

Investigating Synchronized, Spatially Matched Multisensory Feedback Integrated with Neural
Prosthetic Motor Control to Reduce Phantom Limb Distortions

Harshika L.

South Forsyth High School

A Multisensory Framework for Future Neuroprosthetic Design

Abstract

Neuroprosthetic systems increasingly restore voluntary control through myoelectric, peripheral-nerve, and cortical interfaces, yet many devices provide limited somatosensory feedback and are primarily experienced as external tools rather than integrated body parts. Prosthetic embodiment is commonly described through ownership and agency, which depend on coherent integration of visual, tactile, proprioceptive, and motor-related information. This focused narrative review synthesizes multisensory psychophysics with human studies of artificial sensory feedback, phantom limb representation, and bidirectional prosthetic control. Several findings emerge from this review. Visual and haptic cues are weighted according to their relative reliability, and small human studies indicate that artificial intraneural or electrocutaneous signals can participate in comparable multisensory computations. Temporally synchronous stimulation can increase embodiment and reduce some phantom limb distortions, while emerging evidence suggests that exact anatomical matching is not always required when feedback is temporally coherent and functionally interpretable. Motor control and sensory feedback can each support embodiment; however, current evidence does not establish that closed-loop combinations consistently outperform their individual components. Together, these findings suggest that embodiment may be a useful neuroprosthetic design objective rather than only an incidental outcome. Future systems should coordinate voluntary motor intention with reliable, temporally aligned sensory consequences; personalize mappings to the user; and evaluate ownership, agency, function, pain, and daily use as distinct outcomes. This framework is evidence-informed but remains to be tested in larger, independent, longitudinal studies.

Keywords: prosthetic embodiment; multisensory integration; sensory feedback; neuroprosthetics; phantom limb; closed-loop control

1. Introduction

Contemporary neuroprostheses decode motor intention, translating signals from residual muscle activity, peripheral nerves, or cortical signals into movement (Wendelken et al., 2017; Gharabaghi et al., 2014). Despite these advances, the absence or limited fidelity of somatosensory feedback can constrain intuitive control, increase visual dependence, and limit the perceptual incorporation of many prostheses into the body (Schofield et al., 2014; Jabban et al., 2022).

Embodiment refers to the experience that an artificial device both belongs to the body (i.e., ownership) and is controlled as part of the body (i.e., agency) (Zbinden et al., 2022). These experiences are not produced by visual resemblance alone. Rather, they depend on whether sensory events, motor commands, and their consequences can be integrated into a coherent body representation (Zbinden et al., 2022; Di Pino et al., 2020).

Limb amputation removes normal sensory inflow while often preserving vivid phantom sensations and altered representations of the missing limb (Rognini et al., 2019; Risso et al., 2022). Phantom limb distortions may include telescoping, in which the phantom limb is perceived as shorter than the intact limb, as well as abnormal posture or altered perceived size and location of the missing limb (Rognini et al., 2019; Risso et al., 2022). Phantom limb pain can coexist with these distortions, but pain, body representation, ownership, and agency are not interchangeable outcomes and should not be treated as a single construct (Zbinden et al., 2022).

Evidence from multisensory neuroscience provides a potential framework for addressing this problem. The nervous system does not simply average sensory inputs; it weights them according to reliability and combines them when doing so improves the precision of perception (Ernst & Banks, 2002). This reliability-weighted framework provides a basis for considering how artificial sensory feedback might be incorporated with remaining sensory information. For artificial feedback to contribute to perception, it may therefore need to do more than simply produce a detectable sensation; it must provide sufficiently reliable and interpretable information that can be integrated with other sensory cues during an ongoing sensorimotor task (Risso et al., 2019; Risso et al., 2022).

This review examines how principles of multisensory integration can inform future neuroprosthetic design. It focuses on three linked questions: how the nervous system combines

natural and artificial sensory cues; how temporal, spatial, and functional congruence influence embodiment; and how sensory feedback can be coordinated with neural or myoelectric motor control. This review, therefore, evaluates the evidence linking multisensory integration, artificial sensory feedback, and motor control to prosthetic embodiment, while distinguishing experimentally demonstrated effects from proposed implications for future neuroprosthetic design.

2. Review Approach

This article is a focused narrative review with conceptual synthesis rather than a systematic review or meta-analysis. Relevant literature was identified through targeted searches of PubMed, Google Scholar, and IEEE Xplore using combinations of the following terms: prosthetic embodiment, multisensory integration, sensory feedback, phantom limb, neuroprosthesis, peripheral nerve interface, and brain-computer interface. Priority was given to peer-reviewed human studies examining artificial sensory feedback, ownership, agency, phantom limb distortions, and bidirectional prosthetic control. Foundational psychophysical work was included when it directly informed the computational interpretation of sensory integration, while reviews and perspective articles were used primarily to clarify terminology, translational barriers, and measurement frameworks (Ernst & Banks, 2002; Schofield et al., 2014; Jabban et al., 2022; Zbinden et al., 2022).

