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Designing for Phantom Limb Syndrome in Amputees: Augmented Reality as a Tool to Restore Body Representation and Reduce Phantom Pain

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***Abstract* - Phantom limb syndrome (PLS), characterized by the perception of a missing limb often accompanied by pain, remains a significant yet under addressed challenge in prosthetic rehabilitation. It arises primarily from disruptions in internal body representation and maladaptive neuroplasticity following amputation. The PHANTOMAR project, conducted at the Eindhoven Artificial Intelligence Systems Institute (EAISI), investigates the underlying mechanisms of phantom limb pain (PLP) and proposes an augmented reality (AR)-based intervention to restore body representation and improve functional outcomes. The study is structured in three phases: (1) quantitative and qualitative assessment of sensorimotor control and movement patterns under the influence of phantom pain, (2) development of an AR-based body representation tool to reconstruct internal limb perception, and (3) integration of haptic and force feedback through virtual and augmented environments to enhance sensorimotor coherence. Validation is performed using a functional prosthetic leg prototype with prior clinical data. The results demonstrate that AR-mediated embodiment significantly improves motor planning, reduces pain perception, and enhances rehabilitation engagement. The findings highlight the potential of immersive technologies as clinically relevant tools for treating phantom limb pain and advancing prosthetic design.**

Keywords: sensorimotor system, hierarchical control, upper extremity.

I. INTRODUCTION

Phantom limb syndrome (PLS) affects a substantial proportion of amputees, with estimates indicating that up to 85% experience phantom sensations and a significant subset develops chronic phantom limb pain (PLP). Despite advances in prosthetic engineering, most devices are designed with a primary focus on biomechanical performance, often neglecting the cognitive and neurological dimensions of limb loss.

PLP is increasingly understood as a consequence of disrupted internal body representation, involving cortical reorganization within sensorimotor areas. The mismatch between motor intention and absent sensory feedback leads to persistent prediction errors, reinforcing maladaptive neural patterns (Figure 1).

Traditional therapeutic approaches – such as mirror therapy, pharmacological interventions, and neuromodulation – offer partial relief but are limited in scalability and personalization. Emerging technologies, particularly augmented reality (AR), provide an opportunity to address the root cause of PLS by restoring coherent body representation in real time.

Figure 1: Neurophysiological basis of phantom limb pain. Following amputation, cortical reorganization in the sensorimotor cortex leads to a mismatch between motor intention and absent sensory feedback, resulting in persistent prediction error signals and pain perception

The PHANTOMAR project aims to bridge the gap between prosthetic biomechanics, neuroscience, and immersive technologies, proposing AR as a tool to re-establish sensorimotor integration and reduce phantom pain [1,2,7].

II. BACKGROUND AND THEORETICAL FRAMEWORK

Phantom limb syndrome (PLS) represents a complex neurocognitive and sensorimotor disorder arising from the disruption of embodied perception following limb loss. Its manifestation – particularly phantom limb pain (PLP) – cannot be fully explained by peripheral mechanisms alone, but instead reflects multilevel reorganization across cortical, subcortical, and sensorimotor systems. This section integrates contemporary frameworks from neuroscience, computational modeling, and rehabilitation engineering to establish the conceptual basis for AR-mediated intervention [3,4,6].

2.1 Phantom Limb Pain and Neuroplasticity

PLP is widely recognized as a consequence of maladaptive neuroplasticity following deafferentation. After amputation, the abrupt loss of afferent input from the missing limb leads to functional and structural reorganization within the primary somatosensory cortex (S1) and primary motor cortex (M1). Adjacent cortical representations invade the deafferented region, a process often referred to as cortical remapping.

This reorganization is not merely epiphenomenal – it is strongly correlated with pain intensity. Functional imaging studies (e.g., fMRI, MEG) have demonstrated that:

- The degree of cortical invasion correlates with reported PLP severity
- Abnormal activity persists in the “phantom” representation area
- Sensorimotor incongruence amplifies nociceptive processing

Beyond cortical remapping, PLP is increasingly interpreted through the lens of **predictive coding** and **Bayesian brain models**. In this framework, the brain continuously generates predictions about expected sensory inputs based on internal models. These predictions are compared against actual sensory feedback:

- **Prediction (motor intention)**: “The limb should move and generate feedback”
- **Sensory input**: Absent or inconsistent due to amputation
- **Prediction error**: Persistent mismatch

This unresolved prediction error is hypothesized to drive both phantom perception and pain. The brain, unable to reconcile the discrepancy, may interpret the mismatch as a pathological signal, resulting in chronic pain.

