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Review

A Review of Wrist Rehabilitation Robots and Highlights Needed for New Devices

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Abstract: Various conditions, including traffic accidents, sports injuries, and neurological disorders, can impair human wrist movements, underscoring the importance of effective rehabilitation methods. Robotic devices play a crucial role in this regard, particularly in wrist rehabilitation, given the complexity of the human wrist joint, which encompasses three degrees of freedom: flexion/extension, pronation/supination, and radial/ulnar deviation. This paper provides a comprehensive review of wrist rehabilitation devices, employing a methodological approach based on primary articles sourced from PubMed, ScienceDirect, Scopus, and IEEE, using the keywords "wrist rehabilitation robot" from 2007 onwards. The findings highlight a diverse array of wrist rehabilitation devices, systematically organized in a tabular format for enhanced comprehension. Serving as a valuable resource for researchers, this paper enables comparative analyses of robotic wrist rehabilitation devices across various attributes, offering insights into future advancements. Particularly noteworthy is the integration of serious games with simplified wrist rehabilitation devices, signaling a promising avenue for enhancing rehabilitation outcomes. These insights lay the groundwork for the development of new robotic wrist rehabilitation devices or to make improvements to existing prototypes incorporating a forward-looking approach to improve rehabilitation outcomes.

Keywords: wrist; rehabilitation; robotics; review; artificial intelligence

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1. Introduction

Numerous ailments, including physical traumas, strokes, neurological disorders, sports-related injuries, and traffic accidents, can result in impairments to the wrist [1]. In particular, stroke is the leading cause of disability among adults worldwide, causing a high number of individuals to have motor and cognitive deficits [2,3]. The main consequence of this brain injury is the loss or weakening of the movements of the human body, especially of the upper limbs [4]. Soon after the stroke, the brain goes through stages of recovery, where the central nervous system (CNS) can reorganize neural circuits through neuroplasticity [5].

Neuroplasticity is defined as the ability of the nervous system to restructure itself, forming new connections so that another part of the brain takes over the function of the injured part [6]. The basic condition for functional improvement after stroke is increased neuroplasticity [6]. Considering that neuroplasticity begins to develop immediately in the first months after stroke, the type and intensity of interventions in the acute period gain importance [6]. This restructuring of the nervous system, which is responsible for the learning and stimulation processes, occurs both spontaneously and with the aid of rehabilitation and non-invasive cerebral stimulation [7]. Thus, the use of robotic devices can assist in the rehabilitation process by providing improvements in motor and functional performance and permitting the quantitative evaluation of movements [8,9].

Medical rehabilitation serves as a comprehensive process that aims to maximize the physical, social, vocational, psychological, and educational capabilities of individuals facing significant disabilities. These impediments often hinder integration into the family and society, requiring a rehabilitation process to mitigate these negative effects [10]. The overall goal is to facilitate the individual's reintegration into society by addressing the physical and socio-psychological aspects of their challenges. Physical therapy and rehabilitation play a key role in restoring daily activities for individuals experiencing motor problems. The integration of robotic devices in rehabilitation processes has emerged as a promising path, offering improvements in motor and functional performance. These devices contribute to the rehabilitation process by providing quantitative movement assessments, increasing the accuracy and effectiveness of therapeutic interventions. Notably, research in post-stroke rehabilitation has explored the efficiency and benefits of employing robotic devices such as reported, for example, in [11,12].

The possibility of using robotic devices as an efficient means for providing therapy has been the subject of research involving post-stroke rehabilitation [11–13]. Rehabilitation devices for upper limbs have made great advances in recent years. However, further studies related to the subject are still needed, due to the complexity of human hand movements [14,15]. Compared to traditional care, robotic rehabilitation can be better performed at high intensity and frequency, being able to continuously monitor exercise performance so that the level of treatment is tailored to the patient's needs [16]. One of the applications of robotics in medicine is the development of devices to aid in the rehabilitation of the human wrist [1,3]. The human wrist is a joint having three degrees of freedom that connects the hand to the forearm, developing radial/ulnar deviation, flexion/extension, and pronation/supination movements [17].

This review article aims to report the main research on robotic devices to aid the wrist rehabilitation process. The existing devices are classified according to the number of degrees of freedom, wrist movements, type of actuator, control system, experimental evaluation, safety, and the presence of artificial intelligence (AI) in the implementation of serious games or virtual reality games. In addition, this work provides a careful discussion on the safety of the robotic devices since it is critical to ensure the highest safety standards for patients. This aspect is addressed by considering the IEC 80601-2-78:2020 standard [18] (The International Electrotechnical Commission) regarding medical electrical equipment. Another important aspect reported is the integration of serious games into the rehabilitation process. Serious games not only create a playful environment for the patient but also serve as a means of quantitatively measuring the patient's progress and the effectiveness of the rehabilitation device. This functional duality not only enriches the rehabilitation experience but also offers a more engaging and measurable approach to monitor patient development over time. Associated with serious games, AI is applied in order to adjust the level of difficulty of serious games exclusively for each patient, helping to increase engagement and motor improvement. Finally, this article condenses the main parameters necessary for the manufacture of new equipment for the rehabilitation of the human wrist.