Because the available human literature includes single-case studies, small cohorts, different amputation levels, heterogeneous interfaces, and nonuniform outcome measures, the evidence is interpreted qualitatively rather than pooled statistically (Page et al., 2018; Risso et al., 2019; Rognini et al., 2019; Risso et al., 2022). Claims concerning efficacy are therefore limited to the experimental conditions in which they were observed. The proposed design framework is an inference drawn across studies and should be tested prospectively.

Study	Participants / interface	Main outcome	Relevance
Ernst & Banks (2002)	4 human observers; visual-haptic size-discrimination task	Reliability-weighted cue integration	Computational foundation for interpreting multisensory cue integration
Risso et al. (2019)	1 upper-limb amputee; intraneural sensory feedback + myoelectric prosthetic control	Artificial touch integrated with vision	Feasibility of optimal integration
Rognini et al. (2019)	2 upper-limb amputees; intraneural stimulation	Greater embodiment; reduced telescoping	Role of temporal synchrony
Risso et al. (2022)	3 lower-limb amputees; 2 participants in optimal-integration experiment; VR + electrocutaneous feedback	Greater embodiment; reduced distortions	Non-spatial mapping can be integrated and influence body representation
Aurucci et al. (2024)	2 Lower-limb amputees and 16 healthy controls; VR +	Optimal integration despite non-spatial	Challenges assumption that exact spatial matching is

	electrocutaneous stimulation	match; healthy controls optimally integrated spatially matched cues	universally required for optimal integration
Page et al. (2018)	1 long-term (14-month study) upper-limb amputee; peripheral nerve interfaces + prosthetic motor control	Motor and sensory conditions each enhanced embodiment	Component contributions from both motor control and sensory feedback without demonstration superior closed-loop effect

Table 1. Representative evidence informing the conceptual framework. The table summarizes relevance to review.

3. Embodiment as a Multisensory and Sensorimotor Construct

Prosthetic embodiment is not a unitary sensation. Static laboratory paradigms may induce ownership through visuotactile congruence, whereas dynamic prosthetic use additionally requires volitional control and coherent sensory consequences (Zbinden et al., 2022).

In a foundational visual-haptic experiment involving four human observers performing a size-discrimination task, Ernst and Banks (2002) manipulated the reliability of visual information and examined how participants combined visual and haptic estimates. Participants combined the two cues in a manner closely approximating maximum-likelihood integration, with each cue

weighted according to its relative reliability. The combined estimate approached the lowest variance achievable from the available unimodal signals (Ernst & Banks, 2002). This finding established that perceptual dominance is context-dependent: vision dominates when it is more reliable, but haptic information receives greater weight when visual reliability is reduced (Ernst & Banks, 2002).

Taken together, these findings suggest that adding a detectable sensory channel by itself does not establish that the signal will be integrated with other sensory information. In the intraneural study by Risso et al. (2019), artificial somatosensory feedback was successfully combined with visual information according to reliability-weighted integration. This finding suggests that the reliability of artificial feedback, rather than detectability alone, is an important consideration when designing feedback intended to participate in multisensory perception (Ernst & Banks, 2002; Risso et al., 2019).

Evidence from an amputee using a bidirectional hand prosthesis supports this interpretation. During object-size estimation, intraneural stimulation proportional to grasped-object size was combined with blurred visual information in a manner consistent with statistically optimal integration (Risso et al., 2019). The participant controlled the prosthetic hand through surface electromyography, while intraneural stimulation evoked a vibration-like sensation in the phantom hand that substituted for missing haptic feedback (Risso et al., 2019). Although this study involved only one participant and one perceptual task, it demonstrates the feasibility of integrating artificial intraneural somatosensory feedback with visual information in a manner consistent with statistically optimal multisensory integration (Risso et al., 2019).

Collectively, these findings suggest that artificial feedback should be designed as information to be integrated, not simply as stimulation to be perceived. The relevant question is therefore not only whether a user can feel the signal, but whether the nervous system can assign it an appropriate weight during perception and action.

