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Advancements in Active Dynamic Orthoses: A Comprehensive Review of Hand Muscle Rehabilitation Strategies

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ABSTRACT

In the field of rehabilitation, nuanced interventions are imperative due to the intricate anatomical complexity and versatile functionality of the human hand. From fractures and tendon injuries to neurological disorders and congenital anomalies, hand orthoses, both static and active, serve as crucial adjuncts to conventional therapeutic approaches. Active hand orthoses play a pivotal role in coordinating rehabilitation efforts, offering tailored support, dynamic control, and therapeutic facilitation. This review paper explored the scientific landscape surrounding active hand orthoses, consolidating evidence-based insights into their design, functionality, and clinical applications. The paper offered an in-depth examination of various studies, showcasing pioneering designs like hinged gloves, electro-hydraulic orthoses, and those integrating virtual reality exercises. The biomechanical principles underlying the effectiveness of active hand orthoses were emphasized, highlighting their role in optimizing outcomes across different rehabilitation scenarios. The review also covered advancements in electroencephalography (EEG)-controlled orthoses and myoelectric technology, illustrating the diverse applications for hand rehabilitation. By synthesizing current knowledge, this review established a foundation for further research and advancements in the ever-evolving field of active hand orthoses.

Keywords: Active hand orthoses, wearable assistive technology, hand dysfunction rehabilitation, biomechanical interventions

1 Introduction

In the realm of medical rehabilitation, the therapeutic exercise of fingers and wrists serves as a pivotal component in restoring optimal musculoskeletal function [1-2]. The rationale behind this lies in the principles of neuromuscular adaptation, tissue remodeling, and functional restoration [3-4]. An injury or pathology afflicting the fingers or wrists often results in a cascade of detrimental effects, such as muscle atrophy, joint stiffness, and diminished neuromuscular control. The targeted exercises aim to counteract these deleterious consequences through several mechanisms [5]. Firstly, the implementation of controlled, progressive resistance exercises facilitates the activation of motor units within the affected muscles. This

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engagement prompts an adaptive response, fostering muscle hypertrophy and preventing atrophy. Consequently, the restoration of muscle mass contributes to enhanced strength and endurance [6-7]. Moreover, therapeutic exercises are designed to address joint mobility and flexibility. Range of motion exercises mitigate the development of contractures and alleviate joint stiffness, thereby promoting the restoration of functional movement patterns. These interventions are especially crucial in scenarios involving immobilization or prolonged disuse, which can lead to joint restrictions [8-11]. From a neurological perspective, rehabilitation exercises play a pivotal role in neuromuscular re-education. They stimulate proprioceptors and enhance motor control, aiding in the refinement of coordinated movements. This neuroplasticity is instrumental in restoring precision and dexterity to the fingers and wrists [12-13]. Furthermore, therapeutic exercises contribute to the improvement of circulation, fostering an environment conducive to tissue healing. Increased blood flow facilitates the delivery of oxygen and nutrients while promoting the removal of metabolic byproducts, expediting the overall recovery process [14-15]. In essence, the multifaceted approach of therapeutic exercises addresses both muscular and joint components, leveraging physiological adaptations to attain functional restoration. This comprehensive strategy aligns with the overarching goal of promoting the rehabilitation and reinstatement of optimal musculoskeletal function in the context of finger and wrist pathology [16-19]. Active hand orthoses play a pivotal role in the realm of therapeutic and rehabilitation exercises, serving as integral components in the comprehensive management of hand-related pathologies [20]. These orthotic devices are designed with a nuanced understanding of musculoskeletal physiology, aiming to optimize functional outcomes through precise mechanical interventions [21-23]. One primary significance of active hand orthoses lies in their ability to provide targeted support and stabilization to the affected structures [24]. In instances of traumatic injuries, post-surgical interventions, or chronic degenerative conditions affecting the hand, these orthotic devices serve as external aids that strategically immobilize or facilitate controlled movement. This controlled support minimizes undue stress on injured tissues, thereby fostering an environment conducive to healing and preventing maladaptive responses such as contractures or joint stiffness [25-26]. Furthermore, active hand orthoses are instrumental in promoting neuromuscular re-education. Through their carefully engineered design, these devices engage specific muscle groups and encourage coordinated movements. This aspect is particularly pertinent in rehabilitation scenarios where motor control and proprioception may be compromised. The orthoses serve as facilitators in the process of re-establishing optimal neuromuscular pathways, contributing to enhanced functional recovery [27-28]. Moreover, these orthotic interventions are adaptable to a spectrum of therapeutic exercises. Their incorporation into rehabilitation protocols allows for a graduated and progressive approach to recovery. The adjustability of active hand orthoses enables healthcare professionals to tailor the intensity and range of motion of exercises, thereby addressing the evolving needs of the patient's rehabilitation journey [29]. In the context of deformities or contractures, active hand orthoses contribute to the prevention of further structural abnormalities. By providing a corrective influence on joint alignment and soft tissue balance, these devices mitigate the risk of progressive deformity, offering a proactive strategy to preserve or restore optimal hand function [30]. Consequently, active hand orthoses biomechanical precision, adaptability to therapeutic exercises, and role in neuromuscular re-education underscore their paramount importance in fostering optimal functional outcomes for individuals grappling with hand-related pathologies [31-32]. Thus, active hand orthoses have become a focal point for researchers, driving a surge in studies conducted in recent years.