It should be noted that the review articles found in the literature do not have the wrist as their main focus, covering other joints of the upper and lower limbs [3,4,19–22] or are not up-to-date [1]. The review articles [1,3,4,19–22] also do not clearly present how to conduct the mathematical modeling of the new device based on the characteristics of the human wrist as detailed in this paper.

This paper is organized as follows: Section 2 provides the proposed search method, followed by the human wrist description in Section 3. The classification of wrist rehabilitation devices and the selected devices described are presented in Section 4. A brief review of different strategies to control the rehabilitation of wrist robots and security is discussed in Section 5. Serious games with an AI focus in wrist rehabilitation are presented in Section 6, while Section 7 presents the discussion and future directions in the development of wrist rehabilitation devices. Finally, the conclusion is presented in Section 8.

2. Literature Review Search Method

This paper provides an overview of significant research on robotic devices to facilitate the wrist rehabilitation process. To find rehabilitation articles related to the human wrist using robots, four databases were searched: PubMed, ScienceDirect, Scopus, and IEEE. The keywords used in these databases were as follows: rehabilitation, robot, and wrist. The strategy used was the preferred reporting criteria for systematic review and meta-analysis guidelines (PRISMA) [23], as shown in the PRISMA diagram in Figure 1. In the research, in the four databases, it is common for an article to be cited two or more times on the used platforms. Thus, in order to remove the duplication of the citations of the articles, it is necessary to exclude repetitions. In addition, PRISMA is composed of inclusion and exclusion criteria. The inclusion criteria are articles involving human wrist rehabilitation robots, articles published in English, and articles with a publication period between January 2007 and February 2024. The publication period aims to identify the oldest to latest technologies to analyze trends and necessary improvements needed in the development of devices for human wrist rehabilitation. There are also exclusion criteria. Based on the research data, it is necessary to exclude articles involving systematic reviews, reviews and meta-analyses, books, book chapters, letters to the editor, conference abstracts, research protocols, or a protocol study [23]. Therefore, adopting the PRISMA methodology becomes crucial for conducting a literature review based on structured criteria. Moreover, it provides a chance to derive fresh insights into crafting a novel device with refined and effective attributes suited for wrist rehabilitation.

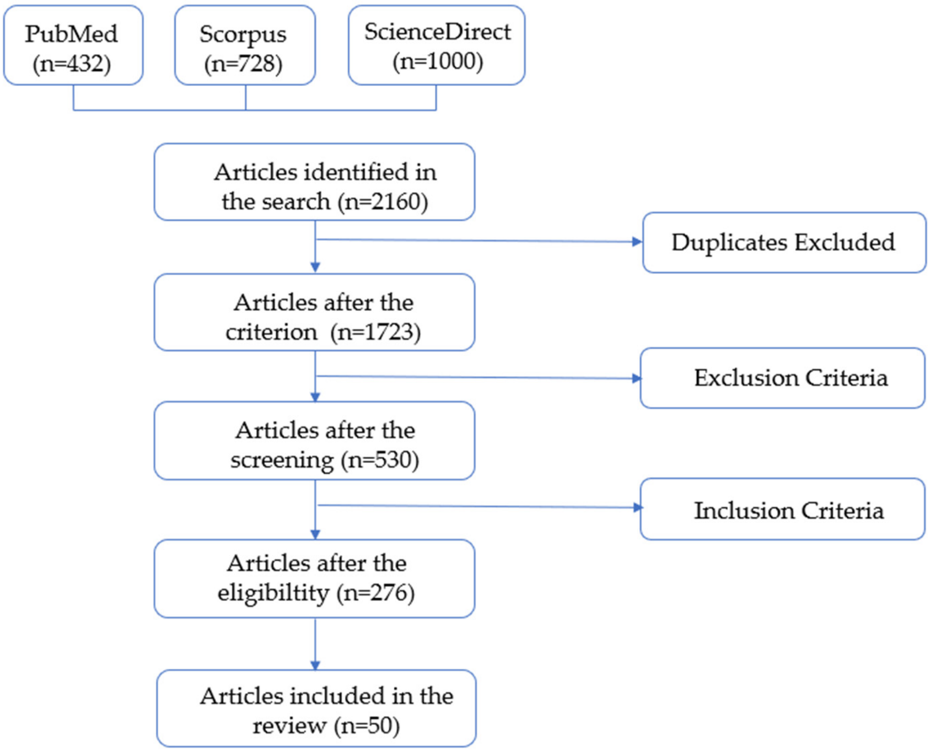


Figure 1. The implemented PRISMA diagram.

