violate this spatial or temporal pathway, detection may remain possible while naturalness is lost.

Useful feedback must also fit the motor loop. Grasp correction depends on corticospinal command, motor unit recruitment, neuromuscular transmission, and proprioceptive estimation [8, 9]. After amputation, residual peripheral pathways can still support prosthetic control and sensation. Targeted muscle reinnervation improves motor command extraction, while targeted sensory reinnervation redirects sensory pathways for sensation restoration [10-12]. This review therefore judges tactile feedback through three linked criteria: pathway matching, motor benefit, and neural evidence.

2. Neuroanatomical basis and search method

2.1. Afferent and motor routes that matter for prosthetic touch

Realistic prosthetic touch should follow hand biology. SA1 afferents support edge and sustained pressure perception, RA1 and RA2 afferents support movement and vibration, and SA2 units contribute to stretch and position related cues. Hand posture also depends on muscle, tendon, joint, and central signals [4, 5, 9]. These signals converge into upper limb nerves and cortical body maps, which is why stimulation site matters as much as waveform.

Figure 1 shows two linked routes for prosthetic tactile feedback. The upper route represents cutaneous afferents, upper limb nerves, dorsal column relay, and S1, while the lower route shows motor command and residual muscle output. The bottom row summarizes the three evaluation criteria used throughout this review. Residual muscles respond to corticospinal commands through motor unit recruitment and neuromuscular junction transmission [8, 9]. Feedback becomes more valuable when it helps regulate force, timing, and correction with less visual compensation. This explains the appeal of residual nerve interfaces, targeted reinnervation, and bidirectional prostheses [10-13].

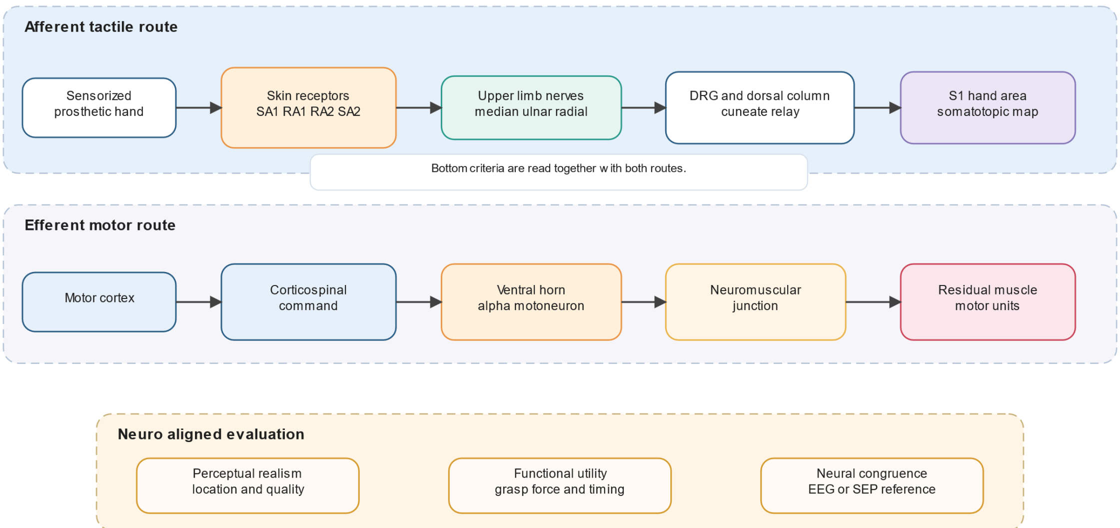

Figure 1. Neuroanatomical framework for prosthetic tactile feedback

DOI: 10.54254/2753-8818/2026.HZ35341

2.2. Search scope and evidence summary

The recent literature was screened using PRISMA 2020 reporting logic for transparency [14]. PubMed searches combined upper limb prosthesis, tactile or sensory feedback, neural stimulation, and EEG or SEP terms from January 1, 2020 to May 31, 2026. After duplicate removal and title, abstract, and full text screening, 16 recent studies were retained, and eight landmark papers were added to support the neuroanatomical framework.

Because this field does not yet have a shared public benchmark dataset, Table 1 summarizes evidence sources by cohort, signal route, task type, and outcome.

Table 1. Evidence sources and validation outcomes in prosthetic tactile feedback studies

Evidence group	Stimulus or signal source	Participants or data type	Task or validation setting	Outcome variables	Ref.
Noninvasive haptic feedback	Vibrotactile, pressure, electrotactile, and bone conduction cues	Able bodied volunteers and upper limb prosthesis users	Contact detection, force matching, wrist or grasp proprioception	Accuracy, force error, response time, comfort, and wearability	[15-24]
Peripheral nerve stimulation	Cuff or intraneural stimulation of residual nerves	Implanted upper limb amputees or clinical cases	Finger localization, tactile quality, and grasp control	Naturalness, sensitivity, task performance, and percept stability	[13, 25-27]
Targeted sensory reinnervation	Reinnervated skin or redirected sensory tissue	Transradial amputee evidence and clinical reports	Sensory mapping and proprioception testing	Finger specificity, embodiment, and proprioceptive restoration	[12]
Neural readout evidence	EEG and somatosensory evoked potentials	Case studies and prosthesis control tasks	Natural touch reference or task feedback comparison	SEP latency, cortical topography, and alpha desynchronization	[28, 29]

3. Focused synthesis

3.1. Modality landscape under pathway constraints

Noninvasive systems remain the fastest route to deployment. Vibration, skin pressure, electrotactile stimulation, and bone conduction can improve contact detection, force control, and wrist or grasp proprioception when the encoding rule is anatomically congruent and task matched [15-20, 23, 24]. Their main limits are comfort drift, weak receptor selectivity, and socket integration. Better discrimination does not necessarily improve embodiment unless the mapping is stable, comfortable, and useful in action [21-24].

