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The importance of advanced technologies in functional rehabilitation of the hand

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Abstract: This systematic review examines groundbreaking advancements in hand rehabilitation, driven by significant progress in medical technology. Adhering to PRISMA guidelines, the review surveyed articles from various databases, emphasizing the utilization of advanced technologies for hand rehabilitation across diverse conditions such as fractures, burns, amputations, and postoperative care. Out of the 1562 studies analyzed, ten articles that met the inclusion criteria were identified. Key technologies like IMES (Implantable Myoelectric Sensor) technology are scrutinized for their potential to transform prosthetic control, providing intuitive functionality and substantial physiological hand function for individuals with limb loss. Similarly, advancements in orthotic devices like the VacoHand Orthosis are showcased for their improvements in stabilizing and aiding the healing process in wrist immobilization and rehabilitation. The integration of virtual reality (VR) emerges as a pivotal convergence point, offering supplementary therapy to enhance direction-specific improvements in wrist and forearm mobility, hand function, and work-related tasks. Additional advantages include program customization, heightened engagement through interactive approaches, and improved functional outcomes such as hand strength and range of motion. While showcasing transformative potential, the review acknowledges the need for further research through larger sample sizes, standardized methodologies and more in-depth investigations to optimize these technologies. Overall, this review underlines the remarkable advancements achieved in hand rehabilitation through technological innovations, offering hope and improved outcomes for individuals grappling with various hand-related challenges.

Keywords: hand rehabilitation, advanced technologies, virtual reality, robotic rehabilitation, multisensory training

1. Introduction

In recent years, the field of medical technology has made remarkable strides in developing innovative devices and techniques aimed at rehabilitating and restoring hand function, which play a pivotal role in facilitating recovery, enhancing motor skills, and improving overall hand functionality.

The advent of cutting-edge technology has brought forth a multitude of devices designed specifically for hand rehabilitation. This systematic literature review embarked on a journey to explore their advancements and the unique contribution of this review lies in its holistic examination of cutting-edge devices and techniques, spanning a range of injuries including burns, wrist fractures, and limb amputations. By synthesizing findings from diverse studies, the review elucidates the evolving landscape of hand rehabilitation, highlighting the efficacy of innovative interventions such as IMES technology, advanced orthotic devices like the VacoHand Orthosis, myoelectric control systems, and Virtual Reality (VR) integration.

One such groundbreaking innovation highlighted was the advent of IMES (Implantable Myoelectric Sensor) technology, heralding a new era for individuals with limb loss [1].

This revolutionary technology enables intuitive control of prosthetic limbs through tiny implanted electrodes, fostering enhanced functionality and control, as evidenced by the positive outcomes observed in the initial study.

In the realm of postoperative immobilization for distal radius fractures, the study examined the efficacy of advanced orthotic devices like the VacoHand Orthosis, showcasing the evolution in stabilizing and aiding the healing process of specific bone fractures through innovative hinge mechanisms and design features.

Moreover, the review shed light on the importance of myoelectric control systems' robustness in individuals with limb amputations, emphasizing the need for technology that can address clinical challenges effectively. The study demonstrated promising outcomes in providing individuals with limb loss a substantial degree of physiological hand function through a postural controller coupled with a multi-functional prosthetic hand.

Integrating Virtual Reality (VR) into rehabilitation emerged as a converging point for advanced medical devices and therapeutic intervention. Studies indicated VR's potential to improve specific movements, hand function, and work-related tasks, signaling its role as a supplementary therapy in enhancing rehabilitation outcomes. Specifically, VR-based interventions utilizing technologies such as the Leap Motion Controller (LMC) and RAPAEL Smart GloveTM system integrated an exoskeleton glove and VR interface, addressing individuals with burn scars [2-4].

Notably, this review synthesized findings from various studies, including those exploring Multi-sensory Training (MST) for wrist fractures, immersive VR training's effectiveness for distal radius fracture patients, and the comparison of control methods for advanced myoelectric hands, each contributing unique insights into holistic approaches and technological interventions in hand rehabilitation.

The integration of advanced medical technical devices in hand rehabilitation offers numerous benefits that significantly impact patients' recovery, such as enhanced customization, with personalized rehabilitation programs and devices cater to individual needs, maximizing effectiveness and outcomes and increasing engagement and compliance with interactive and gamified approaches, which make therapy sessions more engaging, encouraging patients to adhere to their rehabilitation routines [5].

Additionally, improved functional outcomes are possible with the aid of advanced devices that facilitate targeted exercises, leading to improved hand strength, range of motion, and overall functionality.

Technology facilitates the collection of objective and quantifiable data regarding a patient's progress, whereas traditional methods often rely on subjective assessments, which can be prone to bias. Therefore, real-time feedback and data collection enable therapists to monitor patient progress objectively, adjusting rehabilitation plans accordingly for optimal results.

Despite technological strides, the review acknowledged the need for further research. It advocates for larger sample sizes, standardized methodologies, and deeper investigations into specific technological applications to fully harness their potential in hand rehabilitation. Thus, the review not only fills the gap in existing literature by providing a comprehensive overview of technological advancements, but also sets the stage for future research endeavors aimed at refining and optimizing these interventions for improved patient outcomes.