3. Wrist Description

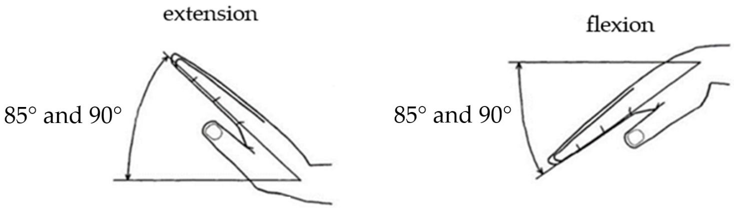
This section describes wrist kinesiology and the simplification of a model for the mathematical modeling of this joint.

The continuous advancement of technology has driven the growth of study methodologies in the field of robotic rehabilitation. This expansion has spurred new research and studies, particularly in areas such as wrist injuries. Wrist injuries, although complex and challenging to treat, have gained increasing attention in recent studies due to the critical role of the wrist in the human body [24].

Understanding the intricacies of wrist movements and the associated degrees of freedom is crucial for developing effective rehabilitation strategies, especially considering the dynamic and intricate nature of this joint. This knowledge forms a fundamental basis for the design and implementation of robotic devices tailored to address specific wrist challenges in the rehabilitation process. To design a safe and ergonomic device for people with wrist problems, the robot needs to be synthesized based on anthropometric and kinesiological data, in conjunction with human wrist kinematics and kinetics.

3.1. Wrist Kinematics

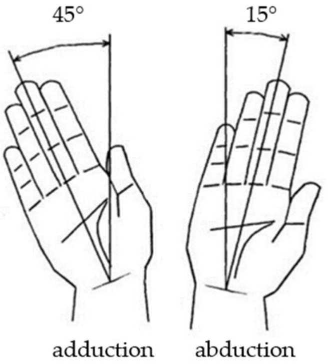
The wrist, in this context, can be compared to a spherical joint with mechanical constraints determined by its associated ranges of motion [17]. Wrist flexion/extension movements occur in the sagittal plane, where flexion brings the palm of the hand toward the anterior surface of the forearm, and extension moves the dorsal surface of the hand toward the posterior surface of the forearm [17]. The range of motion, measured from the reference position, is documented as between 85° and 90°, Figure 2 [17].



(**a**) (**b**)

Figure 2. Schemes of the wrist motion ranges: (**a**) wrist extension; (**b**) the flexion of the wrist.

The wrist abduction movement, known as radial deviation, and the adduction movement, known as ulnar deviation, occur in the frontal plane around the anteroposterior axis. Specifically, the radial deviation has a range of motion of 15° with respect to the reference position. On the other hand, ulnar deviation exhibits different amplitudes based on the adopted reference points. When considering the angle in the line connecting the center of the wrist with the distal portion of the third finger, the amplitude for ulnar deviation is 45°. If the reference is the axis of the hand, the amplitude becomes 30°. In relation to the axis of the middle finger, the ulnar deviation reaches an amplitude of 55° [17]. These specific amplitudes provide valuable information on the range of motion for radial and ulnar deviations, essential for designing targeted rehabilitation strategies and devices that align with natural wrist movement patterns in the frontal plane, Figure 3.



(**a**) (**b**)

Figure 3. (**a**) The adduction of the wrist (ulnar deviation); (**b**) the abduction of the wrist (radial deviation).

The pronation and supination movements involve the rotation of the radius around the ulna, facilitating the rotation of the forearm, and consequently the wrist, around its axis. In the supination position, the palm is facing up with the thumb pointed outwards, while in the prone position, the palm is facing down with the thumb pointed inwards. The range of motion for supination and pronation is 90°. Understanding these specific ranges of motion is crucial for the design of effective rehabilitation strategies and for the design of devices that accommodate the natural rotational dynamics of the forearm and wrist, Figure 4 [17].

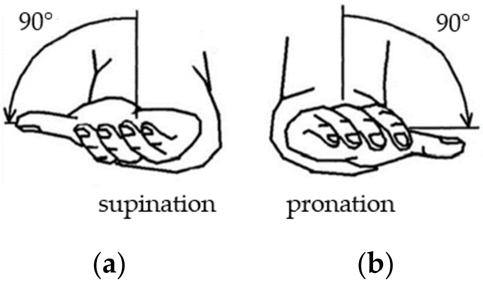


Figure 4. (**a**) Supination; (**b**) pronation movements of the human wrist.

3.2. Wrist Anthropometry and Mathematical Model

Anthropometry is a discipline that is dedicated to the measurement and analysis of the dimensions and proportions of the human body, including the evaluation of physical characteristics such as height, weight, and limb length [25]. Studies of this type assume a peculiar importance, considering the need to develop devices that adapt to the anatomy of hand/wrist users. In this context, the understanding of human anthropometry, as well as its application in the design of medical rehabilitation devices for the wrist, contributes to improving the well-being, health, comfort, and safety of patients who make use of these devices in their rehabilitation processes [25].

Figure 5 gives the main dimensions of the hand necessary to design the wrist device obtained from [26].