This review paper played a critical role in consolidating past knowledge and advancements in the realm of active hand orthoses, offering a comprehensive overview of their clinical significance and therapeutic implications. By synthesizing existing literature, the paper aimed to elucidate the multifaceted importance of active hand orthoses in the context of therapeutic and rehabilitative interventions. It covered a spectrum of topics ranging from the biomechanical principles underlying these orthotic devices to their applications in diverse pathological conditions affecting the hand. Additionally, the review delineated their role in neuromuscular re-education, their adaptability to therapeutic exercises, and their potential in preventing and correcting deformities. By addressing these facets, this paper provided a valuable resource for engineers, researchers, and allied healthcare professionals, fostering a deeper understanding of the nuanced contributions of active hand orthoses to optimal patient outcomes.

The organization of the paper was presented as follows. In the open literature, studies that highlighted the different dynamic actuator-equipped configurations used in the structure for the exercise control of active hand orthoses were examined in Section 2. The investigation of active hand orthoses, controlled via electroencephalography (EEG) and electromyography (EMG) techniques, was covered in Sections 3 and 4. Finally, the concluding remarks were reviewed in Section 5.

2 Dynamic Actuator Controlled Active Hand Orthoses

Venturing into the realm of progressive rehabilitative technologies, this section delved into the intricate domain characterized by sophisticated mechanisms and responsive actuators. These elements converged to redefine the landscape of interventions, aiming to restore hand functionality in individuals grappling with neuromuscular impairments. The open literature contained an abundance of studies (see Figure 1). For example; Becchi et al. (2017) proposed a hinged glove design and orthosis with a DC motor for the transmission of movement for the rehabilitation of finger joints. In this study, it was emphasized that the plate made of thermoplastic material, despite being securely fastened to the hand, does not restrict the movements of the fingers and wrist [33]. Bos et al. (2018) proposed a novel electro-hydraulic hand orthosis for individuals with Duchenne muscular dystrophy. The orthosis was able to move the four-finger module with a linear actuator. Thanks to the orthosis hydraulic system components produced with polyamide (PA 2200) material, it demonstrated high durability against increased system pressures [34]. Ghassemi et al. (2018) integrated a linear servo motor into the X-Glove, which was presented for use in rehabilitation. The system had been integrated with virtual reality (VR)-based exercises. The observation was made that tactile feedback could assist in sensorimotor learning [35]. Kamper et al. (2019) proposed an orthotic glove model that incorporated a linear actuator, which strengthened the hand, regulated finger movement, and prevented excessive extension of finger joints. The device included an operating system to control finger flexion, sensor systems to detect tension, and control systems [36]. Gelanyi et al. (2019) designed an active orthotic device incorporating shape memory materials capable of replicating the movements of the wrist and fingers, thus facilitating the gripping and releasing functions of the hand. This device was specifically designed for individuals with partial or spastic paralysis of the hand. The device consisted of supporting elements that connected the moving components to each other. The moving components generated an activation signal and moved the supported fingers. In addition, the supporting elements provided reinforcement to the lower part of the arm and allowed free movement of the wrist joint [37].