4. Temporal Synchrony, Spatial Mapping, and Functional Congruence

Across the small experimental studies reviewed here, temporal synchrony repeatedly influenced the strength of induced embodiment. In a study of two transradial amputees implanted with transverse intrafascicular multichannel electrodes, synchronous pairing of neurally evoked

phantom-hand touch with visual illumination of the corresponding prosthetic-hand region produced higher embodiment ratings than asynchronous pairing (Rognini et al., 2019). The synchronous condition also reduced telescoping—the perception that the phantom limb is shorter than the intact limb—by shifting the perceived phantom fingertip distally, and this change persisted for approximately ten minutes after stimulation ended (Rognini et al., 2019). The small sample and brief follow-up prevent conclusions about durability, but the condition-specific effect supports a role for temporal coherence.

A noninvasive lower-limb study extended this principle using virtual reality and electrocutaneous stimulation applied to the residual limb (Risso et al., 2022). Three male participants with unilateral transfemoral amputation participated overall; two completed the psychophysical optimal-integration experiment, while all three participated in the embodiment experiment. The two amputees who completed the psychophysical task combined visual and tactile cues in a manner consistent with optimal integration and responded faster under multisensory than unimodal conditions; across the embodiment experiment, synchronous stimulation increased embodiment in all three participants and reduced reported phantom limb distortions in the participants who exhibited those distortions (Risso et al., 2022).

These results also challenge the assumption that successful feedback must reproduce the exact anatomical location of the missing receptor. In the lower-limb paradigm, tactile stimulation was delivered to the stump or thigh while visual stimulation appeared at the virtual foot, yet the cues were still optimally integrated (Risso et al., 2022). A later study reported that two amputees optimally integrated non-spatially matched cues at the amputated leg, whereas healthy controls showed optimal integration only for spatially matched cues (Aurucci et al., 2024). Optimal integration was also associated with shorter reaction times and lower electroencephalography-derived mental workload in that experiment (Aurucci et al., 2024).

5. Motor Control and Artificial Sensory Feedback

In contrast to natural limb control, prosthetic control often relies on residual electromyographic or neural signals with sensory consequences supplied mainly through vision (Schofield et al., 2014; Wendelken et al., 2017). Bidirectional systems seek to decode motor intention and deliver artificial tactile or proprioceptive information through peripheral nerve stimulation or other feedback channels (Wendelken et al., 2017; Jabban et al., 2022).

High-channel-count peripheral interfaces have demonstrated substantial technical capacity. In two participants with upper-limb amputation, Utah Slanted Electrode Arrays implanted in median and ulnar nerves supported multidimensional motor decoding and evoked numerous cutaneous and proprioceptive percepts distributed across the phantom hand (Wendelken et al., 2017). One participant also used evoked sensation as feedback during a closed-loop virtual-hand task (Wendelken et al., 2017). The implants were evaluated for four to five weeks, so long-term stability and routine home use were not established (Wendelken et al., 2017).

In one participant with long-term transradial amputation, open-loop motor control, open-loop sensory stimulation, and closed-loop motor control with sensory feedback each produced significant embodiment effects measured objectively through proprioceptive drift—the perceived location of the phantom hand toward the prosthesis—and subjectively through survey responses assessing the participant’s experience of the prosthesis (Page et al., 2018). Phantom pain also decreased after sessions involving sensory stimulation, motor control, or closed-loop use (Page et al., 2018). However, closed-loop control did not significantly outperform the individual motor-only or sensory-only conditions, and the single-case design prevents generalization (Page et al., 2018).

This result places an important boundary on the interpretation of closed-loop effects. The available evidence supports the conclusion that both volitional control and artificial sensation can contribute to embodiment, but it does not yet prove that combining them always produces additive or superior effects. Their interaction may depend on timing, task demands, training, feedback reliability, and the degree to which the sensory consequence matches the user’s motor prediction.

Studies extending beyond acute laboratory sessions provide additional evidence about the functional and experiential effects of sensory feedback. In a six-month clinical study, three transradial amputees implanted with transverse intrafascicular multichannel electrodes received intraneural tactile feedback while performing grasping tasks. All three participants reported stimulation-induced phantom-hand sensations throughout the six-month trial, integrated the sensory feedback into their motor-control strategies during experimental tasks, and reported reductions in phantom limb pain (Petrini et al., 2019). In a separate four-week home-use study, seven forearm amputees used a noninvasive sensory-feedback system during everyday life.

Participants described the feedback as producing a feeling of touch and contributing to a sense of completeness; however, quantitative measures did not demonstrate corresponding improvements in agency or activity performance (Wijk et al., 2020). These differing outcomes reinforce the need to evaluate detectability, functionality, ownership, agency, pain, and satisfaction as distinct outcomes.

