A Survey of Myoelectric Prosthesis and Virtual Reality in Rehabilitation Technology

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Abstract

This survey paper explores the integration of myoelectric prostheses, virtual reality (VR), and surface electromyography (sEMG) in modern rehabilitation, emphasizing their collective role in enhancing prosthetic training and rehabilitation outcomes. Myoelectric prostheses leverage electromyographic signals for intuitive control, significantly improving the quality of life for individuals with limb loss. The integration of dual-modality haptic feedback systems has been identified as crucial for enhancing prosthetic performance, particularly in dexterous tasks. VR environments provide immersive, gamified platforms that enhance user engagement and motivation, transforming rehabilitation into interactive experiences. The application of sEMG in capturing and analyzing muscle signals is pivotal for precise prosthetic control, allowing for real-time feedback and adaptability. The synergistic integration of these technologies offers a comprehensive framework for rehabilitation, addressing existing challenges and enhancing user experience. Despite facing technological limitations, such as variability in signal quality and high rejection rates, ongoing advancements and research opportunities hold promise for further enhancing the capabilities of myoelectric prostheses. Future directions include developing cost-effective VR solutions, improving electrode interfaces, and conducting longitudinal studies to assess long-term benefits. This integrated approach aims to revolutionize rehabilitation practices, ultimately improving functional outcomes and the quality of life for individuals with limb loss.

1 Introduction

1.1 Significance of Myoelectric Prostheses

Myoelectric prostheses represent a significant advancement in rehabilitation technology, enhancing the quality of life for individuals with limb loss by enabling intuitive control through electromyography (EMG) signals [1]. These devices are crucial for functional recovery, particularly for upper limb amputees, as they facilitate daily tasks and improve dexterity [2]. Effective use of myoelectric prostheses relies on the precise production of EMG signals, which requires extensive user training to optimize performance and functionality [1].

The integration of dual-modality haptic feedback systems is vital for enhancing myoelectric prostheses performance, especially in dexterous tasks. Limitations of single-modality feedback methods highlight the need for comprehensive sensory feedback mechanisms to improve user interaction and control [3]. Inadequate haptic feedback often forces users to depend on visual cues, detracting from the naturalness of interaction [2].

Unpredictability in prosthetic control remains a significant challenge impacting user functionality and everyday use. Addressing the factors contributing to this unpredictability is essential for enhancing the reliability and effectiveness of myoelectric prostheses [4]. Continued research in this area is crucial for developing solutions that improve device adaptability and usability.

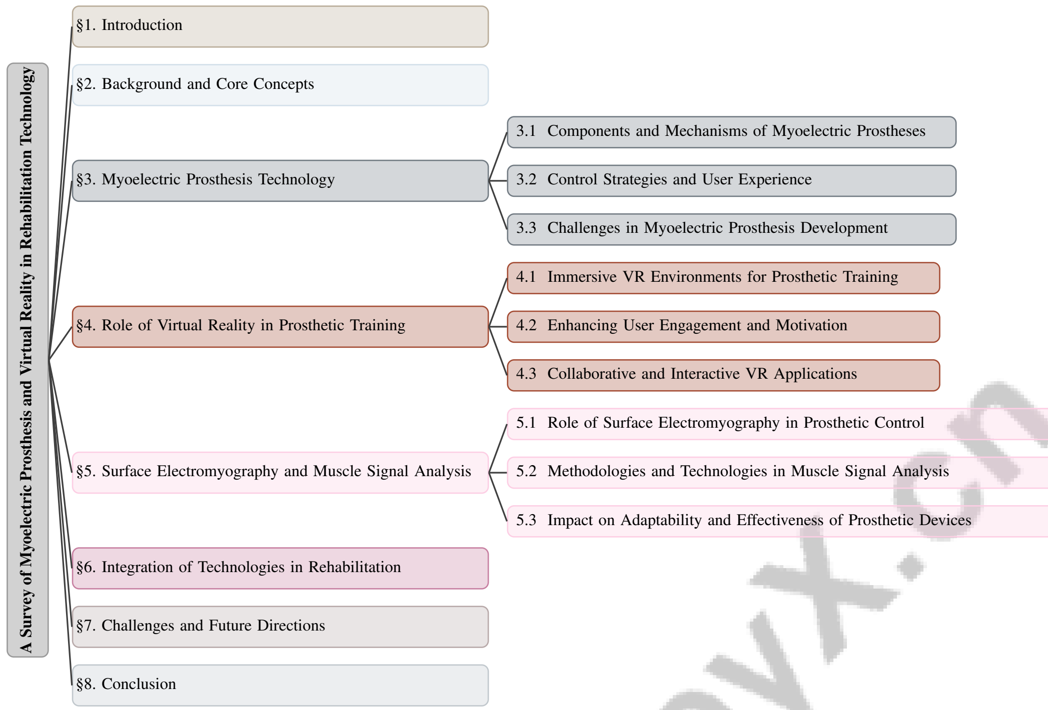


Figure 1: chapter structure

In the broader rehabilitation context, myoelectric prostheses play a key role in restoring mobility and independence for individuals with limb loss. By facilitating seamless integration into daily life, these technologies can significantly enhance quality of life and functional outcomes for amputees [5]. Ongoing advancements are vital to overcoming existing limitations and further enhancing myoelectric prosthesis capabilities.

1.2 Integration of VR and sEMG in Rehabilitation

The integration of virtual reality (VR) and surface electromyography (sEMG) into rehabilitation protocols marks a significant advancement in prosthetic training, transforming user experience and functional outcomes. VR environments simulate real-world scenarios, providing immersive platforms for users to engage in goal-oriented tasks critical for effective rehabilitation [6]. Gamification in VR therapy enhances patient motivation and compliance by personalizing experiences, making rehabilitation more engaging [7]. This is further supported by VR's potential to improve user engagement in therapeutic settings, necessitating innovative rehabilitation tools [8].