Overall, this systematic review encapsulated the transformative potential of various technologies in addressing distinct challenges within the landscape of hand rehabilitation, paving the way for more inclusive, effective, and patient-centric functional rehabilitation strategies.

2. Materials and Methods

The methodology employed in this systematic literature review adhered to the „PRISMA" guidelines, a universally accepted approach for systematic reviews and meta-analyses. To identify suitable articles for our research, we conducted searches across various databases, including the National Center for Biotechnology Information (NCBI) – PubMed, Cochrane, Physiotherapy Evidence Database (PEDro) and Medline.

Initially, we employed the following keywords in our database searches: operated hand + robotic rehabilitation – stroke; hand pathology + burn + post-operatory + robotic rehabilitation; operated hand pathology + burn + robotic rehabilitation; operated hand pathology + burn + assistive robotic rehabilitation; operated hand fractures + assistive robotic rehabilitation; burned hand + assistive robotic rehabilitation; fractured hand + functional rehabilitation; post-surgical hand pathologies + robotic rehabilitation; operated hand pathology + virtual rehabilitation; fractured hand + virtual rehabilitation; burned hand + virtual rehabilitation.

The filters utilized for refining the selection of articles encompassed are: clinical trial, meta-analysis, RCT, review, systematic review, last 10 years, humans.

The inclusion criteria encompass two primary facets: (i) the incorporation of advanced technologies within hand rehabilitation and (ii) the inclusion of patients afflicted by hand injuries, including burns.

The exclusion criteria comprised languages other than English, books, book chapters, conference abstracts, articles published before 2013, pediatric cases, and instances of stroke and degenerative central nervous system (CNS) diseases that could potentially impact mobility or cognitive function.

3. Results

The initial search yielded 1562 studies distributed across various databases: 1520 in PubMed, 37 in Cochrane, and 5 in Medline. Following the elimination of duplicates, the total was reduced to 1523 articles. Subsequently, the filters' refinement led to the exclusion of 1441 studies, with 82 reports sought from retrieval, from which 68 were under a rigorous screening process of titles and abstracts, focusing on advanced technology. Within this subset, 58 studies were omitted, being non-compliant literature based on the set inclusion and exclusion criteria mentioned previously, narrowing the analysis to studies centered specifically on hand rehabilitation of patients with wrist fractures, burns, hand surgery (including amputation), totalling 10 research articles (refer to Figure 1).

The following table presents the acquired research articles, displaying their titles, authors, publication years, specific pathologies studied, respective study designs, and the number of participants involved.

Figure 1. PRISMA flow diagram - the selection process of literature.