6. Evidence Synthesis

Four conclusions emerge across the reviewed evidence. First, artificial sensory signals can participate in reliability-weighted multisensory computations rather than remaining isolated or purely symbolic cues (Risso et al., 2019; Risso et al., 2022). Second, temporal synchrony repeatedly strengthens embodiment relative to asynchronous control conditions in small experimental samples (Rognini et al., 2019; Risso et al., 2022). Third, anatomically exact spatial matching is not universally required for optimal integration in amputees, although stable and interpretable mapping remains necessary (Risso et al., 2022; Aurucci et al., 2024). Fourth, motor control and sensory feedback can each contribute to embodiment, but current evidence does not establish that their closed-loop combination is consistently superior (Page et al., 2018).

Evidence Synthesis and Confidence Boundaries

Established foundation	Converging human evidence	Open translational questions
High confidence	Moderate confidence	Unresolved
Visual and haptic cues are weighted by relative reliability.	Artificial intraneural and electrocutaneous cues can enter multisensory computations.	Whether closed-loop systems reliably outperform simpler conditions.
Congruent sensory cues can improve perceptual precision.	Synchronous stimulation can strengthen ownership or embodiment in small samples.	Whether short-term embodiment effects persist during daily use.
Multisensory integration provides a computational basis for body-related perception.	Motor control and sensory feedback can each contribute to agency and ownership.	Whether stronger embodiment improves acceptance, function, or long-term quality of life.

Interpretation rule: confidence decreases as evidence moves from general multisensory principles to long-term clinical outcomes.

Figure 2. Evidence synthesis and confidence boundaries. The literature strongly supports reliability-weighted multisensory integration as a general principle, while evidence specific to amputees and neuroprosthetic embodiment remains promising but is limited by small samples, short-term designs, and heterogeneous measures. Closed-loop superiority has not been established consistently.

These conclusions support shifting emphasis from interface-centered design to integration-centered design. Interface type remains important because invasiveness, selectivity, stability, and accessibility shape what information can be delivered (Jabban et al., 2022). However, an advanced interface will not necessarily produce embodiment if the resulting cues are delayed, inconsistent, cognitively demanding, or unrelated to the user's motor intention.

The principal unresolved question is not whether sensory feedback is beneficial in general. It is which combinations of motor contingency, temporal alignment, functional mapping, cue reliability, and training produce durable embodiment during daily use. Existing studies identify plausible components of this process, but their small samples and heterogeneous methods do not yet define an optimal configuration.

7. Proposed Framework for Embodied Neuroprosthetic Design

Building on the empirical evidence reviewed above, this review proposes an embodiment-centered framework for future neuroprosthetic design. Prior studies have shown that artificial sensory feedback can be integrated with visual information, temporal synchrony can strengthen experimentally induced embodiment, and motor control and sensory feedback can each contribute to embodiment. These findings are interpreted here to suggest that embodiment may be supported when voluntary motor intention is consistently paired with reliable, temporally aligned, and functionally interpretable sensory consequences. The proposed framework translates this synthesis into a set of design principles involving motor-sensory contingency, temporal alignment, cue reliability, functional mapping, and user-specific adaptation. Because these components have not been tested together as a unified model, the framework should be understood as an evidence-informed synthesis intended to guide testable hypotheses rather than as a validated clinical protocol.

Embodiment-Centered Neuroprosthetic Design Framework

Design variables: temporal alignment • cue reliability • functional interpretability • adaptive personalization