Integrating sEMG with VR systems enhances upper-limb prosthetic control by enabling precise capture and analysis of muscle signals [9], allowing for real-time feedback crucial for device adaptability [10]. sEMG interfaces within VR platforms support personalized training experiences, accommodating diverse learning styles and empowering users to progress at their own pace [11].

Moreover, incorporating electrotactile feedback in VR environments significantly enhances the realism and effectiveness of rehabilitation exercises, particularly in low-visibility situations, thus improving user interaction with myoelectric prostheses [12]. The development of thin, flexible surfaces as haptic interfaces further augments tactile feedback in VR, providing a more immersive rehabilitation experience [13].

Advanced VR applications in rehabilitation include augmented reality and robotic manipulation, which modify sensory stimuli to alter patients' body schema and restore self-efficacy [14]. Additionally, integrating machine learning with multimodal data in virtual rehabilitation environments addresses challenges related to patient motivation and progress tracking, especially in upper limb therapy [15]. The application of VR technology in clinical medicine underscores its benefits in therapeutic treatments, offering innovative solutions across various medical applications [16].

1.3 Overview of the Survey Structure

This survey paper explores the integration of myoelectric prostheses, virtual reality (VR), and surface electromyography (sEMG) in rehabilitation technology. It provides a comprehensive understanding of advancements and applications of these technologies in enhancing prosthetic training and rehabilitation outcomes. The introduction outlines the significance of myoelectric prostheses and the transformative role of VR and sEMG in prosthetic training. The background section reviews the historical development of rehabilitation technologies, focusing on the evolution of myoelectric prostheses and VR.

Core concepts of myoelectric prostheses are examined, elucidating the fundamental principles of their functionality. The role of VR in rehabilitation technology is discussed, emphasizing its significance in creating immersive training environments. Subsequent sections delve into the technology behind myoelectric prostheses, detailing components, mechanisms, and control strategies that enhance user experience and address existing challenges.

The paper further explores VR's utilization in prosthetic training, highlighting the benefits of immersive environments and collaborative applications in enhancing user engagement and motivation. The critical evaluation of sEMG's role in capturing and analyzing muscle signals for prosthetic control emphasizes various methodologies and technologies influencing adaptability and effectiveness. Key aspects include signal generation, the correlation between electromechanical delay and performance, and the impact of sEMG sensor quantity on user embodiment and control functionality. Challenges related to comfort, durability, and algorithm tuning are also addressed, significantly affecting user acceptance and the overall success of myoelectric prostheses [9, 17, 4].

Additionally, the survey discusses the integration of these technologies in rehabilitation, emphasizing their synergistic effects and potential improvements in functional outcomes for individuals with limb loss. It concludes by highlighting pressing challenges in the development and application of rehabilitation technologies, particularly for the estimated 30 million individuals worldwide requiring myoelectric prostheses due to congenital conditions, disease-related amputations, or injuries from conflicts. The necessity for ongoing research and innovation is emphasized to enhance functionality and usability, with advancements in integrated circuits and microelectronics being crucial for improving amputees' quality of life. Furthermore, the need for standardized assessment protocols, such as the Anthropomorphic Hand Assessment Protocol (AHAP) and Prosthetic Hand Assessment Measure (PHAM), is underscored to evaluate prosthetic devices' effectiveness in daily tasks, guiding future research directions in this vital field [1, 18].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Historical Development of Rehabilitation Technologies

The evolution of rehabilitation technologies has significantly advanced, particularly with the advent of myoelectric prostheses and virtual reality (VR). Traditional methods, limited by basic techniques, often failed to address perceptual body schema discrepancies, restricting their efficacy in functional restoration [14]. Myoelectric prostheses introduced a paradigm shift, leveraging electromyographic signals for intuitive control, thereby enhancing the quality of life for individuals with limb loss. Concurrently, VR revolutionized rehabilitation by offering immersive environments that simulate real-world scenarios, facilitating engaging and effective training experiences. Early AR/VR developments often neglected the specific needs of disabled users, creating accessibility barriers that necessitated rectification [5]. Recent innovations integrate artificial intelligence (AI) with VR, producing adaptive and personalized rehabilitation interventions, systematically categorized into medical diagnosis and treatment phases [19]. Advances such as data-driven goal recognition systems and augmented reality training frameworks have improved rehabilitation effectiveness by accurately recognizing user intentions through real-time sensor data, fostering motivation and skill acquisition [20, 11, 21, 1, 22].

2.2 Core Concepts of Myoelectric Prostheses

Myoelectric prostheses function by capturing and analyzing electromyographic (EMG) signals for intuitive device control. Surface electromyography (sEMG) detects muscle signals, acting as the primary interface between the user and the prosthesis, translating muscle activity into actionable commands [23]. This capability allows users to perform complex tasks, enhancing daily activity execution [24]. A major challenge is accurately recognizing hand gestures, especially with variability in forearm orientations affecting control precision [4]. Haptic feedback mechanisms are vital for improving user interaction, providing sensory information absent in artificial limbs [25]. This feedback is crucial for tasks requiring fine manipulation, compensating for the lack of direct visual cues and enhancing the user's perception of the prosthesis as a natural body extension [1]. Developing portable and cost-effective haptic systems remains a core focus, aimed at improving user interaction across applications [25]. Concerns about reliance on the intact limb among users arise, leading to musculoskeletal complaints due to overuse [4]. This underscores the importance of multi-grip myoelectric hands, which demonstrate enhanced daily activity performance and increased prosthesis use compared to single-grip models [25]. Accurate identification of user intentions, particularly in transhumeral prostheses, is complicated by variability in human kinematics and muscle activity signals, necessitating advanced data-driven approaches [24]. Psychological factors, including body ownership and agency, are crucial for successful adoption. Users must perceive the prosthesis as a body extension to achieve effective control and integration into daily activities [5]. Despite technological advancements, high rejection rates persist, emphasizing the need for improved interfaces and training protocols to facilitate myoelectric control mastery [4].