Invasive or semi-invasive routes access the native pathway more directly. Intraneural timing studies, selective nerve fascicle stimulation, targeted sensory reinnervation, and bidirectional systems show that closer access to afferents can improve naturalness, finger specificity, and sensorimotor coupling [12, 13, 25-27]. Spinal stimulation is another option when peripheral access is restricted, but the evidence base is still small [30-32]. Table 2 summarizes representative methods and performance evidence across heterogeneous protocols.

DOI: 10.54254/2753-8818/2026.HZ35341

Table 2. Representative methods and reported performance evidence

Method group	Feedback route	Validation method	Reported performance evidence	Main caveat	Ref.
Cutaneous haptics	Vibration, pressure, electrotactile, or bone conduction	Psychophysics and task based tests	Improves detection, force matching, or proprioceptive judgement in short tasks	Comfort drift and limited receptor selectivity	[15-20, 23, 24]
Anatomically congruent electrotactile feedback	Skin afferent surrogate with hand mapped coding	Closed loop grasp and force control	Supports predictive and corrective grasp force control	User specific remapping and calibration	[19, 20, 24]
Intraneural feedback	Peripheral fascicle access	Bidirectional prosthesis and sensory timing tasks	Improves naturalness, tactile sensitivity, and manual function in selected cases	Implant burden and long term stability	[13, 25, 26]
EEG or SEP informed evaluation	Cortical response to artificial feedback	SEP or EEG readout with task comparison	Separates detectability from neural similarity	Natural touch reference is often missing	[28, 29]

3.2. Neural evidence and the current competitive direction

Neural recordings help test whether artificial feedback shares temporal or spatial features with natural tactile processing when natural touch, intact side stimulation, or matched control references are available. Noninvasive stimulation can elicit measurable SEP responses [28]. Task studies also show that tactile and visual feedback reshape EEG alpha activity and premotor engagement during prosthesis control [27, 29, 31].

The competitive point of this review is not a device ranking, but a compact evaluation framework. Existing summaries often compare modality preference. This paper combines receptor anatomy, upper limb conduction, motor loop constraints, and neural validation into one rule for judging prosthetic tactile feedback.

4. Proposed neuro-aligned evaluation rule

Figure 1 suggests a three part rule. Perceptual realism means plausible hand location, intensity progression, and tactile quality. Functional utility means better grasp success, force regulation, correction speed, or proprioceptive judgment. Neural congruence means EEG or SEP features approach natural touch, intact side stimulation, or a matched reference more closely than a symbolic cue [28, 29, 31].

The three branches should be read together. A pleasant cue is not enough if it does not help control, and a fast task benefit should not be presented as realistic touch if it depends on unnatural remapping. The best feedback is the stimulus that aligns body map, motor benefit, and neural evidence.

A compact experiment can use three phases: record a natural or matched reference, compare two encoding rules under shared contact or proprioception tasks, and score localization, task outcomes,

DOI: 10.54254/2753-8818/2026.HZ35341

and EEG or SEP responses together. This is feasible for a conference scale study because it adds one neural layer without requiring an implant trial.

5. Conclusion

This review clarifies what high performance tactile feedback should mean for upper limb prostheses. By combining receptor physiology, nerve conduction, cortical somatotopy, and motor unit characteristics, it connects haptic engineering with physiological authenticity.

This study remains a focused scoping review. The included studies differ in cohort size, amputation level, task design, and neural readout. Table 3 summarizes the main limitations and near term trends. Future work should report stimulation location, encoding rule, target perception, task design, training duration, comfort, and whether natural touch is used as the neural reference.

Table 3. Limitations and near term trends in prosthetic tactile feedback research

Approach	Trends	Limitations	Reporting priority	Ref.
Noninvasive cutaneous feedback	Wearable vibrotactile, pressure, electrotactile, and bone conduction codes	Comfort drift, socket burden, and limited receptor specificity	Stimulation site, intensity map, training time, comfort, and calibration drift	[15-24]
Peripheral nerve stimulation	Selective fascicle stimulation and bidirectional prosthesis trials	Surgery, small cohorts, and long term stability	Implant type, channel map, percept stability, adverse events, and follow up	[13, 25-27]
Neural validation	EEG and SEP added as evidence for tactile naturalness	Natural reference or intact side control is often missing	Latency, topography, adaptation, baseline, and reference condition	[28, 29, 31]
Review methodology	PRISMA informed scoping and citation chasing	Database coverage and screening reproducibility remain limited	Full query, exclusion reasons, screening dates, and charting fields	[14]

Tactile feedback for upper limb prostheses should follow the nervous system rather than only maximize stimulus strength. This paper reviewed recent tactile feedback studies, integrated classic neuroanatomical evidence, and proposed a rule based on perceptual realism, functional utility, and neural congruence. The framework helps distinguish detectable feedback from feedback that is functional and physiologically credible.