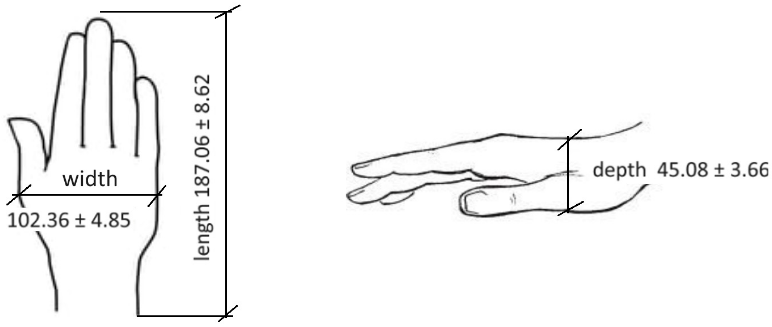


Figure 5. Hand dimensions (mean ± std [mm]) [26].

Figure 6 shows that human wrist movement includes flexion/extension (FE), radial/ulnar deviation (RU), and pronation/supination (PS). According to [26], the rotation ranges and torques required for daily activities range from 70° to 150° and 0.06 Nm to 0.35 Nm, respectively. In the FE and RU movements, the carpus rotates around the radius, while in the PS movement, the carpus, together with the distal end of the radius, performs a rotation around the ulna [27].

According to [28], the parameters of the dynamic models of the human wrist are obtained from an anthropometric and kinetic analysis, shown in Figure 7. The Lagrangian L is expressed as the difference between the kinetic energy T of the system and its potential energy V, in Equation (1). In Figure 7, we are considering the movements FE and RU as those of a rigid body in a plane motion of non-barycentric rotation [29].

$$L = T - V \tag{1}$$

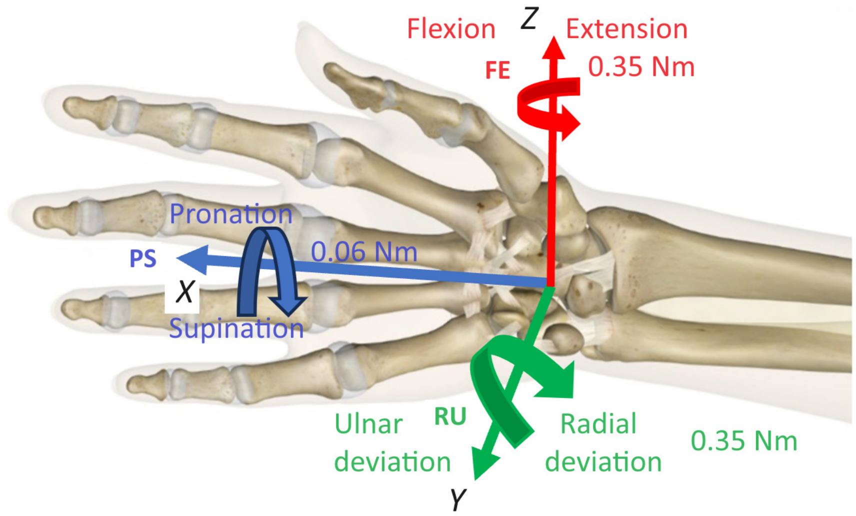


Figure 6. Human wrist movements in the X, Y, and Z directions.

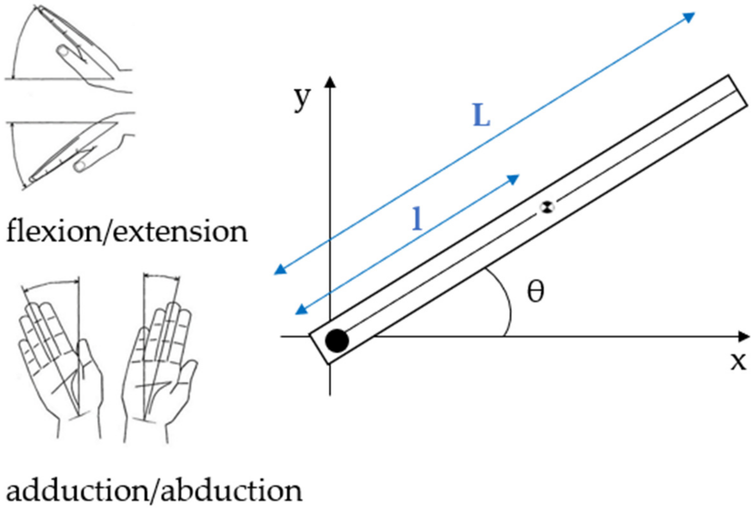


Figure 7. A representation of the simplified dynamic model of the hand (flexion/extension and abduction/adduction).