2.3 Virtual Reality in Rehabilitation Technology

Virtual reality (VR) has emerged as a transformative tool in rehabilitation, offering immersive and interactive environments that enhance training and recovery processes. VR's role is highlighted by its ability to simulate real-world scenarios, providing engaging platforms for motor skill practice and refinement. Serious games, for instance, enhance motor skills through immersive environments, improving patient motivation and adherence to rehabilitation protocols [26]. VR transcends traditional methods, offering unique learning and skill acquisition opportunities. For example, studies on VR training in mechanical assembly demonstrate superior learning efficacy compared to conventional approaches, underscoring its potential to revolutionize training paradigms [27]. Systems like VRMoVi provide detailed 3D visualizations of hand-object interactions, offering comprehensive movement understanding [28]. Challenges in VR-based rehabilitation include managing gesture variability and complex hand movements, alongside the need for real-time processing to ensure effective training [29]. However, integrating immersive learning and gamification principles, as shown in systems like INREX-VR, enhances patient engagement and adherence, showcasing VR's potential in neurorehabilitation [30]. VR's versatility in clinical settings is evident in its categorization into surgical training, pain management, and psychological therapy, each employing unique methodologies to achieve distinct outcomes [16]. By providing tailored and adaptive environments, VR technology addresses not only the physical aspects of rehabilitation but also contributes to psychological well-being, offering a holistic approach to recovery.

In recent years, advancements in myoelectric prosthesis technology have significantly transformed the landscape of assistive devices, enhancing user experience and functionality. A comprehensive understanding of this technology requires an exploration of its hierarchical structure, as depicted in Figure 2. This figure illustrates the intricate components and mechanisms that underpin myoelectric prostheses, categorizing the technology into three primary domains: signal processing, haptic feedback, and data-driven methods. Furthermore, it highlights the control strategies employed in these devices, alongside the development challenges faced by researchers and engineers.

The figure also emphasizes enhancements in user experience through gesture recognition and personalized rehabilitation, showcasing how these innovations contribute to more intuitive and effective prosthetic solutions. However, it is crucial to acknowledge the functional limitations, signal quality issues, and design challenges that persist in the field, underscoring the complexity and multifaceted nature of advancing myoelectric prosthetic technology. By examining these elements, we gain a clearer insight into the ongoing evolution of prosthetic devices and their implications for users.

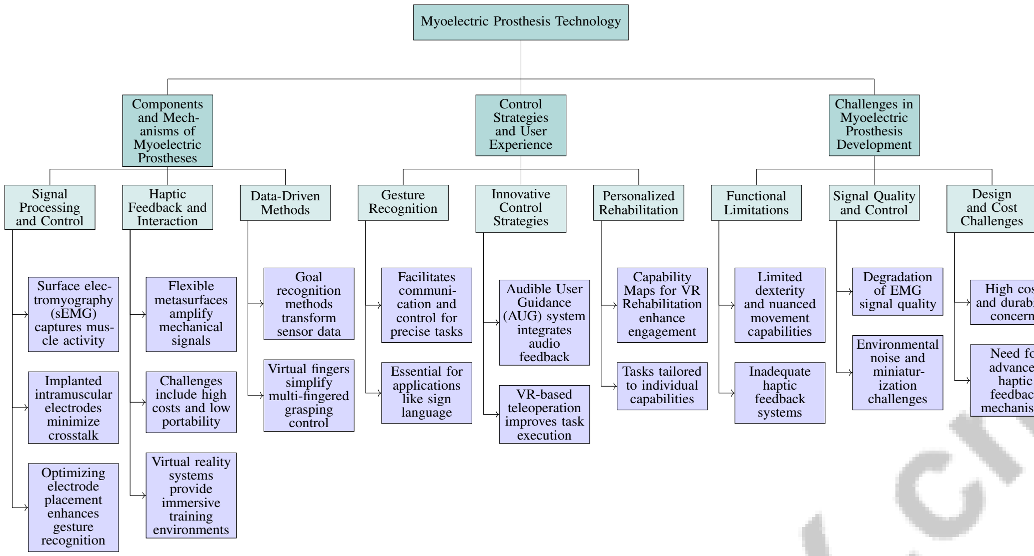


Figure 2: This figure illustrates the hierarchical structure of myoelectric prosthesis technology, highlighting key components and mechanisms, control strategies, and development challenges. It categorizes the technology into signal processing, haptic feedback, and data-driven methods, while detailing user experience enhancements through gesture recognition and personalized rehabilitation. Additionally, it addresses functional limitations, signal quality issues, and design challenges, emphasizing the complexity and multifaceted nature of advancing myoelectric prosthetic technology.

3 Myoelectric Prosthesis Technology

3.1 Components and Mechanisms of Myoelectric Prostheses

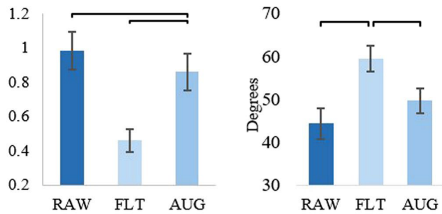
Myoelectric prostheses utilize sophisticated components and mechanisms to interpret electromyographic (EMG) signals, enabling intuitive control for users. Surface electromyography (sEMG) captures muscle activity, translating these signals into commands that guide prosthetic movements, allowing complex actions such as simultaneous hand opening/closing and forearm pronation/supination [18].

A notable advancement is the implementation of implanted intramuscular electrodes, which minimize crosstalk and enhance signal fidelity, facilitating stable control without frequent recalibration [10]. Additionally, optimizing electrode placement on the forearm enhances gesture recognition across various orientations, improving control accuracy [31].

