A Conceptual Mechanistic Framework for Biosensing-Enhanced VR Rehabilitation

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Abstract

Biosensing-enabled Virtual Reality including electroencephalography, electromyography, electrodermal activity, heart-rate variability and other multimodal physiological signals is the next frontier of adaptive and personalised VR rehabilitation systems. This paper reviews the mechanistic evidence of 32 studies utilising biosensing-enabled VR, identified in a broader systematic review, investigating how EEG-based motor imagery, EMG biofeedback, and autonomic biosensors can effectively modulate sensorimotor engagement, volitional activation, emotional and attentional states. This framework outlines neural intention decoding, muscular activation reinforcement, autonomic state modulation, and multimodal integration as potential pathways for incorporating biosensing and closed-loop adaptivity into VR rehabilitation systems.

1. Introduction

Virtual reality (VR) rehabilitation has been shown to be effective in a number of outcome domains for neurological and musculoskeletal conditions. There is increasing use of physiological biosensing modalities, specifically electroencephalography (EEG), electromyography (EMG), electrodermal activity (EDA), and heart-rate variability (HRV), to enable adaptive, personalised closed-loop therapy. However, mechanistic evidence for the use of biosignals in VR-based rehabilitation interventions remains scarce.

A set of 32 mechanistic studies, identified within a broader systematic review, offer a valuable opportunity to consolidate mechanisms across the available literature, including EEG-based motor imagery (MI) (Aamer et al. 2019, Achanccaray et al. 2018), EMG-driven virtual reality (VR) interfaces (Ma et al. 2009, 2010), autonomic biofeedback systems (Rahman et al. 2022, 2023, Parente et al. 2023) and multimodal VR-brain–computer interface (BCI) platforms (Vourvopoulos et al. 2019, Harris et al. 2024). Although these studies are conducted predominantly in healthy adults, each system reports mechanistic outcomes relevant to neurological or musculoskeletal rehabilitation. Despite the informative nature of the mechanistic evidence base, it remains heterogeneous and difficult to synthesise. The absence of a cohesive model integrating neural intention decoding, muscular activation reinforcement, autonomic state modulation, and multimodal integration limits the design of physiologically informed VR systems and their translation into clinical practice.

The results of the 32 biosensing-integrated VR studies were synthesised to produce a theoretical mechanistic framework that describes how physiological signals can promote adaptive VR rehabilitation and the mechanistic pathways through which biosensing can promote closed-loop interaction. This framework forms a reference point for the design, assessment and implementation of biosensing-integrated VR rehabilitation systems into modern clinical practice.

2. Methods

Mechanistic evidence was gathered from a selection of studies included in a systematic review of VR-based rehabilitation systems that use physiological biosensing. For this analysis, studies offering mechanistic, physiological, or system-level insights were classified as mechanistic, regardless of whether they reported clinical outcomes. Figure 1 provides further detail into how the studies were obtained, screened and selected for synthesis.

To qualify, studies needed to:

- Use a physiological biosensing method (EEG, EMG, EDA, HRV or a combination)
- Employ VR or XR as an interactive experience, not just as a response mechanism.
- Apply to neurological or musculoskeletal rehabilitation, even if tested in healthy adults.
- Report mechanistic outcomes such as neural activation patterns, MI classification accuracy, EMG activation, physiological autonomic measures and system performance.

The studies excluded were those focused solely on usability, entertainment, navigation, cognitive neuroscience tasks, and those identifying biosensing outside of the VR system.