The kinetic energy of the system in question is defined in Equation (2), where m is the mass of the hand, l is the distance from the wrist to the center of the mass of the hand, J represents the moment of inertia, and $\dot{\theta}$ denotes the angular velocity of the hand. The potential energy is determined by Equation (3), where θ is the angle of hand movement, and g is the acceleration of gravity.

$$T = \frac{1}{2}\, m\, l^2\, \dot{\theta}^2 + \frac{1}{2}\, J\, \dot{\theta}^2 \tag{2}$$

$$V = -m\, g\, l\, sin\, \theta \tag{3}$$

Substituting Equations (2) and (3) in Equation (1), we obtain the expression denoted in Equation (4).

$$L = \frac{1}{2}\, m\, l^2\, \dot{\theta}^2 + \frac{1}{2}\, J\, \dot{\theta}^2 + m\, g\, l\, sin\, \theta \tag{4}$$

The Euler–Lagrange formulation is specified in Equation (5), where θ represents the generalized coordinate corresponding to the active degree of freedom (angular joint), and Q denotes the set of external (non-conservative) forces.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = Q \tag{5}$$

Wrist flexion/extension and abduction/adduction movements are addressed independently in rehabilitation therapies [28]. Consequently, the Euler–Lagrange equation is applied to a single degree of freedom (DOF) associated with rotation around a specific axis. External forces include torque T and viscous damping at the joint, characterized by a damping coefficient b [27], and with these considerations, the Euler–Lagrange formulation becomes the following:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = T - b\,\dot{\theta} \tag{6}$$

The Lagrangian derivatives of Equation (6) are solved, leading to the solution of a nonlinear second-order differential dynamical Equation (7). This equation encompasses the dynamics of the flexion/extension and abduction/adduction of the wrist.

$$m\,l^2\,\ddot{\theta} + J\,\ddot{\theta} - m\,g\,l\,cos\theta = T - b\,\dot{\theta} \tag{7}$$

Equation (7) is solved to obtain the angular acceleration $\ddot{\theta}$ required for the construction of the dynamical models, which are expressed in Equation (8).

$$\ddot{\theta} = \frac{1}{m\,l^2 + J}\left[T - b\,\dot{\theta} + m\,g\,l\,cos\theta\right] \tag{8}$$

Figure 8 shows the simplified dynamic model of pronation and supination movements considered to be those of a rigid body in a plane motion of barycentric rotation [29]. The kinetic energy of the movement is defined in Equation (9), where J_{PS} represents the moment of inertia, and $\dot{\theta}_{PS}$ denotes the angular velocity of the pronation/supination hand movement. The potential energy in this case is given by Equation (10), where W is the hand width, and θ_{PS} is the angle of hand movement.

$$T_{PS} = \frac{1}{2}\,J_{PS}\,\dot{\theta}_{PS}^{2} \tag{9}$$

$$V_{PS} = -m\,g\,\frac{W}{2}\,sin\theta_{PS} \tag{10}$$

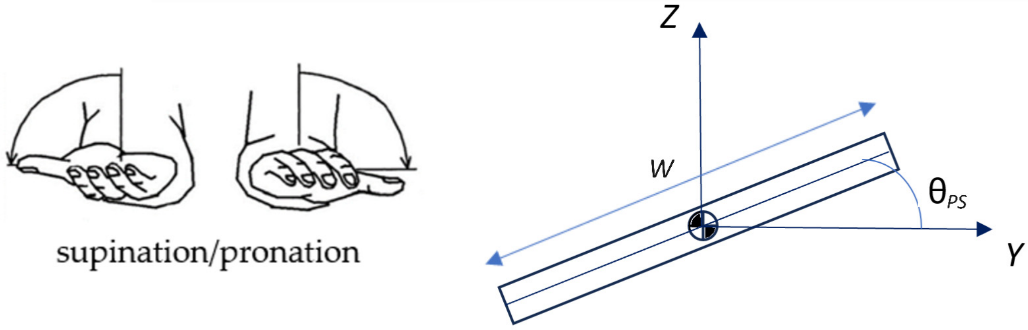


Figure 8. A representation of the simplified dynamic model of the hand to pronation/supination.

Replacing Equations (9) and (10) in Equation (1), we obtain Equation (11).

$$L = \frac{1}{2}\,J_{PS}\,\dot{\theta}_{PS}^{2} + m\,g\,\frac{W}{2}\,sin\theta_{PS} \tag{11}$$

Using Equation (6), it is possible to obtain the following:

$$J_{PS}\,\ddot{\theta}_{PS} - m\,g\,\frac{W}{2}\,cos\,\theta_{PS} = T - b\,\dot{\theta}_{PS} \tag{12}$$

Equation (12) is solved to obtain the angular acceleration $\ddot{\theta}_{PS}$ necessary for the construction of the dynamic wrist pronation/supination models, which are expressed in Equation (13).

$$\ddot{\theta}_{PS} = \frac{1}{J_{PS}}\left[T - \;b\,\dot{\theta}_{PS} + m\,g\,\frac{W}{2}\,cos\,\theta_{PS}\right] \tag{13}$$

Based on anthropometric analysis [28], the parameters for the dynamic model are presented in Table 1. In this table, the mass of the hand is a function of the patient's body mass M, the length of the hand is a function of the patient's height H, and the center of gravity and radius of rotation are functions of the length of the hand, Table 1.

Table 1. Parameters of kinematic hand model [28].