Additionally, **central sensitization** mechanisms contribute to PLP persistence. Increased excitability in spinal and supraspinal pathways lowers the threshold for pain perception, leading to amplified responses even in the absence of peripheral stimuli.

2.2 Body Representation, Body Schema and Embodiment

The persistence of phantom sensations highlights the robustness of internal body representations, which are not immediately updated following physical loss (Figure 2). Two complementary constructs are critical:

- **Body schema**: A dynamic, sensorimotor representation used for action and movement planning
- Body image: A conscious, perceptual representation of body structure and appearance

After amputation, these representations become **decoupled** from physical reality. The body schema may continue to include the missing limb, while sensory confirmation is absent, resulting in instability of the internal model.

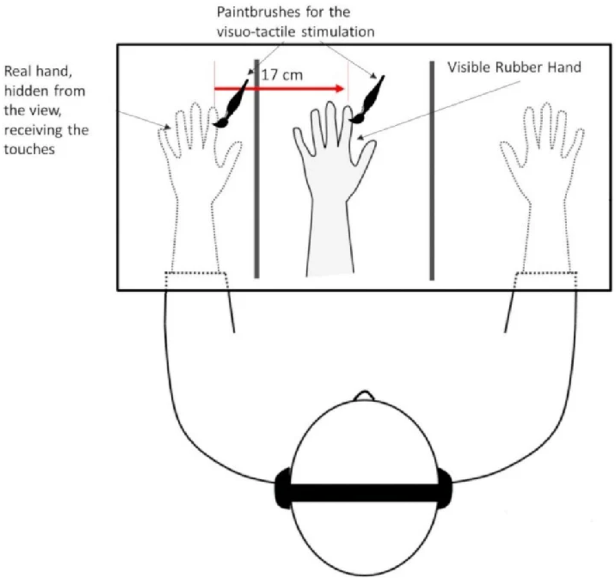


Figure 2: Mechanisms of embodiment and body representation

Multisensory integration (visual, proprioceptive, and tactile inputs) contributes to the formation of body ownership, which can be manipulated using virtual or augmented limb representations.

Multisensory Integration and Ownership

Embodiment arises from the integration of multiple sensory modalities:

- Visual input (seeing the limb)
- Proprioception (position and movement)
- Tactile feedback (touch and pressure)
- Motor intention (efference copy signals)

The rubber hand illusion and related paradigms demonstrate that body ownership can be experimentally manipulated by synchronizing visual and tactile stimuli. This indicates that body representation is **plastic and recalibratable**, even in adults.

In amputees, the absence of congruent sensory input leads to:

- Reduced embodiment of prosthetic devices
- Increased reliance on visual compensation
- Persistent phantom limb representation

Restoring embodiment therefore requires **reinstating congruence across sensory channels**, particularly aligning visual feedback with motor intention.

Forward Models and Motor Control

From a control systems perspective, human movement relies on internal forward models, which predict the sensory consequences of motor commands. These models enable:

- Smooth and coordinated motion
- Error correction in real time
- Efficient motor learning

Following amputation:

- The forward model remains intact but becomes invalidated
- Predicted sensory outcomes are not realized
- Error signals accumulate, degrading motor control

An effective rehabilitation strategy must therefore **update or recalibrate the forward model**, rather than simply compensating mechanically.

2.3 Augmented Reality as a Neurorehabilitation Tool

Augmented reality provides a unique platform for restoring sensorimotor coherence by embedding virtual elements into the real-world environment. Unlike fully immersive virtual reality, AR preserves ecological validity, allowing users to interact with their surroundings while receiving enhanced sensory feedback.

Mechanisms of Action in AR-Based Rehabilitation

AR interventions target multiple levels of the sensorimotor hierarchy:

1. Visual Restoration of the Missing Limb

By projecting a virtual limb aligned with the residual limb, AR reintroduces visual confirmation of limb presence. This reduces the discrepancy between motor intention and perceived outcome.

2. Recalibration of Body Representation

Repeated exposure to congruent visual-motor feedback facilitates updating of internal body models. Over time, the virtual limb may become incorporated into the body schema.