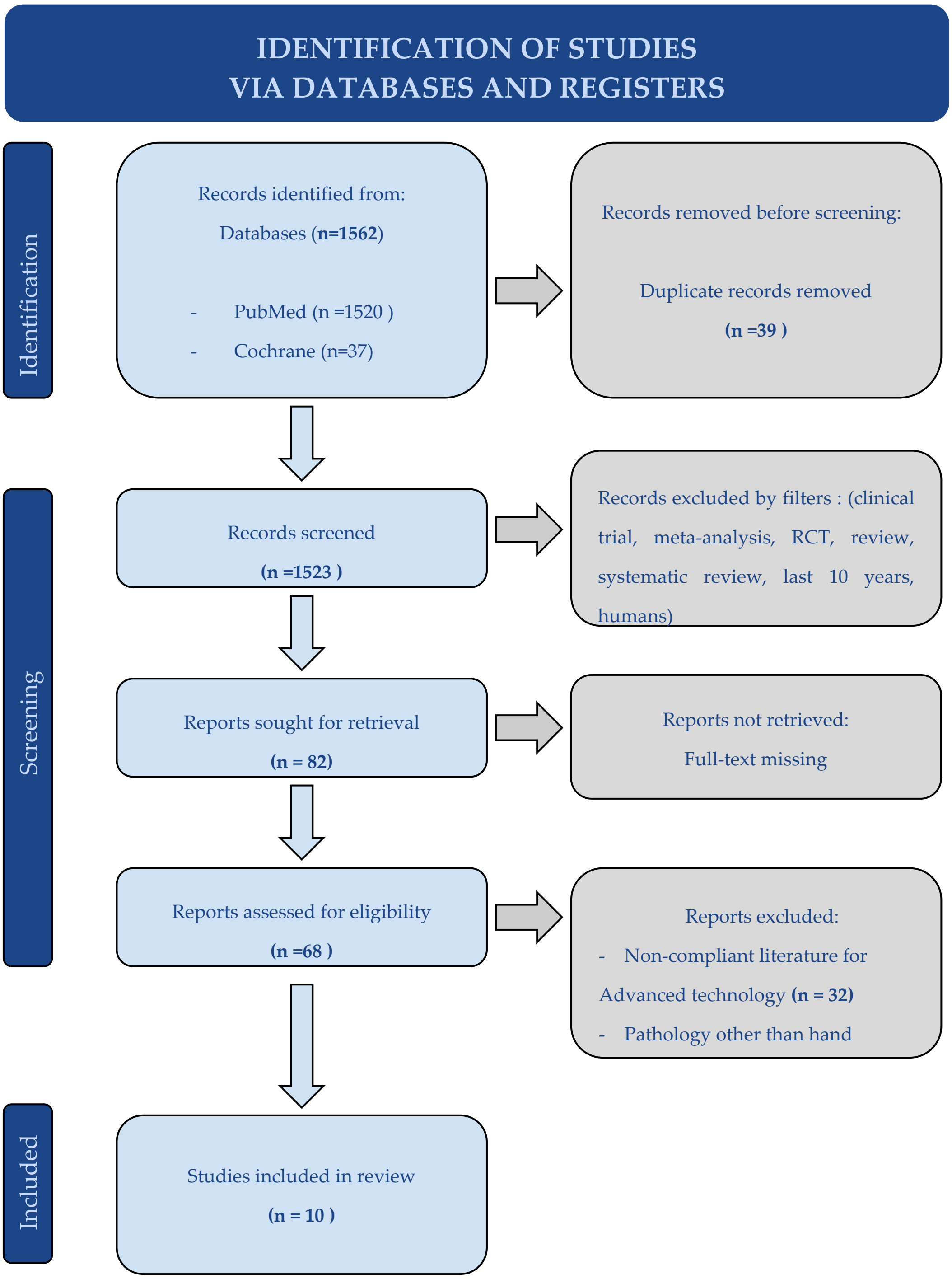

Table 1. The collated research articles

Authors	**Title**	**Year**	**Pathology**	**Study design**	**Patients**
Pasquina PF, et al.	First-in-man demonstration of a fully implanted myoelectric sensors system to control an advanced electromechanical prosthetic hand.	2015	Right transradial amputation	Controlled Clinical trial	1
Stuby FM, et al.	Early functional postoperative therapy of distal radius fracture with a dynamic orthosis: results of a prospective randomized cross-over comparative study	2015	Displaced distal radius fractures	Randomised Controlled Trial	29
Segil JL, et al.	Functional Assessment of a Myoelectric Postural Controller and Multi-Functional Prosthetic Hand by Persons With Trans-Radial Limb Loss	2017	Transradial limb loss	Randomised Controlled Trial	8
Yah-Ting Wu et al.	Evaluation of leap motion control for hand rehabilitation in burn patients: An experience in the dust explosion disaster in Formosa Fun Coast.	2018	Burn injuries	Controlled Clinical trial	16
Joo, S.Y et al.	Effects of Virtual Reality-Based Rehabilitation on Burned Hands: A Prospective, Randomized, Single-Blind Study	2020	Burn injuries	Randomised Controlled Trial	57
Picelli A. et al.	Robot-assisted arm training for treating adult patients with distal radius fracture: a proof-of-concept pilot study	2020	Wrist fracture	Randomized Controlled Trial	20
Baldursdottir B. et al.	Multi-sensory training and wrist fractures: a randomized, controlled trial.	2020	Fall-related wrist fractures	Randomized Controlled Trial	98
Twinkle Y. Dabholkar et al.	Effect of Virtual Reality Training Using Leap Motion Controller on Impairments and Disability in Patients with Wrist and Hand Stiffness	2020	Residual wrist and hand stiffness resulting from wrist fractures/ injuries or due to	Randomized Controlled Trial	50

			rheumatoid arthritis		
Matamala-Gomez M, et al.	Impact of virtual embodiment and exercises on functional ability and range of motion in orthopedic rehabilitation.	2022	Distal radius fracture injury	Randomized Controlled Trial	54
Lee C, et al.	Use of regenerative peripheral nerve interfaces and intramuscular electrodes to improve prosthetic grasp selection: a case study	2022	Unilateral transradial amputation	Controlled Clinical trial	1

Advancements in technology have continuously transformed the healthcare landscape, particularly in the field of prosthetics. Among these groundbreaking innovations, the advent of IMES (Implantable Myoelectric Sensor) technology has emerged as a game-changer, particularly in the realm of hand rehabilitation for individuals with limb loss. This revolutionary technology, approved for its first FDA (Food and Drug Administration) trial in 2015, has ushered in a new era of hope and possibilities for those seeking enhanced control and functionality in their prosthetic limbs. This new method involves tiny electrodes called Implantable Myoelectric Sensors (IMES) that can detect and transmit muscle signals wirelessly to a robotic hand within the prosthetic. These sensors can gather signals from multiple muscles in the residual limb simultaneously, allowing for more natural control of different movements at once. The subject of this first study underwent surgical implantation of the IMES and the surgery was successful, lasting less than 2.5 hours, with no complications aside from the discovery of a metal hemoclip in the residual limb, which posed no interference to the IMES function. His stamina, ability to perform various tasks, and satisfaction with the system notably increased over the study period, as he reported better intuitive control and expressed a greater desire to use the advanced prosthesis compared to previous devices, enabling a broader range of tasks in daily life. These findings suggest that IMES technology might make controlling advanced prosthetics more intuitive and reliable [6].

In the same year, a randomized controlled trial published in PLoS One by Fabian M. Stuby et al. investigates the efficacy of different postoperative immobilization methods following surgical treatment for distal radius fractures. This evaluation is particularly fascinating in the context of advanced medical tools, as they are used both in the surgical procedure and in the postoperative immobilization.