Parameter	Value	Unites
Hand mass [m]	0.006·M	[kg]
Hand length [L]	0.108·H	[m]
Proximal center of gravity [I]	0.506·L	[m]
Radius of gyration of hand [k]	0.297·L	[m]
Gravity [g]	9.81	[m/s^2]
Moment of inertia of hand [J]	m·k^2	[kg·m^2]
Damping coefficient [b]	0.1	[N·m·s]

4. Wrist Rehabilitation Classification

Rehabilitation wrist robots can be classified into two branches [4], that is, according to their structure and according to the type of therapy performed, as shown in Figure 9.

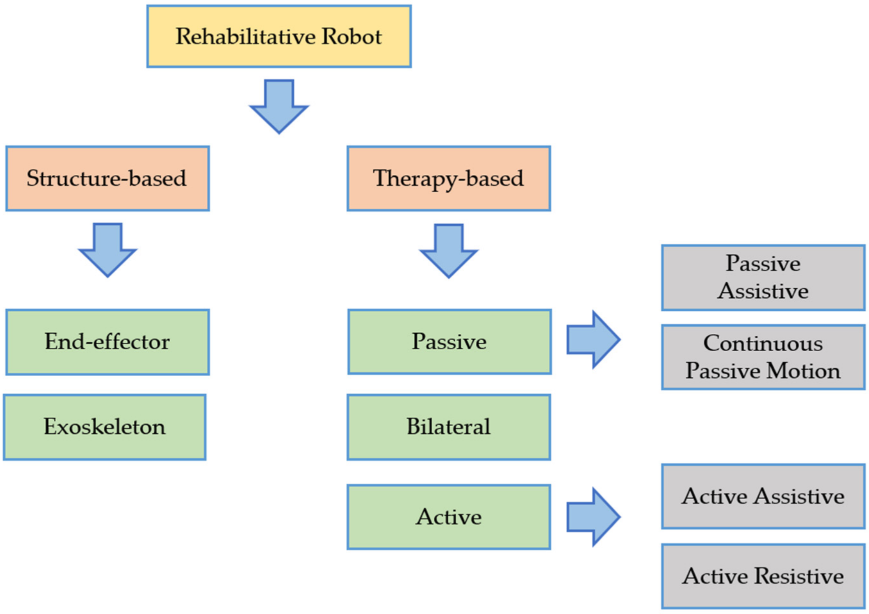


Figure 9. Rehabilitation wrist robots' classification diagram.

Structure-based robotic wrist rehabilitation can be implemented as an exoskeleton or end-effector. Robotic exoskeletons share similarities with human limbs, and they are attached to patients at various points, with their joints coinciding with the natural joints of the human body, as an example, in Figure 10 [30], while the end-effector has only one interface: the patient's hand/forearm.

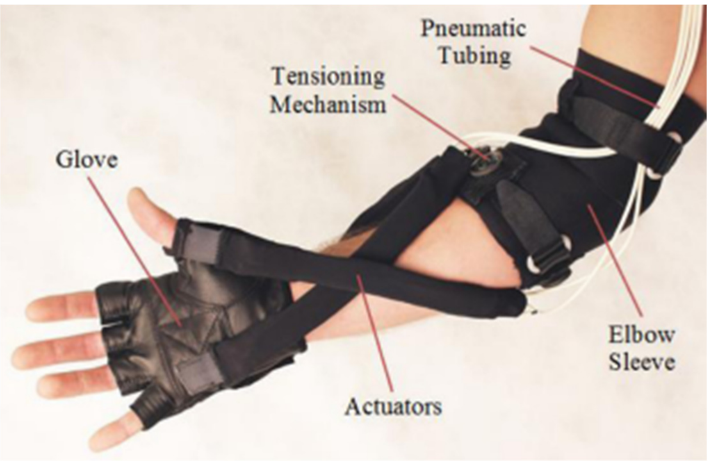


Figure 10. A portable exoskeleton device, soft and lightweight, making it more suitable for out-of-clinic use [30]. Copyright © 2018 Bartlett et al.

The end-effector robots permit an easily attached hand in the device, making the mechanical structure and control system simpler. These devices can avoid abnormal movements because they do not restrain the anatomical joints. However, it is not possible to directly estimate the kinematic configuration of the upper limb, and making isolated movements of a single joint is more difficult. In contrast, exoskeletons can provide movements for a specific joint. Two examples of end-effector devices are shown in Figures 11 and 12. Figure 12 shows a representation of a device created by the Federal University of Uberlandia (UFU wrist robot) [24]. This system stands out for its simplicity and ease of manufacture. In addition, its adaptability is remarkable, and it can be adjusted more flexibly to suit different hand/arm lengths.