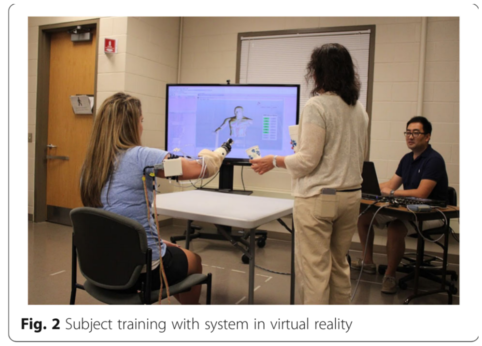
The integration of flexible metasurfaces amplifies mechanical signals to create intricate tactile patterns on human skin, enhancing haptic feedback and user interaction with prostheses [13]. However, challenges such as high costs, low portability, and the need for frequent calibration of haptic devices remain, highlighting the necessity for further advancements to improve practicality and user experience [12].

Virtual reality systems, like INREX-VR, provide immersive environments for neurorehabilitation, tracking movements and progress [30]. These environments are essential for training users to control myoelectric prostheses, offering personalized rehabilitation experiences that engage users. The combination of augmented reality and robotic manipulation to modulate sensory stimuli has been shown to enhance motor capabilities, emphasizing the significance of sensory integration in prosthetic control [14].

Data-driven goal recognition methods transform continuous sensor data into discrete events, refining prosthetic control strategies. By constructing behavior models through process discovery and aligning observed actions with these models, these methods improve the adaptability and responsiveness of myoelectric prostheses [11]. The introduction of virtual fingers further simplifies multi-fingered grasping control, reducing the required degrees of freedom for effective grasping [25].



(a) Comparison of Angular Displacement Between RAW, FLT, and AUG[32]



(b) Subject Training with System in Virtual Reality[21]

Figure 3: Examples of Components and Mechanisms of Myoelectric Prostheses

As illustrated in Figure 3, myoelectric prosthesis technology represents a significant advancement in assistive devices, enhancing functionality and quality of life for individuals with limb loss. This technology harnesses electrical signals from muscle contractions to control prosthetic limbs, enabling more natural movements. The components and mechanisms are depicted through various examples, including angular displacement comparisons and subject training in virtual environments. A bar chart highlights the variance in performance among three groups—RAW, FLT, and AUG. The integration of virtual reality in training scenarios provides users with a dynamic environment to refine their skills, emphasizing the importance of both mechanical and training components in advancing myoelectric prosthetic technology [32, 21].

3.2 Control Strategies and User Experience

Control strategies in myoelectric prostheses are crucial for enhancing user experience through intuitive device interaction. Gesture recognition is a key strategy, facilitating communication and control, especially for tasks requiring precise hand movements [29]. This approach is vital for everyday use and applications like sign language, where accurate recognition is essential.

The Audible User Guidance (AUG) system represents an innovative control strategy, integrating filtered control signals with audio feedback to refine the user's internal model and enhance performance through real-time auditory cues [32]. Such auditory feedback is particularly beneficial in environments where visual feedback may be limited.

Virtual reality (VR) has been employed to enhance control strategies in myoelectric prostheses. A VR-based teleoperation system enables users to interact with a virtual environment using natural hand movements, improving task execution and providing an immersive user experience [6]. By simulating real-world scenarios, VR allows users to practice and refine their control skills safely.

Furthermore, personalized rehabilitation tasks, such as 'Capability Maps for VR Rehabilitation,' enhance user engagement and improve therapy outcomes by tailoring tasks to individual capabilities, ensuring they are challenging yet achievable [7].

3.3 Challenges in Myoelectric Prosthesis Development

The development of myoelectric prostheses faces several challenges impacting functionality and user satisfaction. A primary issue is the limited dexterity and nuanced movement capabilities of current prosthetic hands, which struggle to replicate the intricate motions of a natural hand. Users often rely on visual monitoring to compensate for inadequate haptic feedback systems, which further complicates the use of these devices [2]. The lack of effective sensory and reflexive properties in standard commercial prosthetics inhibits the performance of tasks requiring haptic feedback [33].

Control is further complicated by the degradation of EMG signal quality due to changes in forearm orientation, affecting gesture recognition and limiting the effectiveness of existing methods [31]. This challenge is exacerbated by environmental noise interference and the need for miniaturization to integrate components efficiently [18]. Factors such as skin conditions and muscle fatigue can adversely affect EMG signal clarity, leading to unreliable control [17].

Additionally, users often depend more on their intact limb, complicating the achievement of functional parity between the prosthetic and natural limb [34]. The absence of comprehensive benchmarks for nuanced performance metrics and user satisfaction further complicates the evaluation of multi-grip functionalities [35].

Current feedback systems primarily rely on single-modality feedback, which is inadequate for the complex control strategies utilized by the central nervous system [3]. This limitation highlights the need for advanced haptic feedback mechanisms that provide comprehensive sensory information, enhancing task performance without visual feedback [2].

Moreover, the design of bypass sockets is often restricted to a single terminal device, limiting access to the skin or forearm musculature and hindering effective experimentation and feedback [36]. High costs, durability concerns, and the need for re-tuning algorithms after donning and doffing further complicate the development of user-friendly prosthetic devices [17].

Addressing these challenges necessitates a multifaceted approach, including the integration of high-frequency capacitive sensing and electrohydraulic actuators, such as the F-HASEL actuator, which show promise in improving displacement estimation accuracy and applications in wearable technology and soft robotics [37]. Enhanced signal processing techniques, innovative design solutions, and comprehensive user training programs are essential to improve myoelectric prostheses' functionality and user experience. Ongoing research is required to mitigate issues related to variability in muscle signal generation, signal acquisition quality at the skin-electrode interface, and electromechanical delays in device response [4].

4 Role of Virtual Reality in Prosthetic Training

The integration of virtual reality (VR) into rehabilitation practices has revolutionized prosthetic training by enhancing user experience and rehabilitation outcomes. This section explores VR's transformative role, highlighting its effectiveness in facilitating skill acquisition and improving motor control for prosthetic users.