All patients had Osteosynthesis performed using volar, distal radius locking plates. These plates, such as the Königsee 3.5mm or Synthes LCP 3.5mm, typically have specialized locking mechanisms and are designed to stabilize fractures of the distal radius through surgical implantation. While they might not be as visibly high-tech as some other medical devices, their engineering and material characteristics represent advanced solutions for stabilizing and aiding in the healing of specific bone fractures. Afterward, patients were randomly assigned to either Group A (VacoHand) or Group B (plaster splint) through a pre-labelled and concealed randomization process. VacoHand Orthosis, designed by OPED, is described as a vacuum-fitted orthosis with a wrist hinge. It offers the capability to be used in both a blocked position and an unblocked, flexible mode, allowing various degrees of range of motion. Its design and functionality, particularly with its vacuum-fitted feature and adaptable hinge mechanism, suggest a level of technical advancement in orthotic devices meant for wrist immobilization and rehabilitation. In the final assessment, a significantly larger proportion of patients expressed a preference for the orthosis in the event of another fracture ($p = 0.017$).

The findings suggest advantages of the orthosis in functional outcomes after four weeks, with superior patient satisfaction compared to the plaster splint. The orthosis was favored by most patients for future fracture immobilization. However, after twelve weeks, functional advantages appeared to level between the two methods.

Despite similarities in pain, overall functional ability, and resilience between the groups, the orthosis group showed better evaluations for accuracy of fitting, aesthetics, and hygienic feeling. The flexibility of the orthosis allowed additional exercises, potentially contributing to better functional outcomes after four weeks and a slightly improved range of motion after twelve weeks.

While functional outcomes and clinical parameters like ROM (Range of Motion) didn't consistently favor one method over the other, patient-reported outcomes and preferences leaned towards the orthosi. [7].

One crucial aspect in this domain involves the functional assessment of myoelectric control algorithms, especially in individuals with limb amputations. The overarching aim of prosthetic limb design is to provide individuals with limb loss the ability to regain the functionalities they have lost. However, numerous studies in this field rely on experimental paradigms involving virtual interfaces and able-bodied subjects, failing to accurately capture the challenges inherent in clinical settings with amputee populations.

The assessment and validation of myoelectric control systems must prioritize robustness to address the variable physiology, loading effects of the prosthetic limb on the residual limb, and position effects during various dynamic tasks. "The Functional Assessment of a Myoelectric Postural Controller and Multi-Functional Prosthetic Hand by Persons with Trans-Radial Limb Loss" study addressed these crucial concerns in 2017 by having individuals with transradial limb loss engage in activities of daily living using a postural controller coupled with a multi-functional prosthetic hand. The primary objective was to ascertain the controller's robustness in handling these clinical challenges [8].

This study, employing the Southampton Hand Assessment Procedure, included individuals with limb loss, as well as able-bodied subjects in the evaluation process. Notably, the results demonstrated comparable performance levels between individuals with limb loss and their able-bodied counterparts. This achievement suggested that the postural controller effectively overcame the clinical challenges posed. On average, individuals with limb loss attained 55% of physiological hand function through the use of this technology, being statistically significant ($p < 0.001$). Moreover, the study presented a comparative analysis between the postural controller and other state-of-the-art myoelectric controllers and prosthetic hands that were previously tested. The findings strongly supported the potential clinical viability of the postural controller as a method to control myoelectric multi-functional prosthetic hands efficiently. The findings underscore the importance of the mechanical design of prosthetic hands in influencing functionality, with the Bebionic hand showing superior performance compared to the Azzurra hand.

The successful adaptation and performance parity observed between amputees and non-disabled individuals using the postural controller offers promising prospects for enhancing the quality of life for those reliant on prosthetic technology. By bridging the gap between clinical challenges and technological solutions, such advancements pave the way for more inclusive and effective functional rehabilitation strategies.

Rehabilitation strategies play a pivotal role in restoring hand and wrist function for individuals with burn scars. Scar management and the development of contractures emerge as critical concerns, impacting both physical health and mental well-being. Conventional methods involving massage therapy, compression garments, and steroid injections help mitigate scar tissue formation and contractures. Yet, they possess limitations, ranging from financial and political barriers to physical and communication challenges [9,10].

In light of these obstacles, the efficacy of VR-based rehabilitation compared to conventional standard therapy was evaluated in a 2018 study by Wu YT et al., but this time was aimed at individuals who experienced severe hand burns during a dust explosion incident [11]. All 16 participants had undergone both surgical and medical treatments for their burn injuries, the study being centered around the transformative Leap Motion Controller (LMC), aimed to assess the device's efficacy in comparison to traditional occupational therapy (OT). The LMC, introduced in 2013, is a compact, cost-effective motion capture device that tracks hand and finger movements without direct physical contact [12]. In the LMC group, participants engaged in specific finger and hand movement training facilitated by three leap motion video games: "the cube grasping" game focused on finger flexion, "the flower petal removal" game involved pinching, and "the shooting" game incorporated finger abduction and adduction.

Comparisons of baseline data between the LMC and control groups showed no significant differences. However, after the 4-month training, the LMC-trained hand demonstrated statistically significant improvement in BSHS-B, QuickDASH, iADL, and Barthel index, while the control group showed improvement only in the Barthel index.