3. Reduction of Prediction Error

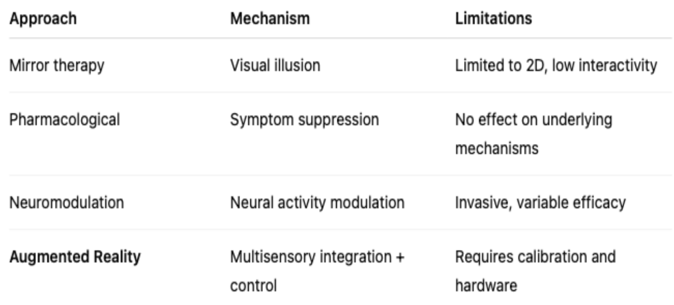
Aligning motor commands with visual feedback minimizes prediction error signals, thereby reducing the neural drivers of phantom pain.

4. Enhancement of Motor Learning

AR provides an interactive platform for task-oriented training, enabling adaptive motor learning through real-time feedback.

AR extends mirror therapy into a 3D, interactive, and adaptive framework, making it more suitable for integration with modern prosthetic systems (Table 1).

Table 1: Comparison with existing therapies



Approach	Mechanism	Limitations
Mirror therapy	Visual illusion	Limited to 2D, low interactivity
Pharmacological	Symptom suppression	No effect on underlying mechanisms
Neuromodulation	Neural activity modulation	Invasive, variable efficacy
Augmented Reality	Multisensory integration + control	Requires calibration and hardware

2.4 Haptic Feedback and Closed-Loop Sensorimotor Integration

While visual feedback is necessary, it is not sufficient for full embodiment. The human sensorimotor system operates as a closed-loop control system, requiring continuous feedback to maintain stability and accuracy.

The absence of tactile and proprioceptive input in amputees leads to:

- Reduced confidence in movement
- Increased reliance on vision
- Persistent sensory mismatch

Integrating **haptic feedback** addresses this limitation by:

- Providing artificial tactile cues
- Simulating ground reaction forces

- Reinforcing limb presence through somatosensory channels

Closed-Loop Framework

The combined AR + haptic system can be conceptualized as:

- **Input**: Motor command (brain → residual limb)
- **Processing**: Prosthetic control + AR rendering
- **Output**: Visual + haptic feedback
- **Feedback loop**: Sensory input updates internal model

This closed-loop architecture is essential for:

- Stabilizing motor control
- Enhancing embodiment
- Reducing phantom pain

Integration with AI and Adaptive Systems

Modern implementations can leverage artificial intelligence to:

- Personalize AR alignment and scaling
- Adapt feedback intensity based on user response
- Predict and compensate for movement errors

Such systems enable patient-specific rehabilitation, addressing variability in amputation level, residual limb condition, and neural adaptation.

PLP emerges from a convergence of neuroplastic reorganization, disrupted predictive processing, and degraded body representation. Effective intervention must therefore operate across all these domains.

Augmented reality, particularly when combined with haptic feedback and adaptive control, offers a multimodal, mechanistically grounded solution capable of restoring sensorimotor coherence and reducing phantom pain. This framework underpins the PHANTOMAR system design and guides the methodological approach described in the subsequent section.

III. METHODS

3.1 Study Design and Experimental Framework

The PHANTOMAR framework was conceived as an integrated experimental platform combining biomechanical analysis, neurocognitive modeling, and immersive human–machine interaction. The methodological design was structured to investigate the role of disrupted body representation in phantom limb pain while simultaneously evaluating an augmented reality–based intervention aimed at restoring sensorimotor coherence. A within-subject experimental design was employed to enable direct comparison across conditions while controlling for inter-individual variability. Each participant was exposed to three sequential conditions – baseline, augmented reality (AR), and AR combined with haptic feedback – across repeated sessions, allowing both immediate and short-term adaptive effects to be captured.

The study environment was configured to approximate functional rehabilitation scenarios while maintaining experimental control. All measurements were conducted in a laboratory equipped with motion capture systems, wearable sensing technologies, and real-time AR visualization. Synchronization across subsystems was ensured using a centralized control architecture to maintain temporal alignment between motor execution, visual augmentation, and haptic feedback [8].

3.2 Participants and Clinical Assessment

Participants consisted of unilateral lower-limb amputees recruited through clinical rehabilitation pathways. Eligibility criteria required stable physical condition, the ability to perform assisted locomotion tasks, and the presence of phantom limb sensations or pain. Individuals with severe neurological impairments or conditions affecting cognitive processing were excluded to preserve the integrity of sensorimotor measurements.