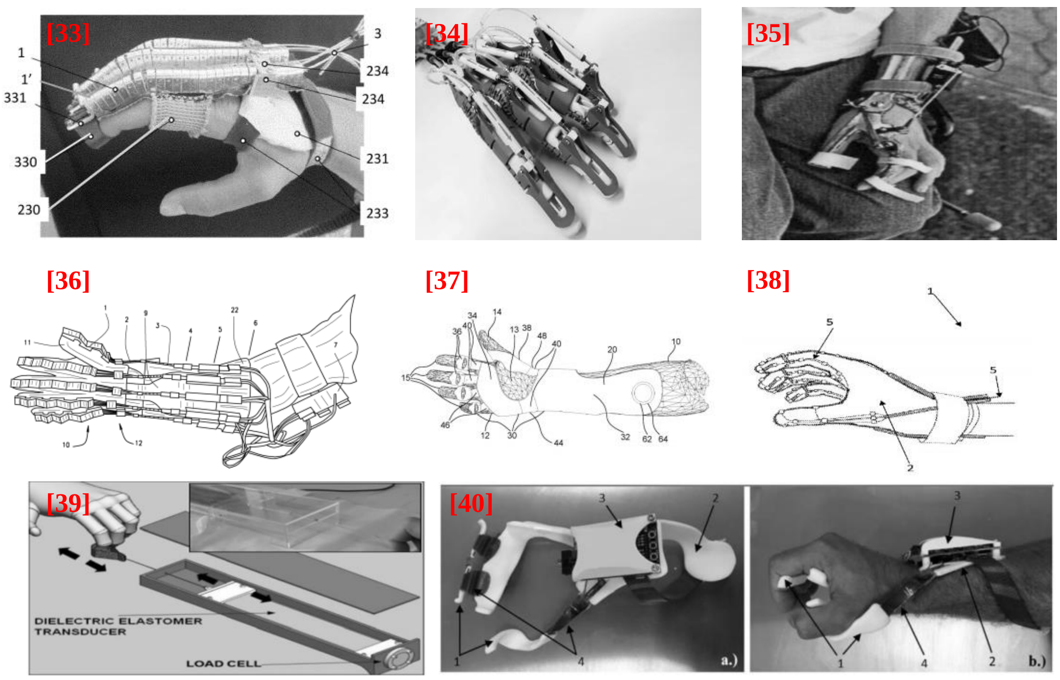

Figure 1: Diverse configurations of some active hand orthoses with dynamic actuators

Abdelhafiz et al. (2020) designed a soft hand orthosis incorporating an exo-tendon system aimed at mimicking the movement of the human hand. In this study, it was emphasized that flexion forces were distributed equally to the distal and proximal phalanges [38]. Toth et al. (2020) developed a cost-effective, personalized, and lightweight active orthosis targeting post-stroke spasticity. The orthosis underwent mechanical characterization using 3D printing and nitinol smart memory alloy. Functionality testing, Likert scale assessments, and movement analysis were conducted on six post-stroke patients, revealing significantly improved functionality and positive overall impressions. This smart and lightweight orthosis proved to be an effective solution for home-based rehabilitation in managing post-stroke spasticity [39]. Muehlbauer et al. (2021) developed a modular orthosis for paralyzed hands, aiming to support finger range of motion and force. Twisted string actuation (TSA) and an antagonistic drive unit were utilized, demonstrating quiet and lightweight force generation without additional gears. The orthotic structure, made of adaptable thermoplastic material, housed the TSA and motors, enabling flexion and extension of paralyzed fingers. The prototype, validated on spastically paralyzed fingers, utilized a constant speed mechanism controlled by user input and demonstrated promising functionality for future applications with paralyzed subjects [40].