Despite limitations, such as small sample size and nonrandom patient allocation, this research presents a pioneering exploration of the potential benefits of incorporating virtual reality (VR) technology, such as LMC, into traditional therapeutic approaches for patients with severe hand burns.

The efficacy of VR-based rehabilitation compared to conventional standard therapy was also evaluated in a single-blind, randomized controlled trial, aimed at individuals with re-epithelialized burn scars, explicitly focusing on the right hand and wrist. The study included 57 patients recruited from the Department of Rehabilitation Medicine at Hangang Sacred Heart Hospital in Korea between June and October 2019 [13].

The study groups were randomly assigned, with 28 patients allocated to the VR (virtual reality)-based rehabilitation group and 29 patients to the standard therapy (CON) group. Both groups received interventions tailored to hand rehabilitation, with the VR group incorporating the use of the RAPAEL Smart GloveTM system, integrating an exoskeleton glove and a VR interface. The interventions were conducted over four weeks, comprising 20 sessions of 60 minutes each. After the intervention, notable improvements were observed in various outcome measures favoring the VR group. Specifically, subtest scores in the Jebsen-Taylor Hand Function Test (JTT), particularly in tasks involving picking up small objects, exhibited significant enhancements in the VR group compared to the CON group. Previous research emphasizing robot-assisted rehabilitation in the acute phase after musculoskeletal injuries aligns with this study's findings, suggesting early mobilization and improvement in motor capacity through such interventions.

The immersive nature of VR proved beneficial in pain reduction, an essential aspect during physical therapy and burn wound care [14]. The focused attention of patients on task completion in VR treatments significantly reduced pain perception, aligning with previous studies showcasing VR's pain reduction efficacy during rehabilitation.

Moreover, the VR-based rehabilitation's multitasking approach, including activities resembling daily life tasks, contributed to improved ROM and satisfaction levels. Tasks designed in the VR system simulated activities of daily living, promoting engagement and providing positive reinforcement, thus enhancing patient satisfaction.

Further investigations are warranted to explore changes in brain activity or peripheral neuromuscular functions to better understand the mechanisms underlying VR rehabilitation after musculoskeletal injuries, including burns. Additionally, future studies should consider parameters like hand ROM for comprehensive evaluation and comparison between VR-based and CON rehabilitation.

A study that sheds light on the potential role of technology in aiding recovery and improving upper limb impairment, especially in patients with wrist injuries, is "Robot-assisted arm training for treating adult patients with distal radius fracture: a proof-of-concept pilot study", published in 2020, aimed to assess the feasibility and efficacy of robot-assisted arm training in treating upper limb impairment among adult patients with distal radius fracture, comparing it to conventional rehabilitation methods. The randomized trial involved twenty adult outpatients who received ten 1-hour sessions over two weeks. The study found that there were no significant differences between the RAT group (robot-assisted arm training along with conventional occupational therapy) and CAT group (conventional arm training along with conventional occupational therapy) in terms of improvement in forearm pronation/supination, wrist extension/flexion, grip and pinch strength, and PRWHE (patient-rated wrist-hand evaluation) score at post-treatment and follow-up evaluations.

Despite not finding significant differences between the two groups in terms of improvements, the study provides nuanced insights into the outcomes of both treatments. It emphasizes the importance of considering cost-effectiveness, feasibility, and safety alongside treatment efficacy, offering a comprehensive perspective for healthcare providers. This showed promise in treating upper limb impairment, offering potential benefits for therapists managing multiple patients simultaneously. It suggests opportunities for optimizing therapy delivery and warrants further investigation to solidify its effectiveness, possible variations in application, and the impact on functional outcomes in the long term [15].

An innovative approach is presented in a 2020 study, "Multi-sensory training and wrist fractures: a randomized, controlled trial", focusing on comprehensive rehabilitation. Instead of solely targeting the injured wrist, the study considers the broader implications of wrist fractures. It explores how these injuries might relate to factors such as postural control, vestibular function, and sensory perception, suggesting a more holistic approach to wrist injury rehabilitation. The study explores a novel approach by comparing Multi-Sensory Training (MST) to Wrist Stabilization Training (WT). Utilizing a multi-sensory training model, "The Reykjavik model", aims to improve not only wrist function but also postural control, vestibular function, foot sensation, and functional ability in individuals with wrist fractures. This broader approach acknowledges the interconnectedness of various sensory systems and their impact on recovery.

The study itself incorporates various advanced medical technologies or tools used for assessment rather than specific devices, such as the Head Shake Test (HST), which involves the use of infrared video goggles to record eye movements in the supine position, and the Video-Head Impulse Test (vHIT) that assesses the function of the horizontal semicircular canals. The previously mentioned test uses a set of ICS impulse video goggles manufactured by GN Otometrics, which include a camera that records the motion of the right eye at a high speed of 250 frames per second.

The study's conclusion suggests several key findings, including the effectiveness of MST, as it exhibited a significant improvement in postural control, evidenced by higher scores on the Sensory Organization Test (SOT) compared to Wrist Stabilization Training (WT). Additionally, improvements in the Dizziness Handicap Inventory (DHI) were observed only in the MST group. In addition, it highlighted that individuals with reduced postural control at baseline benefited more from the MST program compared to WT. However, the outcomes of this study were more modest than expected, potentially due to the relatively young, healthy, and physically active nature of the participants compared to a previous pilot study involving older, frailer individuals with more significant deficits. Furthermore, additional research with larger sample sizes and more rigorous protocols must confirm and generalize these findings before recommending MST as a standard intervention for this population [16].