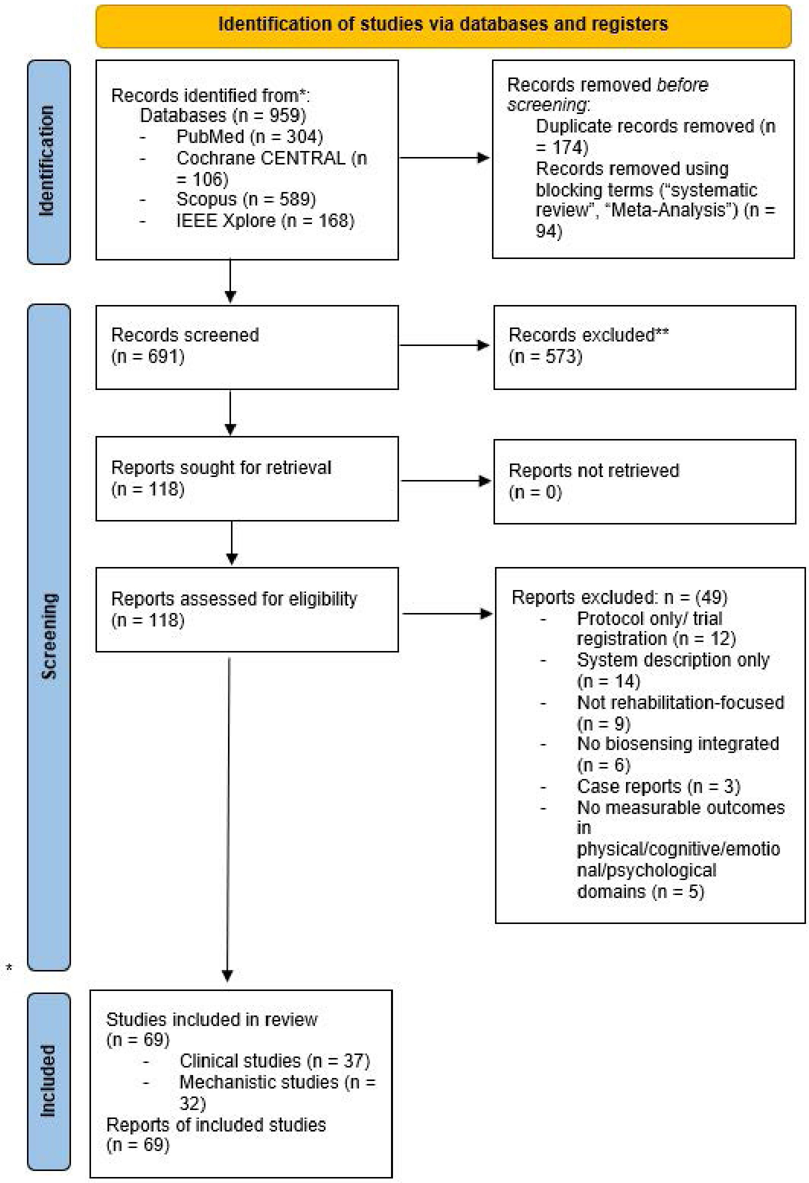

Figure 1: A PRISMA flow diagram detailing the study selection process.

Reference databases were searched using formulated strings of which 32 studies were found to meet the initial criteria, and mechanistic findings were therefore, extracted from each study. The findings were categorised into four neurophysiological domains: Neural Intention Decoding, Muscular Activation, Autonomic Modulation and Multimodal Integration. These findings were combined to create an integrated mechanistic framework that illustrates how biosensing drives the use of VR-based rehabilitation for neurological and musculoskeletal conditions.

3. Mechanistic findings

Neural Intention and Engagement Mechanisms (EEG): Several trends were observed in VR studies based on EEG. MI tasks appear to influence sensorimotor activity in VR environments, and clear ERD (Event Related Desynchronisation) patterns were recorded during MI tasks. Additionally, studies indicated an improved neural engagement when MI is applied to other VR tasks (Achanccaray et al. 2018). Other studies showed a high MI classification accuracy in VR-based

MI-BCI games, indicating that such systems can differentiate MI-related brain signals and decode MI-related activity robustly (Aamer et al. 2019, Karácsony et al. 2019). Supporting evidence comes from increases in cortical activity and power spectral density during active movements in VR (Blanco-Mora et al. 2019, O'Keeffe et al. 2024).

Overall, these findings suggest that EEG can decode motor intention and enhance cognitive engagement in VR rehabilitation systems.