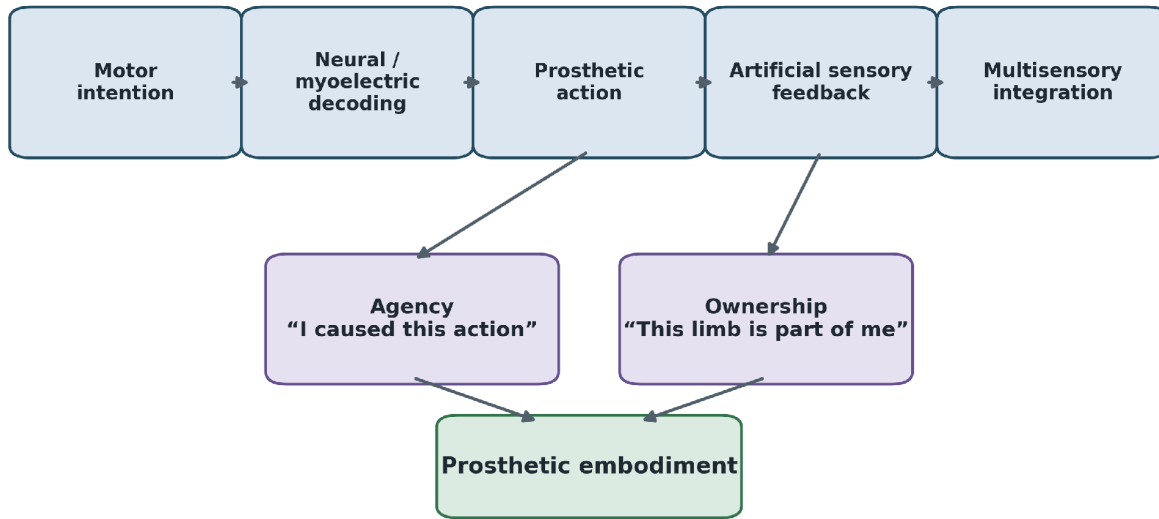


Figure 3. Embodiment-centered neuroprosthetic design framework. Voluntary intention is decoded into prosthetic action, which generates artificial sensory consequences. When those consequences are reliable, temporally aligned, and interpretable, they can contribute to multisensory integration, agency, ownership, and ultimately prosthetic embodiment. The final link to durable functional benefit remains a hypothesis requiring longitudinal validation.

First, sensory consequences should be contingent on the user’s voluntary motor intention. Agency depends partly on the correspondence between intended action and observed outcome, and dynamic prosthetic embodiment therefore requires more than passive stimulation (Zbinden et al., 2022). Feedback should occur within tasks in which the user initiates, predicts, and corrects movement.

Second, temporal alignment should be treated as a core control parameter. Synchronous visual and tactile or neurotactile stimulation has produced stronger embodiment than asynchronous stimulation in both upper- and lower-limb paradigms (Rognini et al., 2019; Risso et al., 2022). Closed-loop systems should therefore minimize variable delays between contact, device state, and perceived feedback.

Third, mappings should be functionally meaningful and stable, even when exact anatomical matching is unavailable. Non-spatially matched feedback can be optimally integrated in amputees under controlled conditions (Risso et al., 2022; Aurucci et al., 2024). The design goal should be a learnable and consistent relationship between device events and perceived sensory consequences.

Fourth, systems should optimize cue reliability rather than maximize the number of feedback channels. Maximum-likelihood integration predicts that unreliable cues will receive little weight, whereas more reliable cues will dominate perception (Ernst & Banks, 2002). Calibration should therefore prioritize discriminability, consistency, and task relevance before adding complexity.

Fifth, the system should adapt to the individual user. Amputation level, residual nerve anatomy, phantom percepts, sensory thresholds, prior prosthesis use, and training history can alter how feedback is perceived and integrated (Jabban et al., 2022; Zbinden et al., 2022). Personalization should include both stimulation parameters and the functional meaning assigned to the feedback.

Finally, embodiment should be measured as a multidimensional outcome. Ownership, agency, functional performance, visual dependence, phantom distortions, pain, cognitive workload, satisfaction, and home-use behavior provide nonredundant information (Zbinden et al., 2022). A system that improves one dimension should not be assumed to improve all others.

In condensed form, the framework is: voluntary motor intention produces prosthetic action; prosthetic action generates temporally aligned and reliable sensory consequences; those consequences are integrated with vision, proprioception, and motor prediction; successful integration supports agency and ownership; and repeated, task-relevant integration may promote more stable embodiment. The final link to durable recalibration of phantom representation remains a testable hypothesis rather than an established mechanism.