Integrating VR into rehabilitation represents a convergence of advanced medical devices and therapeutic intervention. VR technology offers an interactive and immersive platform that can engage patients in therapeutic exercises, potentially enhancing rehabilitation outcomes beyond what traditional devices or methods alone can achieve.

The Indian Journal of Public Health Research & Development published findings that suggest how VR training led to direction-specific improvements in the range of motion of the wrist and forearm. This direction-specific rehabilitation could be crucial in advanced medical devices tailored explicitly for precision in hand rehabilitation, to assist patients in achieving more precise and targeted movements during therapy. Fifty patients (30 female and 20 male) with wrist and hand stiffness were split into two groups: one receiving only conventional physiotherapy and the other receiving both conventional physiotherapy and VR training, with both groups undergoing 8-12 training sessions over 4 weeks. The female predominance in the study is explained by factors like osteoporosis prevalence in women [17]. The group using virtual reality demonstrated notable enhancements in grip strength, hand agility and wrist flexibility, therefore more improvement in specific movements and overall work-related hand function compared to the group receiving conventional treatment. However, both groups showed similar outcomes in aspects such as pain relief, wrist extension, and radial deviation. To sum up, VR training resulted in more significant enhancements in certain areas, emphasizing its potential as an additional therapy. Future studies could explore VR as a home treatment and delve deeper into direction-specific improvements. Limitations include differing treatment durations and the study's single-blinded method, as well as the inclusion of patients with diverse pathologies[18].

Another study from the same year, conducted by Marta Matamala-Gomez, Mel Slater and Maria V. Sanchez-Vives aimed to assess the effectiveness and patient experiences associated with different virtual reality (VR) and conventional rehabilitation training methods, but this time for distal radius fracture patients during the immobilization period and post-cast removal.

The study evaluated several vital factors, one of them being functional arm ability; using the Fugl-Meyer (FM) test, the study found that patients undergoing immersive VR training showed significantly better recovery of arm function after cast removal and at the six-week follow-up compared to those following conventional digit mobilization (CDM) and non-immersive VR training. The immersive VR group had a higher proportion of patients with good prognostic recovery.

The second evaluated factor is arm disability: assessment with the Disability of the Arm, Shoulder, and Hand (DASH) questionnaire revealed that patients in the immersive VR training group experienced significantly lower arm disability scores after cast removal compared to those in the CDM group, indicating better recovery in daily life activities.

Another factor is range of motion; patients undergoing immersive VR training demonstrated more significant improvements in wrist flexion, wrist extension, and radial deviation movements compared to both CDM and non-immersive VR groups after cast removal and during the follow-up period.

The last evaluated factor is subjective experience, where subjective feedback from patients highlighted a significantly more positive experience during immersive VR training sessions. Those in the immersive VR group reported higher levels of embodiment ($p < 0.0001$) and agency ($p < 0.0001$) compared to the non-immersive VR group. Importantly, this positive subjective experience correlated with their functional motor ability recovery.

The correlation between improved functional recovery and a sense of ownership and agency over the virtual arm suggests that the immersive nature of the VR experience plays a significant role in rehabilitation outcomes. However, the study acknowledges limitations, including gender imbalances within training groups and the absence of males in the immersive VR group. It also acknowledges the lack of control over digit mobilization quantity in the CDM group, reflecting the standard procedure post-distal radius fracture.

Overall, the study highlights the potential benefits of immersive VR training for orthopedic rehabilitation, not only for fractures but also potentially for other musculoskeletal and neurological conditions [19].

In 2022, a case study by Christina Lee et al. was published in the Journal of Neural Engineering which evaluated the effectiveness of different control methods for advanced myoelectric hands in a female participant with unilateral transradial amputation.

They compared regenerative peripheral nerve interfaces (RPNIs) and intramuscular electrodes against traditional surface electrodes for controlling these prosthetics.

The participant underwent various tasks, both virtual and physical, to test grasp selection and interaction abilities. Results showed that the RPNI controller significantly improved accuracy during virtual tasks by 10.6% compared to surface controllers. In physical tasks like the "Coffee Task", using the RPNI controller led to completing the task 11.7% faster with 11 fewer errors.

The study highlights how combining RPNIs with intramuscular electrodes can notably enhance accuracy and speed in controlling myoelectric prosthetic hands. These findings promise better control methods, reducing cognitive load and eliminating frequent recalibration needs, offering a more seamless experience for prosthetic users [20].

4. Discussion

A confluence of 5 reviews spanning from 2016 to 2022 found in our search underscores the transformative potential of various technologies in addressing distinct challenges within the landscape of hand rehabilitation. While these investigations explore disparate facets of hand functionality improvement, they collectively aim to augment motor skills, enhance recovery, and improve the quality of life. Ranging from studies elucidating the evolution of upper limb prosthetics, exploring the efficacy of wearable assistive robotics employing teleceptive sensing, to investigations on the integration of virtual reality (VR) for burn rehabilitation, these inquiries delve into distinct yet complementary aspects of this multifaceted field.