Muscular Activation and Volitional Control (EMG): EMG-driven VR systems consistently showed that VR tasks can help users activate their muscles. For instance, EMG input methods have demonstrated EMG-based control and targeted muscle activation during VR tasks such as hand rotation, grasping and upper-limb movements. This indicates that VR environments can enhance the quality and consistency of muscular activity (Ma et al. 2010, Guo et al. 2016).

An EMG-based interaction, with high accuracy for detecting intention, could be used in real-time to control VR tasks. This would allow for the adjustment of task difficulty specifically for the user's current state (Chatragadda et al. 2023, 2025). In earlier EMG-biofeedback systems, real-time feedback suggested improved specific muscle activation, especially in rehabilitation setups involving repetitive training with feedback (Ma et al. 2009).

These results suggest that EMG-driven VR tasks are associated with increased motor engagement and specific muscle activation in VR rehabilitation.

Autonomic and Psychophysiological Modulation (EDA/HRV): Autonomic biosensing in VR rehabilitation can measure emotional and attentional states. Heart-rate-based biofeedback has been used to adapt game difficulty in real-time, reporting increases in mental focus and engagement with biofeedback enabled (Parente et al. 2023).

Though fewer in number, these studies highlight how autonomic signals are associated with emotions, motivation and attention, with the potential to influence them. These factors can impact adherence and success in rehabilitation, but are often ignored in the design of rehabilitation systems.

Multimodal Integration and Closed-Loop Adaptation: Several studies highlighted the use of multimodal biosensing to enhance the responsiveness of VR rehabilitation systems.

EEG-based assessment showed stronger mu (μ) and beta (β) ERD and increased coherence when VR mirror therapy was combined with robot-assisted upper-limb intervention (Liu et al. 2024). This shows consistency with enhanced sensorimotor involvement and engagement. In gait-oriented systems, EEG-based decoding of lower-limb movement intention has enabled real-time control of avatars during VR tasks, with potential applications in closed-loop control for locomotor rehabilitation (Luu et al. 2016).

These multimodal approaches illustrate how neural, muscular and autonomic signals could be combined to support more responsive and personalised rehabilitation interventions.

4. Hypothesised mechanistic framework

The patterns observed in the reviewed studies provide theoretical evidence that biosensing could enable adaptive VR rehabilitation. Although current evidence is limited and heterogeneous, emerging evidence suggests EEG, EMG, and autonomic signals could provide information for estimating motor, cognitive, and emotional states.

In VR, EEG-based MI models have shown sensorimotor rhythm modulation, a potential mechanism for intention decoding. EMG-based interfaces have provided evidence for volitional muscle activation during task execution within VR. Autonomic measures, such as HRV and EDA, can provide insight into arousal and attentional state, offering the potential of making adaptive changes that impact the task itself, but currently there is insufficient evidence to fully support this and these relationships require further validation.

Multimodal systems integrating neural, muscular and autonomic data represent opportunities to provide richer closed-loop interactions, though available studies are exploratory and limited to small, healthy samples. Taken as a collective, these findings support a testable hypothesis that biosensing could enable VR systems to adapt to a user's cognitive, motor and emotional states in real-time.

A potential pipeline could consist of acquiring the aforementioned biosignals to infer a user's physiological state and use machine learning to classify these in real-time. Thus, providing opportunity for closed-loop feedback within a virtual rehabilitation environment or real-time monitoring to enable physicians to adapt tasks accordingly. A visualisation of the described pipeline is depicted in Figure 2