4.1 Immersive VR Environments for Prosthetic Training

Immersive VR environments are pivotal in prosthetic training, offering engaging platforms that enhance motor skills and control. These environments enable real-time tracking of upper limb movements, crucial for improving range of motion and supporting occupational therapy [1]. The incorporation of deep learning models enhances usability, allowing users with minimal technical expertise to intuitively engage in complex tasks [24].

A key feature of immersive VR is dual-modality haptic feedback, such as vibration and squeezing, which improves grasp-and-hold tasks with virtual electromyography (EMG)-controlled grippers [3]. This sensory integration fosters realistic training environments, enabling effective skill refinement. Additionally, synthetic reflexes and haptic feedback mechanisms enhance user engagement and performance in dexterous tasks, even without visual cues [2].

Immersive VR applications simulate real-world interactions, such as controlling an avatar's movement in brain-computer interface (BCI) systems, enriching the training experience [24]. This method enhances user interaction and facilitates the development of natural user interfaces (NUIs), vital in assistive technologies [23]. Furthermore, immersive VR enhances the sense of embodiment and action simulation, aiding patients in aligning perceived and actual body positions [38]. By leveraging advanced feedback mechanisms and personalized scenarios, VR environments significantly improve user experience and functional outcomes in prosthetic training, as evidenced by their application in therapy chambers and serious games for rehabilitation [8].

4.2 Enhancing User Engagement and Motivation

VR environments play a crucial role in enhancing user engagement and motivation during prosthetic training, offering immersive, interactive experiences that are both educational and therapeutic. VR's integration into rehabilitation allows for the simulation of complex clinical scenarios, offering flexibility in learning pace while reducing reliance on expensive traditional equipment [39]. This adaptability is essential for personalizing rehabilitation tasks, resulting in a more engaging training experience.

VR's capacity to create immersive contexts improves spatial data understanding, vital for task performance compared to traditional interfaces [40]. Research shows VR training leads to significantly higher post-test scores than desktop and physical training groups, underscoring its efficacy in skill acquisition and cognitive engagement [39]. Additionally, VR facilitates bimanual interactions with a single motion controller, enhancing accessibility for individuals with limited mobility [41].

Haptic shared control systems, integrating vibrotactile feedback with autonomous grasping controllers, improve user performance and reduce cognitive load [42]. Electrotactile feedback offers advantages such as improved portability and nuanced tactile sensations, enhancing user interaction [12]. These feedback mechanisms are crucial for sustaining motivation and engagement throughout rehabilitation.

Myoelectric input methods enhance user interaction by providing non-intrusive and non-invasive options [23]. Enhanced signal quality and recognition performance from advanced electrode positioning contribute to a more effective training environment [31].

4.3 Collaborative and Interactive VR Applications

Collaborative and interactive VR applications have emerged as transformative tools in prosthetic training, enabling users to engage in shared experiences that enhance learning and rehabilitation outcomes. These applications leverage VR's immersive nature to create dynamic environments for interaction with virtual objects and avatars, facilitating a more engaging training process [6]. The integration of machine learning algorithms enhances these environments by enabling real-time adaptation to user inputs, supporting personalized rehabilitation pathways [15].

Collaborative VR, exemplified by multi-user platforms for joint training sessions, enables participation regardless of physical location, fostering community among users and providing opportunities for peer learning and support, crucial for maintaining motivation and adherence to rehabilitation protocols [5]. Incorporating interactive elements, such as serious games, transforms traditional exercises into engaging activities that promote sustained user engagement [26].

Interactive VR applications facilitate the development of NUIs, essential for intuitive interaction with prosthetic devices. These interfaces allow users to perform complex tasks with simple gestures, reducing cognitive load and enhancing overall user experience [23]. Furthermore, VR enables teleoperation and remote control of prosthetic devices, providing real-time feedback for skill practice and refinement in a controlled environment [6].

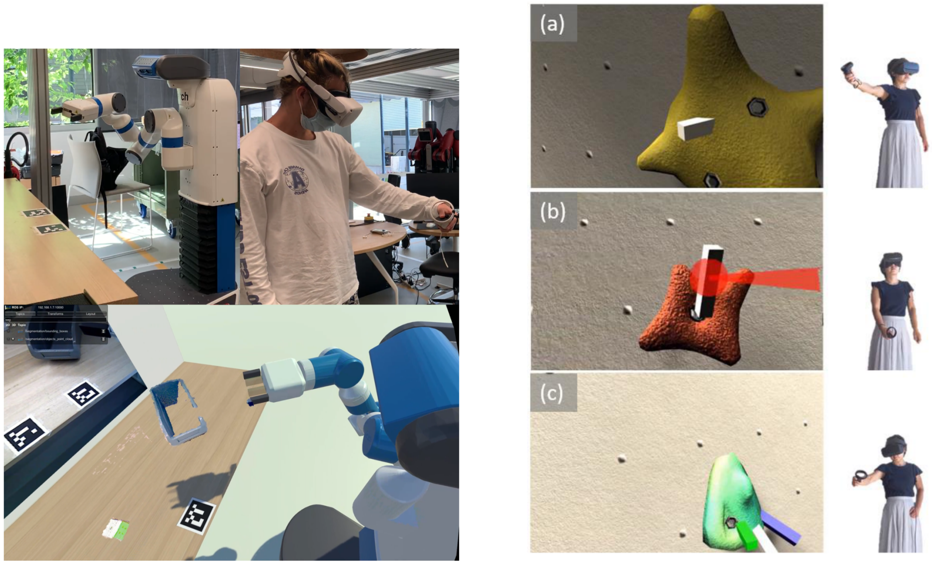
Collaborative VR applications can integrate with emerging technologies like augmented reality (AR) and robotics, creating hybrid environments that offer sophisticated training experiences. These systems can modify sensory stimuli to improve motor capabilities and restore self-efficacy in users, highlighting VR's potential to address complex rehabilitation challenges [14].