Regarding rehabilitation strategies post-Carpal Tunnel Release (CTR), in recent studies, several cutting-edge devices and therapies have been investigated for their efficacy, such as laser therapy, electrical modalities, ultrasound therapy, and controlled cold therapy. In spite of presenting intriguing possibilities for improving rehabilitation outcomes, their definitive role remains uncertain. Despite promising potential, studies comparing low-level laser therapy with a placebo did not yield significant differences, neither did the ones evaluating electrical modalities nor ultrasound, as they did not offer comprehensive or interpretable data regarding their impact on CTR symptoms or recovery after surgery [21].

The field of hand rehabilitation and upper limb prosthetics stands at the precipice of a technological revolution. With advancements in hardware, socket technology, and control strategies, individuals with upper limb loss or impairment are experiencing unprecedented opportunities for functional recovery and improved quality of life. From basic cosmetic prostheses to highly functional and intuitive devices, the landscape of hand rehabilitation has undergone a profound transformation. A comprehensive study published in the Orthopaedic Research and Reviews Journal, delves into this realm, exploring the advancements mentioned above, all contributing to enhancing the lives of individuals with upper limb loss or impairment. Cutting-edge hardware has emerged as a beacon of hope for individuals seeking increased functionality and natural movement. The study outlines the rise of multi-actuated hands, exemplified by products like i-limb Quantum, BeBionic v3, and Ottobock's Michelangelo. Furthermore, control mechanisms in upper limb prosthetics have undergone a significant transformation, transitioning from simple direct proportional control to more sophisticated approaches. The advanced strategies involving pattern recognition, machine learning, and biologically inspired algorithms, aim to provide users with more intuitive and efficient control over multiple degrees of freedom, catering to diverse needs. The integration of sensory feedback remains an area of immense potential. While not covered extensively in the study, advancements in providing it are crucial for natural interaction and manipulation. Innovations centered on user-centric design, affordability, and long-term user adaptation stand as essential pathways for future research and development in the field of hand rehabilitation technology [22].

A study from 2019 focuses on the burgeoning field of using teleceptive sensing to enhance the performance and functionality of wearable assistive robotics. Upper-limb assistive devices primarily employ RGB cameras, often combined with EMG (electromyographic) sensors or IMUs, for grasp preshaping. For individuals with impaired hand function, the findings related to grasp prediction using teleceptive sensing technologies offer potential advancements. The ability to predict and pre-shape grasps based on environmental cues or object detection can assist in enabling more natural and functional hand movements. Teleceptive sensing, when integrated with wearable devices for hand rehabilitation, can provide real-time feedback to users. This feedback fosters engagement, motivation, and active participation in rehabilitation exercises, which are crucial factors influencing the effectiveness of rehabilitation programs. While preliminary findings show promise, the systems exhibiting good performance in accuracy, comparable to EMG-based approaches, concerns persist regarding timing, lag, and adaptability to real-world environments [23].

Among the array of advanced devices, mobile applications (apps) have emerged as integral components in the spectrum of hand rehabilitation tools, integrating various principles and mechanisms, aligning with the broader objectives of facilitating recovery and improving motor skills related to hand injuries, including Distal Radius Fracture (DRF).

Intelligent intervention apps were found most frequently, aiding in personalized exercise programs post-fracture healing. Angle measurement apps focused on monitoring wrist movement angles, while rehabilitation games aimed to engage patients in exercises through interactive gameplay.

The analysis highlighted that intelligent monitoring apps provided a more comprehensive approach, combining online consultation with offline care, enhancing doctor-patient communication, and offering remote services. However, most apps in the market lacked substantial evidence to support their efficacy and medical value [24].

VR-based interventions hold promise in improving certain aspects of hand rehabilitation for burn patients, particularly in reducing pain and enhancing emotional experiences, according to the systematic review and meta-analysis of 16 clinical trials, most of them being conducted in the United States and Egypt. The study revealed that while VR interventions positively impacted pain intensity and unpleasantness, reducing anxiety and enhancing fun experiences during rehabilitation, there were inconsistencies in improving hand grip/pinch strength and ROM gain across different trials. The variability in VR applications, ranging from immersive games to simple video-based interventions, might explain the diverse outcomes observed in hand rehabilitation. Nevertheless, it brought out the need for further research with larger sample sizes and standardized methodologies to understand the effectiveness better and optimize the use of this technology [25].

The findings underscore the transformative impact of technology on hand rehabilitation, emphasizing enhanced functionality, intuitive control, and improved quality of life for individuals with hand impairments. The studies highlighted the importance of robust control systems, immersive training, and the potential for VR to complement traditional rehabilitation methods. Additionally, the literature shed light on the need for more comprehensive, holistic approaches that address not only specific injuries but also broader aspects such as postural control, sensory perception, and patient-reported outcomes.

The findings align with existing literature on technological advancements in hand rehabilitation, showcasing the efficacy of novel interventions in improving functional outcomes. Similarities are evident in studies exploring myoelectric control systems, VR-based interventions, and advanced orthotic devices, highlighting their potential to enhance rehabilitation for various hand injuries [26,27].