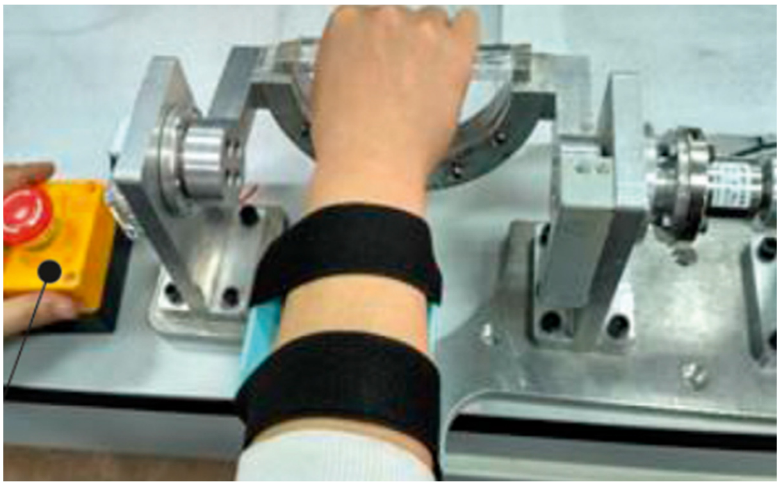


Figure 11. The use of the WReD system in a healthy subject [31]. Copyright © 2019 Dong Xu et al.

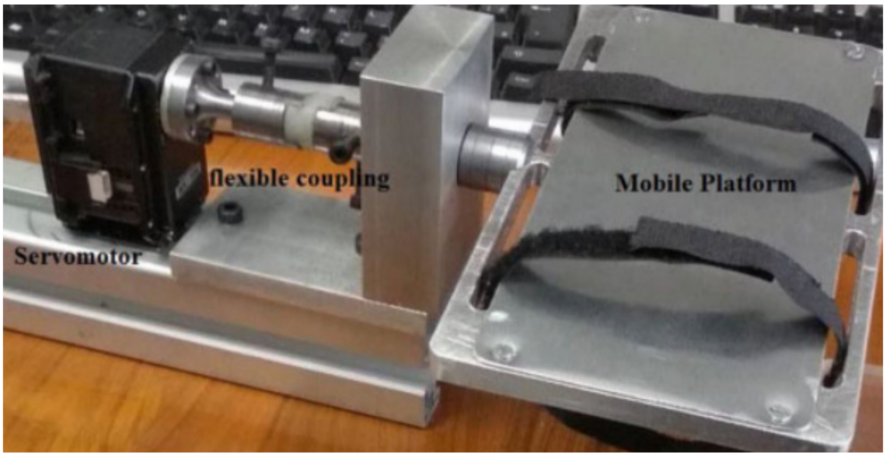


Figure 12. A proposed end-effector prototype for the wrist [24]. Copyright © 2020 Gonçalves et al.

Often, exoskeletons adopt a wearable configuration, as shown in Figure 10. Wearable exoskeletons are electromechanical devices designed to assist, augment, or enhance motion and mobility in the wrist [19]. Occasionally, wearable exoskeletons can use pneumatic elements like pneumatic muscles, which have the potential to create a more compliant interaction with the patient. The compliance of this kind of device can help reduce the joint alignment issues of traditional exoskeleton robots for wrist rehabilitation.

The wrist robots are further classified based on their types of motion assistance: active, passive, and bilateral, as shown in Figure 9. Active devices, equipped with at least one actuator, assist in the production of movement in the wrist and are typically used by patients with limited mobility, as shown in Figure 13. Passive devices, such as actuators that provide resistive force, are used in the rehabilitation of individuals capable of moving their wrists, and bilateral devices are conducted by mirroring the patient's arm movements [12].

Figure 13. Free University Berlin active computer-aided robot [12]. Copyright 2003 American Congress of Rehabilitative Medicine and American Academy of Physical Medicine © and Rehabilitation. Published by Elsevier Inc. All rights reserved.

In passive therapy, the patient does not actively participate in the movement [12]. Passive robots are categorized into continuous passive motion and passive assistive robots. In continuous passive motion (CPM), a machine is used to move the joint without requiring effort from the patient. Unlike CPM robots, passive assistive devices do not follow a pre-programmed schedule; however, their movement does not require control input [32]. The active devices respond to the patient's input to determine their movement, either by providing assistance or resistance. Active assistive devices share similarities with their passive counterparts in that they both assist the user in performing movements. However, active robots incorporate sensors to capture the patient's motor activity. Active resistive devices, on the other hand, are controlled by some input from the user, promoting motor adaptation [12]. There is also bilateral therapy that is conducted by mirroring the movements of the patient's hand. In this case, the reflected hand/arm is used to complement the exercise, and the patient does not actively participate in the movement. Bilateral therapy had its origins with the development of the Mirror-Image Motion Enabler (MIME) [12].

Notable robotic devices for wrist rehabilitation have been developed, contributing to the evolution of robotic rehabilitation, as described in Section Wrist Rehabilitation Devices.

Wrist Rehabilitation Devices

This review article aims to present the main investigations related to robotic devices intended to assist the wrist rehabilitation process, categorized based on the number of degrees of freedom, the movements associated with the wrist, the type of actuator, the control method, the feedback signal, the experimental evaluation, the safety, and the presence or absence of serious games/AI. It can be seen that there are distinct types of devices with multiple characteristics and architectures, which are categorized in Tables 2 and 3.