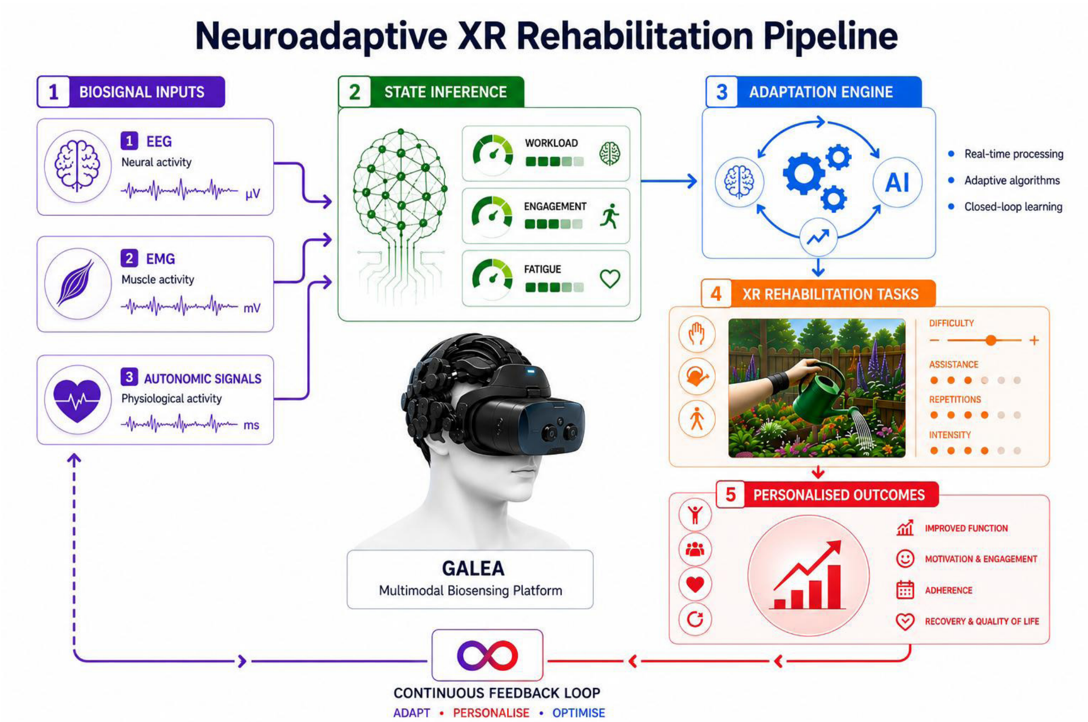

Figure 2: A Neuroadaptive XR Rehabilitation Pipeline Visualisation.

5. Discussion

The synthesis of mechanistic findings across the 32 biosensing-integrated VR studies highlights several potential pathways in which physiological signals can inform real-time adaptation within VR-based rehabilitation interventions. EEG-based MI tasks consistently modulate sensorimotor rhythms and indicate the possibility of decoding intention using EEG within VR rehabilitation. When EMG-driven input was used, a general increase in VR task engagement was demonstrated which can be inferred from a corresponding increase in muscular activity. HRV and EDA correspond to arousal and attentional engagement and are an alternate source of information that could be used to adjust tasks within VR.

Despite the similarities across modalities, the evidence base remains preliminary, heterogeneous, and largely based on small, healthy samples. As such, the proposed pathways should be interpreted as conceptual mechanisms rather than established causal processes. However, the recurring trends across integrated EEG, EMG and autonomic systems provide a coherent foundation for formulating mechanistic hypotheses regarding how biosensing can contribute to closed-loop neuroadaptive VR rehabilitation. Further empirical work is required to evaluate these mechanisms and determine their relevance within clinical rehabilitation

6. Conclusion

This work proposes a preliminary set of mechanistic pathways (Neural Intention Decoding, Volitional Muscle Activation, Autonomic State Modulation and Multimodal Integration) as a collective mechanistic framework derived from the convergent patterns identified across 32 biosensing-integrated VR studies from a broader systematic review. These pathways represent testable hypotheses regarding how physiological signals could inform adaptation within VR rehabilitation interventions rather than as definitive mechanisms.

Future research should evaluate these hypotheses within clinical contexts, examining their generalisability across various populations, and explore their potential for the design and development of personalised, closed-loop VR rehabilitation systems. Furthermore, the pipeline discussed as an example of the framework should be pursued in further detail to evaluate the capability of combining mechanistic insights with VR rehabilitation for the vulnerable target populations undergoing rehabilitation.

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