Theoretical implications arise from the exploration of technologies such as teleceptive sensing, myoelectric control systems, and VR-based interventions. These technologies offer novel paradigms for understanding the neural mechanisms underlying hand function and rehabilitation. For instance, the integration of teleceptive sensing into wearable assistive robotics not only enhances the performance and functionality of these devices, but also provides insights into the interplay between environmental cues, sensorimotor integration, and motor learning. Similarly, myoelectric control systems and VR-based interventions offer unique opportunities to study neural plasticity, sensory-motor integration, and the mechanisms underlying motor learning and recovery.

Practically, the findings have significant implications for clinical practice, rehabilitation protocols, and patient outcomes. The emergence of advanced orthotic devices, multi-actuated prosthetic hands, and intelligent intervention apps signifies a paradigm shift towards more personalized, adaptive, and engaging rehabilitation strategies. These technologies not only improve functional outcomes but also promote active participation, motivation, and adherence to rehabilitation programs. Moreover, the integration of objective data collection mechanisms enables therapists to monitor patient progress objectively, adjust rehabilitation plans dynamically, and tailor interventions based on individual needs and preferences.

An overarching pattern across the reviewed literature is the significant potential of technology-driven interventions in revolutionizing hand rehabilitation. The studies collectively emphasize the importance of tailored, patient-centric approaches that integrate advanced technologies to address diverse hand injuries and impairments.

However, contradictions or differences arise in specific areas, such as the effectiveness of particular interventions in achieving long-term functional improvements [28]. While some studies showed immediate benefits and positive patient experiences, others underscored limitations or modest outcomes, indicating the need for further research.

Future research directions in hand rehabilitation technology encompass a wide range of areas, including but not limited to optimization of control strategies in the first place (further advancements in control strategies for prosthetic hands, orthotic devices, and wearable robotics are warranted. Future research may focus on refining pattern recognition algorithms, enhancing real-time feedback mechanisms, and integrating sensory feedback to improve the naturalness and efficiency of hand movements.

Secondly, personalized patient-centric approaches that take into account individual differences in anatomy, physiology, and pathology are essential for optimizing rehabilitation outcomes. Future research may explore machine learning algorithms and predictive modeling techniques to develop personalized rehabilitation protocols tailored to each patient's unique needs and preferences.

Moreover, there is a need for larger-scale longitudinal studies with standardized methodologies to evaluate the long-term effectiveness of technological interventions in hand rehabilitation. Future research may focus on identifying robust outcome measures that capture not only functional improvements but also patient-reported outcomes, quality of life, and societal participation.

Nevertheless, addressing issues of cost-effectiveness and accessibility is crucial for ensuring the widespread adoption of advanced hand rehabilitation technologies. Future research may explore innovative funding models, reimbursement strategies, and collaborative partnerships to make these technologies more affordable and accessible to all individuals in need. Furthermore, while technological innovations show promise in improving functionality and patient outcomes, there remains a need for more robust evidence, standardized methodologies, and larger-scale studies to solidify their effectiveness across different populations and injury types. The synthesis highlights the importance of continuous research and development in this field to optimize interventions and bridge existing gaps in hand rehabilitation technology.

5. Conclusions

The advancements in medical technology within the realm of hand rehabilitation showcased in the systematic review underscore a promising era marked by transformative innovations.

The review delves into technologies such as IMES (Implantable Myoelectric Sensor) technology, demonstrating its potential to revolutionize prosthetic control for those with limb loss. Through tiny implanted electrodes, IMES enables intuitive control, fostering enhanced functionality and providing a substantial degree of physiological hand function.

Similarly, studies examining advanced orthotic devices like the VacoHand Orthosis have shown significant advancements in stabilizing and aiding the healing process of specific bone fractures, showcasing the evolution in design and functionality for wrist immobilization and rehabilitation.

Furthermore, the emphasis on myoelectric control systems' robustness in individuals with limb amputations, as evidenced by studies employing a postural controller coupled with a multi-functional prosthetic hand, highlights the strides made in addressing clinical challenges and providing more natural control for daily tasks.

The integration of VR into rehabilitation emerges as a pivotal convergence point for advanced medical devices and therapeutic intervention. VR's potential to enhance specific movements, hand function, and work-related tasks signifies its role as a supplementary therapy in improving rehabilitation outcomes.

This review not only synthesizes findings from various studies, but it also underscores the benefits offered by advanced medical technical devices in hand rehabilitation, including enhanced customization for personalized rehabilitation programs, increased engagement through interactive and gamified approaches, and improved functional outcomes through targeted exercises, leading to enhanced hand strength, range of motion, and overall functionality.

Moreover, incorporating technology in rehabilitation facilitates objective data collection, offering therapists real-time feedback to monitor patient progress objectively. This ability to adjust rehabilitation plans according to quantifiable data ensures optimal results compared to traditional subjective assessment methods.

However, the review also acknowledges the need for further research to optimize the effectiveness of these technological applications in hand rehabilitation. Larger sample sizes, standardized methodologies, and deeper investigations into specific technological interventions are deemed essential to unlock their full potential in facilitating recovery and enhancing the lives of individuals undergoing hand rehabilitation.

In conclusion, this systematic review encapsulates the remarkable strides made in hand rehabilitation through technological advancements. These innovations pave the way for more inclusive, effective, and patient-centric functional rehabilitation strategies, offering hope and improved outcomes for individuals facing various hand-related challenges.

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