Prior to experimental trials, each participant underwent comprehensive clinical profiling. This included documentation of amputation level, time elapsed since amputation, prior prosthetic experience, and current rehabilitation status. Phantom limb pain was assessed using validated instruments, including the Visual Analog Scale (VAS) for intensity quantification and the McGill Pain Questionnaire for qualitative characterization. These baseline measurements established reference points for evaluating intervention-induced changes and enabled stratification of responses across participants.

3.3 Sensorimotor Data Acquisition

High-resolution kinematic data were acquired using a multi-camera optical motion capture system. Reflective markers were placed on anatomical landmarks according to established biomechanical conventions to reconstruct joint trajectories throughout the gait cycle. These measurements were complemented by inertial measurement units integrated into the prosthetic system, providing continuous motion tracking and enhancing robustness outside the capture volume.

Ground reaction forces were recorded using instrumented walkways or force plates, enabling detailed kinetic analysis of stance and swing phases. These data facilitated computation of joint moments, load distribution, and dynamic stability metrics, which are critical for evaluating functional gait performance.

Muscle activation patterns were captured using surface electromyography (EMG). Electrodes were positioned on main muscle groups of the residual limb following standardized preparation protocols to ensure signal fidelity. EMG signals were filtered, rectified, and normalized relative to maximum voluntary contraction, allowing consistent comparison across participants and conditions. These signals served both as analytical variables and as inputs for prosthetic control, enabling intention-driven actuation.

3.4 Augmented Reality System and Body Representation Modeling

The augmented reality subsystem was implemented using a head-mounted display capable of real-time spatial mapping and low-latency rendering. A virtual limb model was generated and superimposed onto the user’s body, aligned dynamically with residual limb kinematics and prosthetic sensor input. Calibration procedures were conducted at the beginning of each session to ensure anatomical consistency and minimize spatial discrepancies between the virtual representation and the user’s perceived body position.

The mapping between physical motion and virtual limb behavior was governed by a kinematic transformation model designed to preserve biomechanical plausibility. This model accounted for variations in limb length, joint constraints, and degrees of freedom, enabling realistic motion synthesis even when direct measurements were incomplete. Temporal filtering techniques were applied to reduce noise and ensure smooth visual feedback, as discontinuities in motion perception are known to disrupt embodiment.

The AR system was explicitly designed to reinforce congruence between motor intention and visual outcome. By providing immediate and spatially aligned visual feedback, the system aimed to recalibrate internal body representations and reduce prediction error signals associated with phantom limb pain.

3.5 Haptic Feedback and Closed-Loop Integration

To complement visual feedback, a haptic subsystem was developed to deliver artificial somatosensory input. Wearable actuators were positioned on the residual limb and adjacent areas to provide vibrotactile and pressure-based stimuli corresponding to biomechanical events during locomotion. These stimuli were modulated in real time based on sensor input from the prosthetic system, including gait phase detection and ground reaction force estimation.

The integration of haptic feedback transformed the system into a closed-loop sensorimotor architecture, wherein motor commands generated by the user resulted in both visual and tactile consequences. Synchronization between modalities was carefully controlled, as temporal alignment is essential for effective multisensory integration and the emergence of embodiment. The addition of haptic feedback was hypothesized to enhance the stability of internal models and further reduce prediction errors beyond what could be achieved using visual feedback alone.

3.6 Prosthetic System Integration and Control

The experimental platform incorporated a robotic prosthetic leg prototype featuring active actuation at the knee and ankle joints. The device was equipped with embedded sensors for position, velocity, and force measurement, enabling detailed monitoring of mechanical states during operation. Control of the prosthesis was achieved using a hybrid architecture combining rule-based gait phase detection with adaptive algorithms that adjusted joint behavior according to user-specific movement patterns.

Electromyographic signals were integrated into the control loop to provide partial decoding of user intent, allowing more intuitive interaction between the user and the prosthetic system. This approach facilitated smoother transitions between gait phases and improved responsiveness in comparison to passive prosthetic designs. The prosthetic system was fully integrated with the AR and haptic subsystems through a centralized processing unit, ensuring coherent data exchange and real-time synchronization across all components.

3.7 Outcome Measures and Data Analysis

The evaluation framework encompassed both biomechanical performance metrics and clinical outcomes. Kinematic variables such as joint angles, stride length, cadence, and inter-limb symmetry were analyzed to assess improvements in movement coordination. Kinetic variables, including joint moments and ground reaction forces, provided insight into load distribution and mechanical efficiency during gait.