3 EEG Controlled Active Hand Orthoses

In the rapidly evolving landscape of active hand orthoses, this section comprehensively examined the integration of EEG-based control paradigms, exploring the pivotal role of neural signals in shaping the next frontier of precision and adaptability in rehabilitative interventions for individuals with impaired hand function. Many scholarly inquiries populated the open literature (see Figure 2). Consider, for example; Pfurtscheller et al. (2000) developed an electrically powered hand orthosis to regain grasping movement of the hand. A Computer Control interface was designed with a 60-channel EEG system. It was emphasized that in the experiment conducted on a tetraplegic patient, the hand could be effectively opened and closed by straightening it [41]. Diab et al. (2016) developed an EEG-controlled brain-computer interface. In this study, an Artificial Neural Network model was utilized by incorporating a linear actuator into a commercial orthosis to classify the opening and closing movement. In conclusion, it was obtained that the developed system demonstrated good performance on real-time EEG data; however, it was emphasized that the achieved performance was lower than the expected performance [42]. Osayande et al. (2020) developed a hand orthosis using a Brain-Computer Interface to detect signals for finger movement in participants. A force sensor was added to the orthosis with the aim of enhancing hand muscle strength after paralysis. The robotic orthosis demonstrated a detection accuracy of 64.1% for unclenching and 62% for clenching activities, effectively actuating the orthosis digits in response [43]. Kina et al. (2021) investigated a brain-computer interface (BCI) system for hand rehabilitation. The system was comprised of an EEG amplifier, a desktop computer, and a hand orthosis. A healthy subject participated in the experiment, and during hand movement tasks, his EEG signals were recorded. A support-vector machine (SVM)-based classifier was trained using the processed data. Subsequently, the system, equipped with the learned SVM-classifier, was tested using test data.

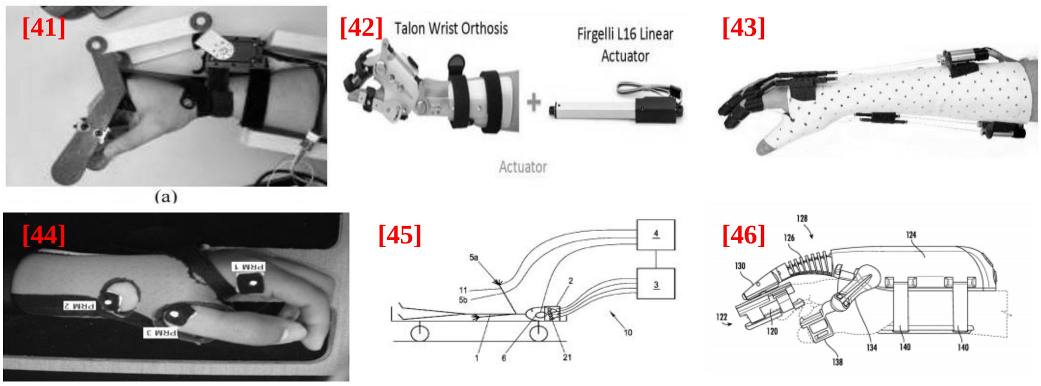

Figure 2: Diverse configurations of some EEG-controlled active hand orthoses

The results confirmed that the classifier had a test accuracy of 73.3%, and the finger movements (extension and flexion) of the experimental subject were executed by the hand orthosis, activated through the subject's intention [44]. Guger et al. (2021) developed a training and simulation system with mental assessment using EEG measurements. The focus of the study was on a mechanical orthosis dedicated to moving a specific body part, encompassing diverse mental activities to facilitate the test activation stimulus [45]. Bhugra et al. (2022) designed a wearable orthotic device incorporating sensors, imaging apparatus, and a computer system for patients with hemiplegic cerebral palsy. The device was used to process signals derived from patients' thoughts using built-in therapeutic equipment and subsequently to move the affected part of the body under the control of BCI [46].