As shown in Figure 4, the integration of VR into prosthetic training has opened new avenues for enhancing user experience and rehabilitation outcomes. The first scenario illustrates a robotic arm interacting with a VR headset in a laboratory setting, demonstrating precise control and feedback in prosthetic training. This setup enables users to practice and refine motor skills in a safe environment. The second scenario highlights an augmented reality experience within VR, where a user engages with a 3D model of a skull, emphasizing VR's capability to enhance spatial awareness and understanding of complex structures, crucial for developing intuitive control over prosthetic devices. Together, these examples underscore VR's transformative role in creating collaborative and interactive training modules that significantly improve the efficacy of prosthetic use and rehabilitation [43, 44].

5 Surface Electromyography and Muscle Signal Analysis

5.1 Role of Surface Electromyography in Prosthetic Control

Surface electromyography (sEMG) plays a crucial role in the intuitive control of myoelectric prosthetic devices by capturing muscle signals through skin-surface electrodes. This process translates



(a) Robotic Arm and VR Headset Interaction in a Laboratory Setting[43]

(b) Augmented Reality Experience in Virtual Reality[44]

Figure 4: Examples of Collaborative and Interactive VR Applications

muscle activity into prosthetic movements, enhancing user interaction and facilitating natural control [11, 2]. High-density sEMG data enables detailed muscle activity analysis, crucial for precise control of prosthetics in tasks requiring fine motor skills, thereby improving accuracy and coordination [3, 2]. Real-time processing of sEMG signals is essential for fluid movements, vital for intricate tasks [2].

sEMG's adaptability supports diverse accessibility settings and customizable input techniques, tailoring prosthetic control to individual needs and enhancing user satisfaction [1]. It allows modifications for different terminal devices while maintaining access to the intact limb, illustrating its flexibility in prosthetic applications [34]. Integrating sEMG with virtual environments further enhances its potential in rehabilitation and training. For instance, overlaying a virtual prosthesis onto the user's residual limb via a head-mounted display allows interaction with virtual objects, fostering intuitive control strategies aligned with natural movements [8, 15].

5.2 Methodologies and Technologies in Muscle Signal Analysis

Method Name	Signal Processing	Control Algorithms	Training Environments
FOI-HGR[31]	Feature Extraction Methods	Gesture Recognition Classifiers	-
DMHF[3]	Emg Practice Task	Grasp-and-hold Task	Virtual Task Environment
SRHF[2]	Tactile Sensing	Reflex Controllers	-
TSMLA[15]	Time-domain Features	Lstm Model	Virtual Rehabilitation Context
HSI-Control[6]	-	Physics Engine Integration	Virtual Reality

Table 1: Overview of methodologies and technologies utilized in muscle signal analysis for myoelectric prostheses, detailing the specific signal processing techniques, control algorithms, and training environments employed by various methods. This table summarizes the diverse approaches and their contributions to enhancing prosthetic control and user adaptability.

Table 1 provides a comprehensive summary of the methodologies and technologies applied in muscle signal analysis, highlighting the specific signal processing methods, control algorithms, and training environments used to improve the functionality of myoelectric prostheses. Advanced methodologies and technologies in muscle signal analysis enhance the precision and responsiveness of myoelectric prostheses. sEMG is fundamental for capturing muscle signals, which are processed to control prosthetic devices [18]. Electrode placement significantly influences the accuracy of sEMG-based control systems, as optimal positioning reduces signal interference and improves gesture recognition across various forearm orientations [31]. High-density sEMG collects detailed data, vital for developing sophisticated control algorithms that enable fine motor skills and dexterity [3]. These algorithms process sEMG signals in real-time, allowing fluid and natural movements necessary for complex tasks [2].

Machine learning techniques integrated with sEMG data enhance control systems' adaptability, enabling them to learn and predict user intentions based on muscle activity [15]. Advanced signal processing methods, including wavelet transforms and neural networks, extract meaningful features from sEMG signals for classifying hand gestures and movements [17]. These techniques ensure robust control strategies that adapt to variations in muscle signal patterns, ensuring consistent prosthetic performance [11].

Combining sEMG with virtual reality (VR) environments creates a powerful platform for training and rehabilitation. By overlaying virtual prostheses onto the user's residual limb, users can practice controlling the prosthetic in a simulated environment, enhancing task performance with the actual device [8]. This integration improves user engagement and allows for refining control strategies in a risk-free setting [6].

5.3 Impact on Adaptability and Effectiveness of Prosthetic Devices

Advanced muscle signal analysis via surface electromyography (sEMG) significantly enhances prosthetic devices' adaptability and effectiveness. sEMG's precise capture and interpretation of muscle activity are essential for seamlessly integrating prosthetics into users' daily lives [18]. High-density sEMG reveals detailed muscle activation patterns, facilitating sophisticated control algorithms that enhance prosthetic responsiveness and fluidity [3]. Machine learning approaches with sEMG data augment prosthetic adaptability, enabling systems to anticipate and execute user intentions with increased accuracy [15]. This predictive capability is crucial for performing complex tasks, improving prosthetic effectiveness [11].

Real-time feedback mechanisms further enhance prosthetic adaptability by using sEMG data to provide immediate feedback, allowing users to adjust control strategies in alignment with natural movements [2]. This interaction improves user engagement and facilitates control technique refinement, increasing prosthetic functional utility [1]. The integration of virtual reality (VR) environments supports prosthetic adaptability by offering users a platform to practice and hone control skills in a simulated setting. This immersive training experience enhances users' abilities to perform tasks with greater precision and confidence, leading to improved prosthetic performance in real-world scenarios [6]. VR systems provide a risk-free environment for experimentation and skill development, contributing to prosthetic rehabilitation's overall effectiveness [8].