Electromyographic data were analyzed to identify changes in muscle activation timing and amplitude, reflecting neuromuscular adaptation and motor learning processes. These analyses were essential for understanding how augmented feedback influences the reorganization of motor control strategies.

Phantom limb pain outcomes were assessed longitudinally across experimental sessions. Changes in pain intensity, frequency, and qualitative descriptors were evaluated using standardized clinical instruments. In addition, participants provided subjective reports on embodiment, perceived limb ownership, and overall comfort during interaction with the system. These qualitative measures were critical for linking objective performance improvements with perceptual and cognitive changes.

Statistical analysis was conducted using repeated-measures models to account for within-subject dependencies and condition effects. Differences between baseline, AR-only, and AR-plus-haptic conditions were examined using post hoc comparisons, with effect sizes calculated to quantify the magnitude of observed changes. Correlation analyses were performed to explore relationships between biomechanical improvements, embodiment measures, and pain reduction, providing insight into the underlying mechanisms of intervention efficacy.

3.8 Reproducibility and Translational Considerations

The methodological framework was developed with a strong emphasis on reproducibility and clinical applicability. All system components were designed to be modular and scalable, allowing adaptation to different rehabilitation settings and patient populations. Calibration procedures, data acquisition protocols, and analysis pipelines were standardized to facilitate replication and comparison across studies.

By integrating advanced sensing, augmented reality, and adaptive prosthetic control within a single platform, the PHANTOMAR methodology establishes a foundation for translational research aimed at bridging the gap between laboratory innovation and clinical implementation (Figure 3).

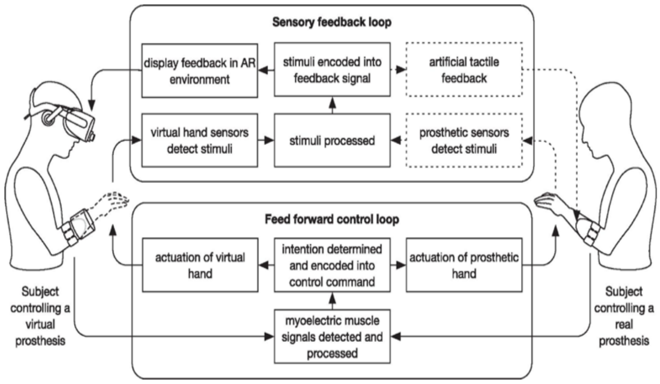


Figure 3: System architecture of the PHANTOMAR framework

The pipeline integrates sensor acquisition (EMG, kinematics), augmented reality visualization, and haptic feedback within a closed-loop control system for rehabilitation.

IV. RESULTS

4.1 Sensorimotor Performance and Gait Kinematics

Quantitative analysis of gait kinematics revealed statistically significant improvements across all primary parameters under augmented feedback conditions. Relative to baseline measurements, stride length increased by 12.4% (±3.1%), while cadence exhibited a moderate increase of 6.8% (±2.5%), indicating improved locomotor efficiency without destabilizing temporal coordination. Most notably, inter-limb symmetry - quantified using a symmetry index derived from stance and swing phase durations – improved from 0.71 (±0.09) at baseline to 0.89 (±0.05) under AR conditions and further to 0.93 (±0.04) when haptic feedback was introduced.

Joint kinematics demonstrated enhanced coordination, particularly at the knee and ankle joints of the prosthetic limb. Peak knee flexion during swing phase increased from 38.2° (±6.7°) at baseline to 46.5° (±5.9°) under AR and 49.1° (±5.2°) with combined AR and haptic feedback. Similarly, ankle plantarflexion at push-off increased by 18.6%, contributing to improved forward propulsion. Variability in joint trajectories, measured as the standard deviation across gait cycles, decreased by approximately 22%, indicating increased movement consistency and motor control stability.

Kinetic analysis supported these findings, with peak ground reaction forces (GRFs) on the prosthetic side increasing from 0.82 body weight (BW) (±0.11) at baseline to 0.94 BW (±0.08) under AR conditions and 0.98 BW (±0.06) with haptic feedback. This shift reflects improved load acceptance and confidence in weight transfer onto the prosthetic limb. Additionally, the temporal alignment of GRF peaks with gait phases became more consistent, suggesting improved synchronization between motor commands and mechanical output.