References

[1] Raspopovic, S., et al. (2021). Sensory feedback for limb prostheses in amputees. *Nature Materials, 20*, 925–939.

[2] Malesevic, N., & Antfolk, C. (2024). Sensory feedback in upper limb prosthetics: Advances and challenges. *Nature Reviews Neurology, 20*, 449–450.

[3] Sensinger, J. W., & Dosen, S. (2020). A review of sensory feedback in upper-limb prostheses from the perspective of human motor control. *Frontiers in Neuroscience, 14*.

[4] Johansson, R. S., & Vallbo, A. B. (1979). Tactile sensibility in the human hand. *Journal of Physiology, 286*, 283–300.

[5] Vallbo, A. B., & Johansson, R. S. (1984). Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human Neurobiology, 3*, 3–14.

[6] Abraira, V. E., & Ginty, D. D. (2013). The sensory neurons of touch. *Neuron, 79*, 618–639.

DOI: 10.54254/2753-8818/2026.HZ35341

[7] Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man. *Brain, 60*, 389–443.
[8] Henneman, E., et al. (1965). Functional significance of cell size in spinal motoneurons. *Journal of Neurophysiology, 28*, 560–580.
[9] Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses. *Physiological Reviews, 92*, 1651–1697.
[10] Dhillon, G. S., et al. (2004). Residual function in peripheral nerve stumps of amputees. *Journal of Hand Surgery, 29*, 605–615.
[11] Kuiken, T. A., et al. (2007). Targeted reinnervation for enhanced prosthetic arm function. *Lancet, 369*, 371–380.
[12] Gardetto, A., et al. (2025). Restoration of genuine sensation and proprioception following transradial amputation. *Plastic and Reconstructive Surgery*.
[13] Cady, S. R., et al. (2025). First-in-human implementation of a bidirectional somatosensory neuroprosthetic system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*.
[14] Page, M. J., et al. (2021). The PRISMA 2020 statement. *BMJ, 372*, n71.
[15] Su, S., et al. (2022). Optimizing non-invasive sensory feedback interfaces in neural prosthetic control. *Journal of Neural Engineering, 19*, 016028.
[16] Barontini, F., et al. (2023). Tactile feedback in upper limb prosthetics. *IEEE Transactions on Haptics*.
[17] Han, Y., et al. (2023). Substitutive proprioception feedback of a prosthetic wrist by electrotactile stimulation. *Frontiers in Neuroscience, 17*.
[18] Mayer, R. M., et al. (2023). Bone conduction as non-invasive haptic sensory feedback for upper-limb prosthesis. *Frontiers in Neuroscience, 17*.
[19] Garenfeld, M. A., et al. (2023). Closed-loop control with anatomically congruent electrotactile feedback. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*.
[20] Gasparic, F., et al. (2021). Sensory feedback for predictive and corrective grasp force control. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*.
[21] Smither, F. C., et al. (2022). Opinions on noninvasive sensory feedback of upper limb prosthetic users. *Prosthetics and Orthotics International, 46*, 591–600.
[22] Zbinden, J., et al. (2022). Prosthetic embodiment. *Journal of NeuroEngineering and Rehabilitation, 19*.
[23] Ivani, A. S., et al. (2024). PULSE: A dual haptic feedback device in a prosthetic socket. *IEEE ICRA*.
[24] Gholinezhad, S., et al. (2021). Electrotactile feedback outweighs natural feedback in grasp force control. *Journal of Neural Engineering, 18*, 056024.
[25] Valle, G., et al. (2018). Biomimetic intraneural sensory feedback enhances sensation. *Neuron*.
[26] Valle, G., et al. (2020). Sensitivity to temporal parameters of intraneural tactile sensory feedback. *Journal of NeuroEngineering and Rehabilitation*.
[27] Ranieri, F., et al. (2024). Sensorimotor integration by selective nerve fascicle stimulation. *Journal of Neuroscience*.
[28] Artoni, F., et al. (2020). Somatosensory evoked potentials following upper limb noninvasive electrical stimulation. *IEEE EMBC*.
[29] Su, S., et al. (2023). Neural evidence for tactile and visual feedback in myoelectric prosthesis use. *Journal of Neural Engineering, 20*, 016038.
[30] Soghoyan, G., et al. (2023). Peripheral nerve stimulation enables somatosensory feedback while suppressing phantom pain. *Brain Stimulation*.
[31] Soghoyan, G., et al. (2024). Restoration of natural somatic sensations to amputees. *Frontiers in Neuroscience*.
[32] Kharboush, R., et al. (2026). Transcutaneous spinal cord stimulation provides sensations to the missing hand. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*.