6 Integration of Technologies in Rehabilitation

6.1 Synergistic Integration of Myoelectric Prostheses, VR, and sEMG

The convergence of myoelectric prostheses, virtual reality (VR), and surface electromyography (sEMG) marks a transformative step in rehabilitation technology, enhancing both training efficacy and user involvement. This integration leverages the distinct advantages of each technology, crafting a personalized rehabilitation framework that aligns with individual user capabilities [1]. Myoelectric prostheses, driven by electromyographic signals, benefit from augmented haptic feedback and reflexive control, which are vital for tasks demanding precision without visual cues [2].

VR significantly enhances this synergy by providing immersive environments that facilitate skill acquisition and user engagement. The gamification of rehabilitation through VR increases patient motivation and adherence, offering a more engaging experience compared to conventional methods [8]. Furthermore, VR supports the development of natural user interfaces (NUIs), crucial for intuitive prosthetic interactions, thereby boosting rehabilitation outcomes.

The integration of sEMG with VR magnifies these benefits by allowing real-time prosthetic control adjustments based on user input. This feedback loop enhances the adaptability and responsiveness of prosthetic devices, facilitating precise movements that mirror natural muscle activity [1]. The potential inclusion of electrotactile feedback in VR applications is a promising research avenue, potentially benefiting both commercial prosthetics and immersive VR systems.

Collaboration among researchers, developers, and users is essential to create accessible AR/VR experiences that integrate seamlessly with rehabilitation technologies, ultimately enhancing functional outcomes [5]. This synergy of myoelectric prostheses, VR, and sEMG offers a promising rehabilitation approach, improving the quality of life for individuals with limb loss.

6.2 Technological Innovations and Applications

Recent advancements in integrating myoelectric prostheses, VR, and sEMG have propelled rehabilitation technology forward. Notable developments include emotion recognition models that enrich user-device interaction by utilizing multimodal physiological signals [45]. Sophisticated machine learning algorithms, particularly deep learning techniques like recurrent convolutional neural networks with transfer learning, have refined sEMG data analysis, leading to more adaptive prosthetic control systems. These systems learn from user-specific muscle activity patterns, enabling precise predictions of user intentions, crucial for executing complex tasks and enhancing prosthetic efficacy [21, 46, 17].

In VR, innovations focus on creating immersive training environments that enhance user engagement and motivation. The integration of serious games within VR platforms transforms traditional rehabilitation exercises into engaging activities, promoting sustained participation and adherence. This approach improves clinical outcomes, such as learning retention and physical function, especially for individuals with neurological conditions. Real-time movement tracking and feedback mechanisms allow for personalized rehabilitation programs that adapt to user capabilities, fostering a more effective rehabilitation process [47, 30, 48, 7]. Additionally, incorporating haptic feedback in VR environments enriches the user experience by simulating real-world interactions.

Collaborative VR applications enhance multi-user interactions and rehabilitation experiences, fostering a supportive community atmosphere. Participants can learn from one another, share progress, and motivate each other, which is particularly valuable in therapeutic contexts where peer support can enhance motivation and improve clinical outcomes [47, 28, 30, 49, 40]. These applications leverage VR's immersive nature to create dynamic environments for skill practice and refinement.

The integration of these technological innovations paves the way for personalized and effective rehabilitation solutions, ultimately improving the quality of life for individuals with limb loss. Ongoing research into multimodal approaches and dataset expansion promises further advancements in the integration of myoelectric prostheses, VR, and sEMG [45].

6.3 Benchmarking and Evaluation of Integrated Systems

Benchmark	Size	Domain	Task Format	Metric
MyoEval[46]	1,000	Rehabilitation Technology	Functional Task Assessment	Success Rate, Peak Hand Velocity
BMI-EEG[50]	1,080	Prosthetic Control	Movement Classification	Accuracy, F1-Score
P300-BCI-VR[51]	21	Brain-Computer Interface	P300 Classification	Accuracy, P300 Latency
DTW-MP[52]	2,710,000	Medical Training	Skill Classification	Accuracy, F1-score
VTF[53]	12	Rehabilitation	Functional Task Performance	Performance time, Accuracy
MyoProBench[34]	20	Prosthetics	Goal-Directed Task	Median MGMPH[35]
9	Prosthetics	Performance Evaluation	COPM, PDI	
XR-Benchmark[1]	1,000	Prosthetic Rehabilitation	Training Evaluation	User Engagement, Skill Transfer Rate

Table 2: Table presents a comprehensive overview of various benchmarks used in the evaluation of integrated rehabilitation systems. The table details the benchmark names, their respective sizes, domains, task formats, and the metrics employed for assessment. This information is pivotal for understanding the diverse methodologies applied in assessing the effectiveness of rehabilitation technologies.

Comprehensive benchmarking and evaluation of integrated rehabilitation systems, including myoelectric prostheses, VR technologies, and sEMG, are crucial for assessing their effectiveness and impact on user outcomes. Recent studies highlight the role of sEMG interfaces in enhancing the embodiment experience of users with prosthetic limbs, showing that configurations with more sensors significantly improve functional performance and users' sense of self-location. Innovative VR systems, such as the Immersive Neurorehabilitation Exercises Using Virtual Reality (INREX-VR), enable real-time movement capture and joint mobility evaluation, addressing accessibility and cost challenges in neurorehabilitation. Augmented reality (AR) training frameworks have also demonstrated potential in improving motor skills and user engagement during rehabilitation exercises [20, 28, 30, 9, 7]. A comprehensive evaluation framework includes multiple dimensions, such as user satisfaction, functional performance, and system adaptability, ensuring that integrated systems meet diverse user needs. Table 2 provides a detailed comparison of representative benchmarks crucial for evaluating integrated rehabilitation systems, highlighting their domains, task formats, and evaluation metrics.