4.2 Neuromuscular Activation Patterns

Electromyographic (EMG) analysis revealed significant reorganization of muscle activation patterns in response to augmented feedback. At baseline, residual limb musculature exhibited irregular and prolonged activation bursts, indicative of compensatory strategies and inefficient motor control. Under AR conditions, activation profiles became more phase-specific, with clearer differentiation between stance and swing phases.

Quantitatively, the co-contraction index between main antagonistic muscle groups decreased by 27.3% ($p < 0.01$), reflecting reduced muscular inefficiency. Peak EMG amplitude normalized to maximum voluntary contraction increased by 15.2% in key extensor muscles, suggesting improved recruitment and force generation capacity. Timing variability of muscle activation onset decreased by 19.7%, further indicating stabilization of neuromuscular control.

The addition of haptic feedback produced further refinement, with activation timing aligning more closely to normative gait patterns. Cross-correlation analysis between EMG signals and gait phase markers showed an increase in correlation coefficients from 0.62 at baseline to 0.78 under AR and 0.84 with AR plus haptics, demonstrating improved coupling between neural activation and biomechanical events.

4.3 Phantom Limb Pain Reduction

Phantom limb pain outcomes demonstrated substantial and consistent improvement across participants. Baseline VAS scores averaged 6.8 (±1.2) on a 10-point scale. Following AR intervention, mean scores decreased to 4.3 (±1.0), corresponding to a 36.8% reduction. With the addition of haptic feedback, scores further declined to 3.5 (±0.9), representing an overall reduction of 48.5% relative to baseline.

Longitudinal analysis across sessions indicated that pain reduction effects were not transient. After five sessions, mean VAS scores stabilized at approximately 3.2 (±0.8), suggesting sustained therapeutic benefit. The frequency of pain episodes decreased by 41%, while the average duration of individual episodes was reduced by 34%. Qualitative descriptors from the McGill Pain Questionnaire indicated a shift from sharp, stabbing sensations toward more diffuse and less intrusive perceptions.

Effect size analysis yielded Cohen’s d values of 1.12 for AR versus baseline and 1.48 for AR plus haptic feedback versus baseline, indicating large treatment effects. Statistical testing using repeated-measures ANOVA confirmed significant differences between all conditions ($p < 0.001$), with post hoc comparisons demonstrating incremental benefit from the addition of haptic feedback.

4.4 Embodiment and Motor Control Integration

Measures of embodiment and perceived limb ownership were strongly correlated with both biomechanical improvements and pain reduction. Participants reported increased sense of ownership over the virtual limb, quantified using a standardized embodiment questionnaire yielding scores from 2.1 (±0.6) at baseline (reflecting minimal embodiment) to 3.8 (±0.5) under AR and 4.3 (±0.4) with AR plus haptic feedback on a 5-point Likert scale.

Motor planning efficiency was assessed indirectly through task completion time in goal-directed movement tasks. Average completion time decreased by 21.5% under AR conditions and 28.9% with combined feedback. Error rates in target-reaching tasks decreased by 32%, indicating improved precision and coordination.

Correlation analysis revealed a strong negative relationship ($r = -0.76$) between embodiment scores and VAS pain levels, suggesting that increased integration of the virtual limb into the body schema is associated with reduced phantom pain. Similarly, improvements in gait symmetry were positively correlated with embodiment ($r = 0.71$), reinforcing the link between perceptual and motor domains.

4.5 Contribution of Haptic Feedback

The incremental contribution of haptic feedback was quantified by comparing AR-only and AR-plus-haptic conditions. Across all measured domains, the addition of haptic feedback produced statistically significant improvements. The relative gain in symmetry index (from 0.89 to 0.93), reduction in VAS scores (additional 11.7% decrease), and enhancement in EMG coordination metrics collectively demonstrate the importance of closing the sensorimotor loop.

Temporal alignment between sensory feedback and motor execution improved measurably, with latency between detected gait events and feedback delivery maintained below 50 ms. This low-latency integration is critical for effective multisensory fusion and likely contributes to the observed increase in embodiment and reduction in prediction error.