4 EMG controlled active hand orthoses

In the realm of biomechanics-focused advancements within active hand orthoses, this section conducted a detailed exploration of EMG-controlled systems. It delved into the intricacies of EMG signals and their integration into orthotic design, navigating the biomechanical landscape to elucidate the profound impact of EMG-controlled active hand orthoses on enhancing both precision and functionality. This approach provided a nuanced perspective on the biomechanical considerations that shaped rehabilitative interventions for individuals with compromised hand function. The open literature was replete with a multitude of studies (see Figure 3). For example; Ochoa et al. (2011) examined an EMG-controlled orthosis for the purpose of hand rehabilitation. In this study, five subjects with significantly chronic hand disability due to stroke participated, and the initial results demonstrated improvement in performance. It had been determined that the full potential range of the EMG signal increased by an average of 177 mV during hand opening [47]. Loconsole et al. (2013) introduced a pioneering EMG-driven robotic hand exoskeleton designed for bilateral active training of grasp motion in stroke patients. The system enabled precise control of grasping force in the impaired hand, utilizing EMG readings from the unaffected arm to modulate the exoskeleton force. The study detailed the design, integration, and experimental evaluation, demonstrating successful optimal force tracking during the grasp of two cylindrical objects [48]. Bryant (2016) developed a hand orthosis that could assist patients in moving and controlling their fingers using EMG signals. The patent involved a microprocessor-controlled, shape-memory alloy wire designed to restore the functional use of the hand [49].