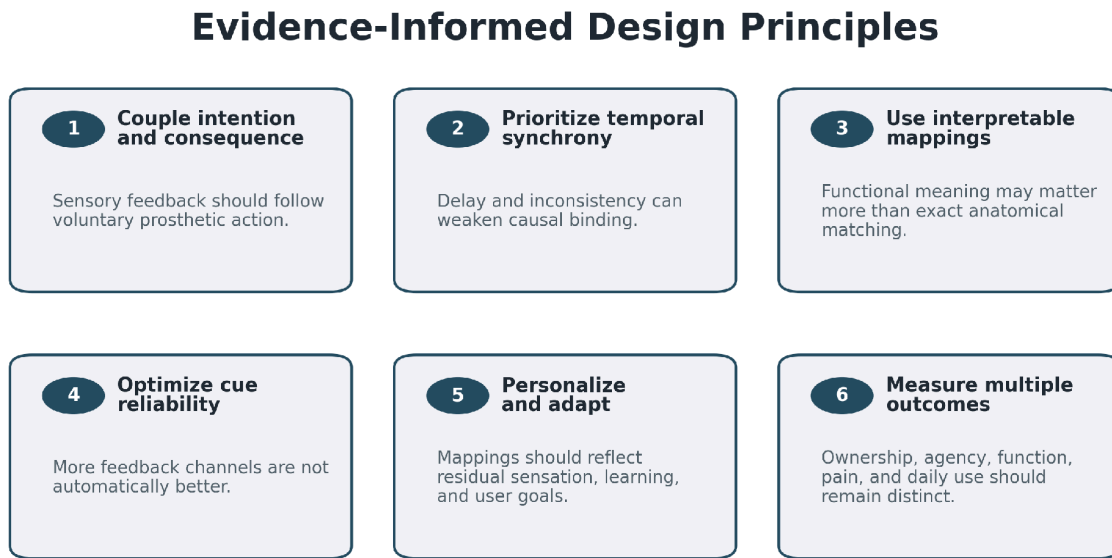
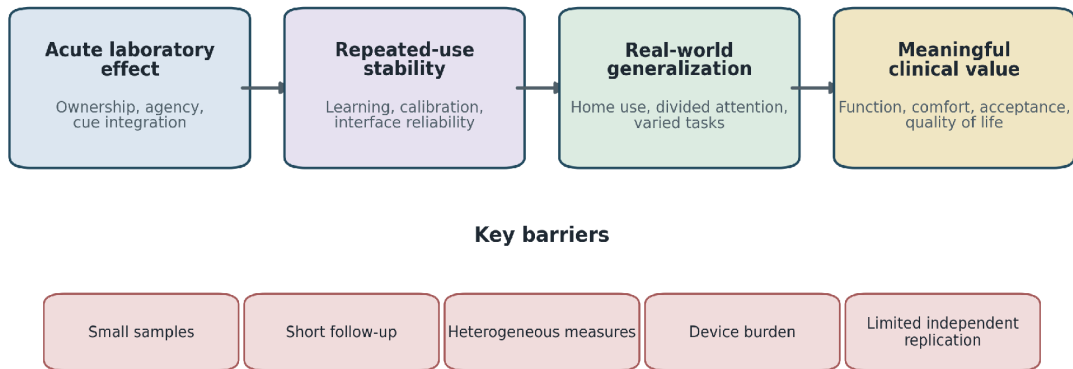


Figure 4. Evidence-informed design principles for embodiment-centered neuroprostheses. The proposed framework emphasizes coupling motor intention with sensory consequences, prioritizing temporal synchrony, using functionally meaningful mappings, optimizing cue reliability, personalizing feedback, and measuring ownership and agency separately from performance and pain.

8. Clinical and Translational Significance

Treating embodiment as a design objective could improve how neuroprosthetic systems are evaluated. Device performance is commonly assessed through task completion, decoding accuracy, or grasp success, but these measures do not determine whether the device is experienced as part of the body (Zbinden et al., 2022). Embodiment-related outcomes may capture clinically relevant effects that conventional engineering metrics miss.

Translational Pathway from Laboratory Integration to Clinical Value



Clinical translation requires persistence, generalization, and user-relevant benefit—not embodiment scores alone.

Figure 5. Translational pathway from laboratory integration to clinical value. Acute embodiment effects must persist through repeated use, generalize to daily environments, improve outcomes valued by users, and remain safe and stable before they can support long-term prosthesis adoption.

The framework may also reduce unnecessary dependence on perfect biomimicry. Fully reproducing natural touch and proprioception remains technically difficult, particularly with interfaces that must remain safe and stable over long periods (Jabban et al., 2022). Evidence that stable remapped feedback can be integrated suggests that useful embodiment may be possible without recreating every natural afferent pattern (Risso et al., 2022; Aurucci et al., 2024).

However, embodiment should not be assumed to guarantee prosthesis acceptance. Current reviews note that claims linking embodiment directly to acceptance are not yet adequately established, and user priorities also include comfort, reliability, appearance, maintenance, cost, and functional value (Zbinden et al., 2022; Jabban et al., 2022). Embodiment is therefore best understood as one important translational objective within a broader patient-centered design process.

9. Limitations of the Evidence

The strongest limitation is sample size. Several influential studies involved one to three amputees, which permits detailed mechanistic investigation but provides limited information about between-user variability (Page et al., 2018; Risso et al., 2019; Rognini et al., 2019; Risso et al., 2022). Findings from these studies should not be interpreted as prevalence estimates or definitive clinical effects.

Outcome heterogeneity creates an additional problem. Embodiment has been assessed through questionnaires, proprioceptive drift, body-landmark judgments, peripersonal-space measures, and task-specific reports, and these measures do not necessarily assess the same construct (Di Pino et al., 2020; Zbinden et al., 2022). Phantom pain, phantom distortions, ownership, and agency are sometimes discussed together despite representing distinct outcomes.