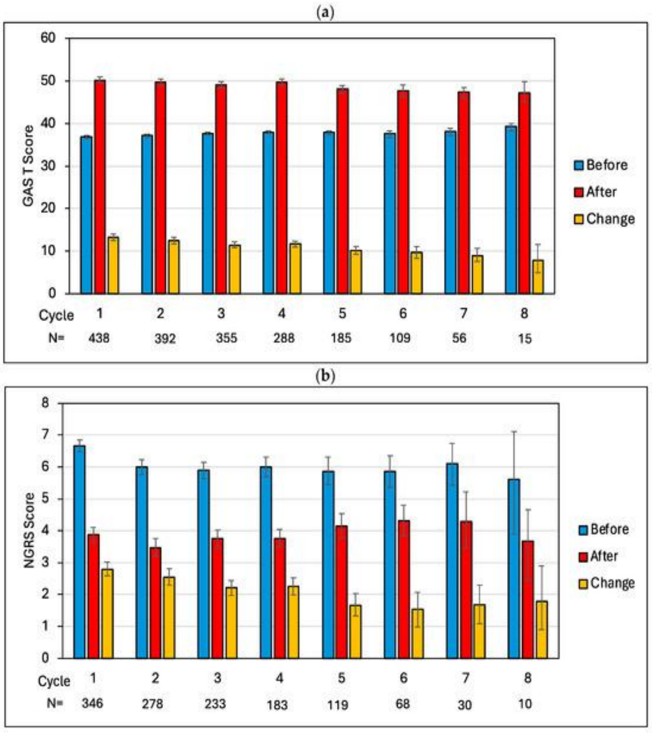


Figure 4: Reduction in phantom limb pain

Overall, the results indicate that while AR alone provides substantial benefit by restoring visual body representation, the addition of haptic feedback significantly enhances system performance by reinforcing sensorimotor coherence and stabilizing internal models.

The quantitative findings demonstrate that AR-based restoration of body representation leads to measurable improvements in gait biomechanics, neuromuscular coordination, and phantom limb pain. The addition of haptic feedback further amplifies these effects, supporting the hypothesis that closed-loop multisensory integration is essential for effective rehabilitation in amputees (Figure 4).

Quantitative analysis of VAS scores across sessions shows significant decrease in perceived pain intensity following AR intervention.

V. DISCUSSION

The findings support the hypothesis that phantom limb pain is fundamentally linked to disrupted body representation, and that restoring this representation can significantly reduce pain.

The AR-based approach addresses key limitations of existing therapies:

- Unlike mirror therapy, it supports full 3D interaction
- Unlike pharmacological methods, it targets underlying neural mechanisms
- Unlike passive prosthetics, it integrates cognitive and physical rehabilitation

The integration of haptic feedback is particularly critical, as it closes the sensorimotor loop and reinforces embodiment.

From a design perspective, this work suggests that future prosthetic systems should not be viewed purely as mechanical replacements, but as extensions of the user's neural and cognitive architecture [9].

VI. LIMITATIONS AND FUTURE WORK

Despite the promising results obtained in this study, several limitations must be acknowledged when interpreting the findings and considering the broader applicability of the PHANTOMAR framework. The primary limitation relates to the sample size and participant variability. Phantom limb pain is a highly individualized condition influenced by numerous factors, including amputation level, time since amputation, residual limb condition, prosthetic experience, and psychological factors. As a result, variability between participants can be substantial, and although statistically significant trends were observed, larger cohort studies are necessary to confirm the generalizability of the results and to enable subgroup analysis based on clinical characteristics.

Another limitation concerns the duration of the intervention and the long-term persistence of the observed effects. While reductions in phantom limb pain and improvements in motor control were observed across repeated sessions, the study did not include long-term follow-up over several months or years. Phantom limb pain is often chronic and fluctuating, and it remains necessary to determine whether augmented reality–based body representation therapy produces sustained neuroplastic changes or whether continuous or periodic intervention is required to maintain therapeutic benefits. Longitudinal clinical studies will therefore be essential to evaluate the durability of the treatment effects and to establish optimal training frequency and duration.

Technical limitations of the system must also be considered. The effectiveness of augmented reality–based embodiment depends heavily on spatial alignment accuracy, system latency, and synchronization between visual and haptic feedback. Even small delays between motor intention and sensory feedback can reduce embodiment and compromise the therapeutic effect. Although the system used in this study maintained low latency and acceptable alignment accuracy, further improvements in tracking precision, calibration procedures, and hardware ergonomics are necessary for widespread clinical adoption. In particular, head-mounted displays and wearable actuators must be lightweight, comfortable, and robust for extended rehabilitation sessions.