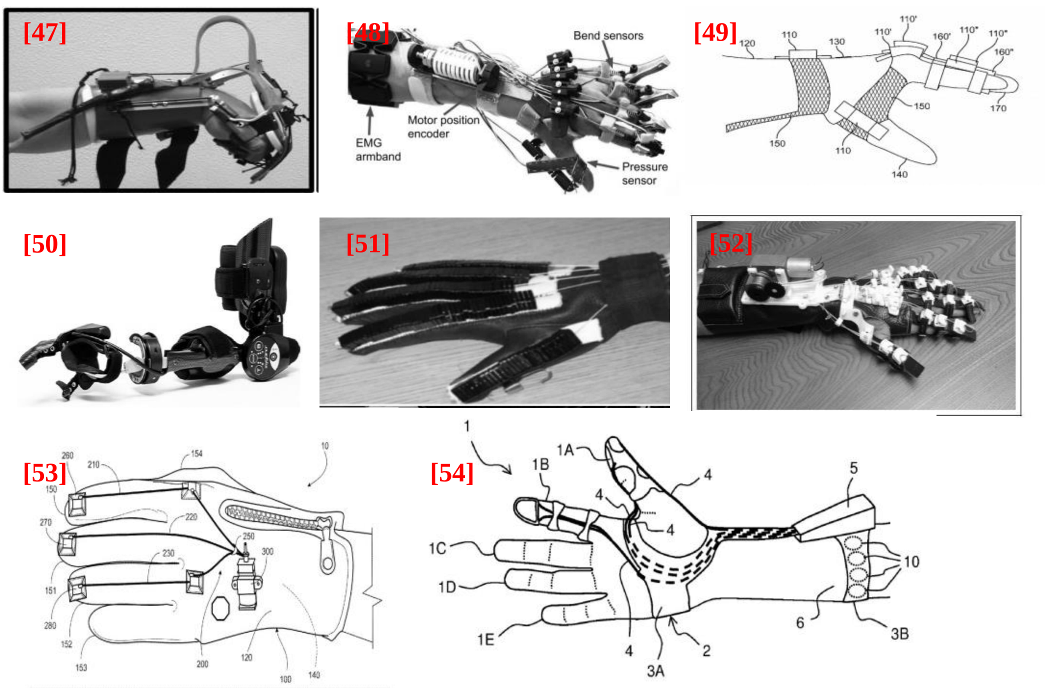

Figure 3: Diverse configurations of some EMG-controlled active hand orthoses

Dunaway et al. (2017) investigated the application of a myoelectric elbow–wrist–hand orthosis (MEWHO) in a chronic stroke survivor. The noninvasive orthosis, driven by EMG signals, provided powered assistance for elbow flexion/extension and grip. Over a series of outpatient sessions, the participant demonstrated increased range of motion, strength, and functional improvements, indicating the potential of custom myoelectric orthoses in neurological rehabilitation [50]. Fardipour et al. (2018) addressed the common post-stroke issue of finger extensor weakness, which was often overlooked in existing powered hand orthoses. They introduced a novel EMG-controlled glove-like orthosis aimed at actively restoring and training hand extension in stroke patients. Testing on two patients showed promising results, with significant improvements observed in functional tests after an 18-session training approach. The prototype demonstrated potential effectiveness in enhancing finger extension tasks and could have served as a valuable rehabilitation tool for individuals with paretic hands [51]. Park et al. (2018) proposed a multimodal sensing and interaction paradigm for an active hand orthosis. During the augmentation of a hand orthosis through multimodal sensing, the exo-tendonal system was augmented with an aluminum forearm splint, alongside the integration of 3D-printed fingertip components dedicated to cable routing. In the study conducted on four subjects, they found that the accuracy of two control methods with arm support was much closer [52]. Ciocarlic et al. (2019) designed a wearable hand orthosis for the purpose of providing support and assistance to individuals with hand impairment or injury. The device consisted of a fundamental component attached to the forearm and an exo-tendonal network attached to the hand. The exo-tendon had a longitudinally extending body that included a distal end and a proximal end. The hand component included support elements for fingers that could be adjusted according to the user's specific hand shape and size. In addition, the device also featured a control mechanism allowing the user to selectively activate or deactivate the finger support elements [53]. Woge et al. (2020) developed a hand orthosis that generates the necessary force for gripping objects. The orthosis had the capability to acquire EMG signals through a bioelectric sensor. Bioelectric sensors were used to estimate the applied force from force sensors [54].

5 Conclusions

In conclusion, that review provided a comprehensive overview of the recent advancements in active hand orthoses, focusing particularly on the utilization of dynamic actuators. The integration of EEG [55-56] and EMG [57-58] signals for the control of those dynamic actuators represented a paradigm shift in the field of biomechanics, offering innovative solutions for enhancing the functionality of active hand orthoses. The investigation of dynamic actuators showcased in that review underscored their pivotal role in enabling more natural and adaptive hand movements. Those actuators, characterized by their responsiveness to neural signals, contributed significantly to the development of sophisticated active hand orthoses capable of mirroring the intricate motions of the human hand. The amalgamation of cutting-edge technology and biomechanical principles paved the way for a new era in assistive devices, where users could experience a more intuitive and personalized interaction with their orthotic devices. Moreover, the incorporation of EEG and EMG signals for real-time control emerged as a transformative approach. By harnessing the power of neural signals, active hand orthoses became not only more responsive but also attuned to the user's intentions. This innovation held great promise for individuals with motor impairments, providing them with a means to regain dexterity and autonomy in their daily activities. As the realms of biomechanics and neuroengineering converged, the strides made in dynamic actuation and neural interfacing for active hand orthoses not only signified a transformative chapter but also illuminated the boundless possibilities awaiting the next wave of innovations in augmentative and rehabilitative technologies. Finally, researchers delving into active hand orthoses are advised to embrace interdisciplinary synergy, fostering innovative solutions through collaborative efforts and a steadfast commitment to user-centric design.

6 Declarations

6.1 Study Limitations

None.

6.2 Acknowledgements

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6.3 Funding Source

None.

6.4 Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.5 Authors' Contributions

Hamid ASADI DERESHGI provided supervision and guidance throughout the review process, ensuring the methodological rigor and integrity of the study. He participated in the conceptualization and design of the review, critically reviewed and revised the manuscript, and provided valuable intellectual contributions. He offered expertise in the field of active hand orthoses and contributed to the final approval of the manuscript.

Dilan DEMIR assisted in the conception and design of the review study, contributed to the selection and screening of relevant literature, and provided critical revisions to the manuscript for important intellectual content. She significantly contributed to synthesizing information from the reviewed papers, ensuring a cohesive narrative.

Sedanur YILMAZ contributed to the critical evaluation and synthesis of the reviewed literature, ensuring the accuracy and integrity of the information presented.

Aya ABDERRAHMANE contributed to the data collection process by identifying and retrieving relevant papers, and contributed to the development of figures included in the manuscript.

Belkis ABDERRAHMANE contributed to the data collection process by identifying and retrieving relevant papers, and contributed to the development of figures included in the manuscript.

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