Most experiments were conducted under tightly controlled laboratory conditions and over short periods (Rognini et al., 2019; Risso et al., 2019; Risso et al., 2022). Short-term embodiment illusions may not predict sustained daily-life embodiment, and implanted-interface performance over weeks or months may not predict stability over years (Wendelken et al., 2017; Petrini et al., 2019).

The field also contains substantial methodological diversity. Studies differ in amputation level, interface type, stimulation modality, spatial mapping, task complexity, training duration, and availability of visual feedback (Jabban et al., 2022). This diversity is scientifically informative but prevents simple ranking of approaches.

A further limitation is the concentration of evidence. Several influential findings concerning optimal multisensory integration and phantom limb representation originate from overlapping investigators and closely collaborating research groups (Risso et al., 2019; Rognini et al., 2019; Risso et al., 2022; Aurucci et al., 2024). Independent replication across centers, interfaces, and participant populations is needed before these effects can be considered broadly generalizable. Finally, the framework proposed in this review is interpretive. Its components are supported individually by the literature, but the complete causal sequence has not been tested in a sufficiently powered longitudinal trial. It should therefore guide hypothesis formation and experimental design rather than be treated as a validated clinical protocol.

10. Future Directions

Future studies should directly manipulate timing, mapping, reliability, and motor contingency within the same participants. Factorial designs could determine whether temporal synchrony remains beneficial when cue reliability is low, whether remapped feedback performs as well as somatotopic feedback after training, and whether closed-loop combinations produce effects beyond motor or sensory components alone.

Longitudinal trials should evaluate whether embodiment persists outside the laboratory and whether it changes prosthesis use, visual attention, confidence, pain, participation, and device abandonment. Home-use studies are particularly important because they can evaluate whether embodiment effects remain durable over longer periods, whether sensory-feedback systems remain feasible and stable during daily use, and whether these effects persist across changing activities and environmental demands (Zbinden et al., 2022).

Standardized reporting would improve comparison across studies. At minimum, investigators should report ownership, agency, task performance, phantom pain, phantom distortions, stimulation stability, adverse events, training exposure, and the degree of visual feedback available. Multidimensional measurement would prevent improvement in one outcome from being generalized to all aspects of embodiment.

Adaptive systems represent another important direction. Real-time adjustment of stimulation intensity, timing, or coding could maintain cue discriminability as thresholds or electrode responses change. Such adaptation should be constrained by user comprehension and perceptual stability, because a constantly changing code may reduce rather than improve integration.

Finally, future research should compare invasive and noninvasive strategies according to the same integration principles. The relevant contrast is not simply surgical versus nonsurgical. It is whether each approach can deliver reliable, temporally coherent, functionally interpretable information during meaningful voluntary action.

11. Toward the Next Generation of Embodied Neuroprostheses

Current evidence supports the view that neuroprosthetic embodiment arises from coordinated multisensory and sensorimotor integration rather than from motor performance or sensory restoration alone. Artificial tactile information can be combined with vision according to

reliability-weighted principles, synchronous multisensory stimulation can strengthen embodiment and reduce some phantom distortions, and anatomically exact feedback is not always required for integration in amputees (Ernst & Banks, 2002; Risso et al., 2019; Rognini et al., 2019; Risso et al., 2022; Aurucci et al., 2024). Motor control and sensory feedback each contribute to embodiment, but evidence for a consistently superior closed-loop effect remains insufficient (Page et al., 2018).

The most defensible innovation is therefore conceptual rather than technological: embodiment should be treated as a primary design objective. Future neuroprostheses should coordinate voluntary motor intention with temporally aligned, reliable, and functionally meaningful sensory consequences, while evaluating ownership, agency, function, pain, and daily use as separate outcomes. This framework remains to be validated, but it provides a testable basis for moving neuroprosthetic development from the restoration of isolated functions toward the integration of artificial limbs within the user's body representation.

References

- Aurucci, G. V., Preatoni, G., Risso, G., & Raspopovic, S. (2024). Amputees but not healthy subjects optimally integrate non-spatially matched visuo-tactile stimuli. *iScience*.
<https://doi.org/10.1016/j.isci.2024.111685>
- Di Pino, G., Romano, D., Spaccasassi, C., Mioli, A., D'Alonzo, M., Sacchetti, R., Guglielmelli, E., Zollo, L., Di Lazzaro, V., Denaro, V., & Maravita, A. (2020). Sensory- and action-oriented embodiment of neurally-interfaced robotic hand prostheses. *Frontiers in Neuroscience*, 14, 389. <https://doi.org/10.3389/fnins.2020.00389>
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870), 429–433. <https://doi.org/10.1038/415429a>
- Gharabaghi, A., Naros, G., Walter, A., Roth, A., Bogdan, M., Rosenstiel, W., Mehring, C., & Birbaumer, N. (2014). Epidural electrocorticography of phantom hand movement following long-term upper-limb amputation. *Frontiers in Human Neuroscience*, 8, 285.
<https://doi.org/10.3389/fnhum.2014.00285>
- Jabban, L., Dupan, S., Zhang, D., Ainsworth, B., Nazarpour, K., & Metcalfe, B. W. (2022). Sensory feedback for upper-limb prostheses: Opportunities and barriers. *IEEE Transactions*