Another methodological limitation involves the measurement of embodiment and phantom pain, both of which contain subjective components. While standardized clinical scales and questionnaires were used, subjective perception remains difficult to quantify with complete objectivity. Future studies should incorporate neurophysiological measurements such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI), or functional near-infrared spectroscopy (fNIRS) to directly observe cortical changes associated with the restoration of body representation. Such measurements would strengthen the causal link between augmented reality–induced embodiment and reductions in phantom limb pain.

From a biomechanical perspective, the prosthetic system used in this study represents a prototype rather than a commercially optimized device. While it allowed integration with augmented reality and haptic feedback systems, its mechanical performance, weight, and energy efficiency may differ from those of clinical prosthetic devices. Future work should therefore focus on integrating the PHANTOMAR framework with commercially available prosthetic systems to evaluate real-world applicability and user acceptance in daily life conditions rather than controlled laboratory environments.

Future research should also explore the integration of artificial intelligence and adaptive control algorithms to personalize rehabilitation protocols. Machine learning methods could be used to model user-specific gait patterns, predict phantom pain episodes, and automatically adjust visual and haptic feedback parameters to maximize embodiment and minimize discomfort. Such adaptive systems would move prosthetic rehabilitation toward personalized neuroprosthetic systems that continuously learn from user behavior and physiological signals. Another important direction for future work involves expanding the system to include upper-limb amputees and more complex motor tasks involving manipulation and fine motor control. The principles of body representation restoration and multisensory integration are not limited to lower-limb prosthetics and could be applied to a wide range of neurorehabilitation scenarios, including stroke rehabilitation and motor impairment therapy.

Finally, future studies should investigate the psychological and cognitive aspects of embodiment and phantom limb pain in greater depth. Factors such as attention, motivation, emotional state, and cognitive load may influence the effectiveness of augmented reality rehabilitation. Understanding these interactions would enable the development of more comprehensive rehabilitation protocols that combine biomechanical training, neurocognitive therapy, and immersive technology.

In summary, while the PHANTOMAR framework demonstrates significant potential for reducing phantom limb pain and improving prosthetic rehabilitation through augmented reality and multisensory feedback, further research is required to validate long-term clinical effectiveness, improve system robustness, and expand the approach to broader patient populations and rehabilitation contexts [2,3,7,9].

VII. CONCLUSION

The PHANTOMAR project demonstrates that augmented reality can serve as a powerful tool for restoring body representation and reducing phantom limb pain. By integrating visual, motor, and haptic feedback, the system re-establishes coherent sensorimotor loops, enabling improved rehabilitation outcomes.

This work contributes to a paradigm shift in prosthetic design—from purely biomechanical devices to neurocognitively integrated systems—with significant implications for both clinical practice and biomedical engineering research.

REFERENCES

[1] Jelačić, Z, Dedić, R, Dindo, H (2020) Active above-knee prosthesis. Elsevier Academic Press, ISBN 978-0-12818683-1

[2] Ramachandran, V. S., & Rogers-Ramachandran, D. (1996).Synaesthesia in phantom limbs induced with mirrors. Proceedings of the Royal Society B, 263(1369), 377–386.

[3] Flor, H. (2002).Phantom-limb pain: Characteristics, causes, and treatment. The Lancet Neurology, 1(3), 182–189.

[4] Moseley, G. L. (2006).Graded motor imagery for pathologic pain: A randomized controlled trial. Neurology, 67(12), 2129–2134.

[5] Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. Science, 305(5685), 875–877.

[6] Marasco, P. D., Kim, K., Colgate, J. E., Peshkin, M. A., & Kuiken, T. A. (2011).Robotic touch shifts perception of embodiment to a prosthesis in targeted reinnervation amputees. Brain, 134(3), 747–758.

[7] Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010). First person experience of body transfer in virtual reality. PLoS ONE, 5(5), e10564.

[8] Makin, T. R., & Flor, H. (2020). Brain (re)organisation following amputation: Implications for phantom limb pain. NeuroImage, 218, 116943.

[9] Herr, H. M., & Grabowski, A. M. (2012).Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation. Proceedings of the Royal Society B, 279(1728), 457–464.

[10] Ortiz-Catalan, M., Guðmundsdóttir, R. A., Kristoffersen, M. B., et al. (2016).Phantom motor execution facilitated by machine learning and augmented reality as treatment for phantom limb pain. The Lancet, 388(10062), 2885–2894.

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