Standardized performance metrics are primary methods for benchmarking these systems, focusing on the precision and accuracy of prosthetic control, crucial for complex task performance in real-world scenarios. High-density sEMG data, combined with advanced machine learning algorithms, enable nuanced assessments of user interaction and control effectiveness [15].

User-centered evaluations are vital for understanding the subjective experiences of individuals using integrated rehabilitation systems. Surveys and interviews provide insights into user satisfaction, perceived ease of use, and the technology's overall impact on daily life, identifying areas for improvement, such as enhancing haptic feedback or refining user interfaces [3].

Integrating VR environments into rehabilitation systems offers unique benchmarking opportunities. VR platforms can simulate various scenarios, allowing for controlled assessments of user performance and the effectiveness of training protocols. This capability is particularly useful for evaluating skill transfer from virtual to real-world environments, providing insights into user interaction and potential barriers to effective rehabilitation [6].

Collaborative benchmarking efforts involving researchers, clinicians, and users are crucial for developing comprehensive evaluation methodologies that capture the full spectrum of user experiences and system capabilities. Such collaborations can establish standardized benchmarks that facilitate effective comparisons of various rehabilitation methods—utilizing virtual reality, motion sensors, and electrotactile feedback—promoting ongoing advancements in therapeutic practices. These benchmarks can enhance rehabilitation program quality, facilitate remote monitoring and assessment of patient performance, and drive innovation in neurorehabilitation solutions tailored to improve patient outcomes [26, 28, 30, 12].

7 Challenges and Future Directions

7.1 Technological Limitations and Challenges

The integration of myoelectric prostheses, virtual reality (VR), and surface electromyography (sEMG) in rehabilitation technologies presents several challenges. A major issue is the variability in human kinematics and muscle activity, complicating the development of reliable goal recognition algorithms for prosthetic applications [11]. This variability hinders accurate user intention prediction across diverse populations. VR-based rehabilitation faces ecological validity concerns due to reliance on simulated data, which may not accurately reflect real-world interactions [41]. Discrepancies between virtual and physical environments can impede skill transfer, affecting training protocol effectiveness [1]. The complexity of interpreting haptic feedback can impact initial user performance, highlighting the need for intuitive training protocols [33]. Additionally, therapist involvement in parameter adjustments introduces variability in patient responses, complicating VR intervention standardization [14].

Myoelectric prostheses face high rejection rates due to comfort and usability issues, exacerbated by low input bandwidth and interference from biological signals. Challenges in replicating human dexterity and force control complicate prosthetic system development [25]. Current methods often fail to provide continuous, accurate predictions of hand configurations and finger joint angles, limiting real-time application effectiveness [54]. The generalizability of findings is restricted by a focus on healthy participants, affecting applicability to clinical populations [15]. Individual differences in kinaesthetic motor imagery execution further influence the effectiveness of brain-computer interface (BCI) systems, crucial for advanced prosthetic control strategies [24].

VR technologies encounter challenges such as high equipment costs, the need for specialized training, and variability in patient responses, hindering broader implementation [16]. Inadequate design considerations for various impairments create significant barriers to user experience and engagement with AR/VR technologies [5]. Technical challenges in VR implementation and the need for further validation of rehabilitation effectiveness remain critical issues [8]. A comprehensive strategy is necessary to address AR/VR limitations, including developing diverse datasets, enhancing user interfaces for accessibility, and implementing evaluation frameworks to assess effectiveness and usability across a wide range of impairments [5, 8]. Overcoming these challenges will optimize the integration of myoelectric prostheses, VR, and sEMG, enhancing rehabilitation outcomes and user satisfaction.

7.2 Future Directions and Research Opportunities

The integration of myoelectric prostheses, VR, and sEMG in rehabilitation technologies presents numerous research opportunities. One promising direction is the development of cost-effective VR solutions to democratize access to advanced rehabilitation tools, thereby expanding their availability in clinical settings [16]. Exploring new therapeutic applications of VR, such as cognitive rehabilitation and mental health interventions, could extend its utility beyond traditional physical rehabilitation.

Future research should prioritize longitudinal studies to evaluate the long-term benefits of VR in clinical contexts, providing insights into its efficacy and sustainability over extended periods [16]. Such studies are crucial for understanding the lasting impact of VR-based interventions on patient outcomes and refining treatment protocols. Larger sample sizes in future studies are essential for exploring the interactions between control factors and user performance, particularly in the context of myoelectric prostheses. These studies could yield valuable data on how various factors influence prosthetic control system effectiveness, leading to more personalized rehabilitation strategies.

Enhancements to the electrode interface and the reduction of electromechanical delays are critical areas for further investigation [4]. Improving the reliability and responsiveness of the sEMG interface can significantly enhance user experience, enabling more precise and natural control of prosthetic devices.

8 Conclusion

The convergence of myoelectric prostheses, virtual reality (VR), and surface electromyography (sEMG) represents a transformative leap in rehabilitation technology, offering substantial improvements in the lives of individuals with limb loss. This survey underscores the essential contribution of these technologies to enhancing functional outcomes and user satisfaction. Myoelectric prostheses, particularly those equipped with advanced multi-grip functionalities, have proven to significantly improve user performance in everyday tasks, underscoring their indispensable role in prosthetic rehabilitation. The integration of VR into rehabilitation strategies provides immersive experiences that boost patient engagement and motivation, with promising implications for advancing medical diagnostics and therapeutic results.

Additionally, the amalgamation of AI-enhanced VR with novel sensory stimuli methods holds potential for restoring self-efficacy, especially for patients dealing with chronic pain, thereby leading to improved rehabilitation outcomes. This integrative approach fosters a comprehensive, adaptable, and personalized rehabilitation framework that caters to diverse user requirements, facilitating effective skill transfer from virtual simulations to real-world applications. As research in this domain continues to evolve, the potential for these integrated technologies to revolutionize rehabilitation practices and significantly enhance the quality of life for individuals with limb loss remains profound.

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