on Neural Systems and Rehabilitation Engineering, 30, 738–747.

<https://doi.org/10.1109/TNSRE.2022.3159186>

Page, D. M., George, J. A., Kluger, D. T., Duncan, C., Wendelken, S., Davis, T., Hutchinson, D. T., & Clark, G. A. (2018). Motor control and sensory feedback enhance prosthesis embodiment and reduce phantom pain after long-term hand amputation. *Frontiers in Human Neuroscience*, 12, 352. <https://doi.org/10.3389/fnhum.2018.00352>

Petrini, F. M., Valle, G., Strauss, I., Granata, G., Di Iorio, R., D'Anna, E., Čvančara, P., Mueller, M., Carpaneto, J., Clemente, F., Controzzi, M., Bisoni, L., Carboni, C., Barbaro, M., Iodice, F., Andreu, D., Hiairassary, A., Divoux, J.-L., Cipriani, C., Guiraud, D., Raffo, L., Fernandez, E., Stieglitz, T., Raspopovic, S., Rossini, P. M., & Micera, S. (2019). Six-month assessment of a hand prosthesis with intraneural tactile feedback. *Annals of Neurology*, 85(1), 137–154. <https://doi.org/10.1002/ana.25384>

Risso, G., Valle, G., Iberite, F., Strauss, I., Stieglitz, T., Controzzi, M., Clemente, F., Granata, G., Rossini, P. M., Micera, S., & Baud-Bovy, G. (2019). Optimal integration of intraneural somatosensory feedback with visual information: A single-case study. *Scientific Reports*, 9, 7916. <https://doi.org/10.1038/s41598-019-43815-1>

Risso, G., Preatoni, G., Valle, G., Marazzi, M., Bracher, N. M., & Raspopovic, S. (2022). Multisensory stimulation decreases phantom limb distortions and is optimally integrated. *iScience*, 25(4), 104129. <https://doi.org/10.1016/j.isci.2022.104129>

Rognini, G., Petrini, F. M., Raspopovic, S., Valle, G., Granata, G., Strauss, I., Solcà, M., Bello-Ruiz, J., Herbelin, B., Mange, R., D'Anna, E., Di Iorio, R., Di Pino, G., Andreu, D., Guiraud, D., Stieglitz, T., Rossini, P. M., Serino, A., Micera, S., & Blanke, O. (2019). Multisensory bionic limb to achieve prosthesis embodiment and reduce distorted phantom limb perceptions. *Journal of Neurology, Neurosurgery & Psychiatry*, 90(7), 833–836. <https://doi.org/10.1136/jnnp-2018-318570>

Schofield, J. S., Evans, K. R., Carey, J. P., & Hebert, J. S. (2014). Applications of sensory feedback in motorized upper extremity prosthesis: A review. *Expert Review of Medical Devices*, 11(5), 499–511. <https://doi.org/10.1586/17434440.2014.929496>

- Wendelken, S., Page, D. M., Davis, T., Wark, H. A. C., Kluger, D. T., Duncan, C., Warren, D. J., Hutchinson, D. T., & Clark, G. A. (2017). Restoration of motor control and proprioceptive and cutaneous sensation in humans with prior upper-limb amputation via multiple Utah Slanted Electrode Arrays implanted in residual peripheral arm nerves. *Journal of NeuroEngineering and Rehabilitation*, 14, 121. <https://doi.org/10.1186/s12984-017-0320-4>
- Wijk, U., Carlsson, I. K., Antfolk, C., Björkman, A., & Rosén, B. (2020). Sensory feedback in hand prostheses: A prospective study of everyday use. *Frontiers in Neuroscience*, 14, 663. <https://doi.org/10.3389/fnins.2020.00663>
- Zbinden, J., Lendaro, E., & Ortiz-Catalan, M. (2022). A multi-dimensional framework for prosthetic embodiment: A perspective for translational research. *Journal of NeuroEngineering and Rehabilitation*, 19, 122. <https://doi.org/10.1186/s12984-022-01102-7>