In [33,34], a wrist robot developed at the Massachusetts Institute of Technology (MIT) with three degrees of freedom was presented, incorporating a load cell and a direct force control scheme to minimize interaction forces. This device, presented in 2007, was one of the pioneers in the rehabilitation of the human wrist, had a commercial version, and was validated with patients showing improvements in the wrist functions.

In [32,35], a Haptic Knob was developed at the National University of Singapore, designed for hand opening/closing and forearm pronation/supination with two degrees of freedom. This robot has a simple mechanical structure, and based on the clinical tests conducted, the hypothesis was raised that distal training in a functional way could benefit the whole arm.

An electrically driven forearm/wrist haptic exoskeleton with an impedance-based position and force controller named RiceWrist was presented in [36]. Subsequently, the RiceWrist-S, a serial robot mechanism, was developed in [37]. RiceWrist-S [37] made improvements to provide high torque output, covering the entire working space of the human wrist. The OpenWrist presented in [38] was an evolution of the RiceWrist-S, featuring a fourth degree of passive linear freedom to accommodate misalignments.

In [39], a UHD (Universal Haptic Unit) was developed for wrist rehabilitation, providing actuation for three degrees of freedom with flexion/extension, pronation/supination, and abduction/adduction movements. The mechanical design is based on a sequence of joints that can be locked or unlocked to allow for individual wrist movements.

In [40], a robotic exoskeleton was presented with one degree of freedom for flexion/extension movements in the wrist joints of patients associated with other movements of the shoulder and elbow. The integration between the shoulder, elbow, and wrist aims to support clinicians with a quantitative neuromechanical outcome evaluation at the level of individual joints, multiple joints, or considering the whole arm.

In [41], the wrist rehabilitation IIT Genova Robotic System with three degrees of freedom for abduction/adduction, flexion/extension, and pronation/supination movements was presented. The use of the proposed device permitted improvements in the wrist's active range of motion.

In [42], a SCRIPT 1 prototype was developed at the University of Sheffield, providing physiotherapy to stroke survivors with passive flexion/extension movements. The patients need to have neurological/motor control to use the device.

In [30], a robotic device was developed at Harvard University and assessed with a healthy participant, with a focus on the range of motion and torque. The device permits the flexion/extension and pronation/supination movements using pneumatic actuators.

The robot known as WRES was developed in [43]. This wrist robotic exoskeleton has three degrees of freedom, providing abduction/adduction, flexion/extension, and pronation/supination movements.

It should be noted that the structures that present three degrees of freedom, Table 2, are based on that presented in [33].

In [31], a wrist robotic exoskeleton developed at Kyushu University named WReD with a single degree of freedom was developed, providing flexion/extension movement. In [44,45], a portable and reconfigurable wrist robot was presented, named CR2-Haptic, with one DOF; with changing the robot orientation, it is possible to train the three wrist movements: abduction/adduction, flexion/extension, and pronation/supination.

In [46], a wrist exoskeleton was developed using two linear actuators connected to two elastic elements, permitting flexion/extension and adduction/abduction movements. Although elastic elements allow for compliance for the mechanisms, their use can reduce the precision and repeatability of the necessary wrist movements and require more complex control techniques.

In [10], a wrist robot with one degree of freedom was presented to make the wrist flexion/extension. The device combines a three DOF force sensor to enable better human–robot interaction in wrist rehabilitation. An evolution of this device was presented in [47] that added more DOFs to realize all the individual wrist movements.

In [12], a robot developed at Free University Berlin that permits the flexion/extension of the wrist with bilateral movements is presented.

In [24], a robotic rehabilitation prototype focusing on wrist rehabilitation movements was evaluated with healthy volunteers and stroke survivors in a case study. The device uses a palm rest base, coupled to a servo motor, and employs impedance control, allowing the patient to resist or assist the movements. The structures with one degree of freedom presented in Table 2 have a simpler mechanical design than those with three degrees of freedom and can be interesting alternatives aimed at reducing the development cost of this equipment.

It is noteworthy that the cost of equipment is rarely quantified or discussed in the papers reviewed. The only commercial option analyzed in this paper was the MIT wrist robot, which has been discontinued. In [24], the cost of developing the UFU wrist robot equipment is around USD 1000. In [45], it was discussed that the necessity of wrist rehabilitation robots should be cost-effective to be able to apply in rehabilitation procedures, and the higher complexity of the design leads to a higher cost and more supervision needed. In [39], it was discussed that the cost of robotic devices for wrist rehabilitation could be reduced by using standard mechanical and control components. End-effector devices usually have a lower cost than exoskeletons because they require a less complicated setup to place the patient in therapy.

Table 3 presents the outcomes of the use of wrist rehabilitation devices in patients.

Table 2. Features of wrist rehabilitation devices selected.

Device Name	DOF	Structure-Based	Joint	Type of Operation	Control Method	Feedback Signal	Safety	Serious Games and/or AI
MIT wrist robot [33,34]	3	Exoskeleton	Wrist—FE, RU, PS	DC Motors	Impedance Control (AAN)	Load cell, encoders	Not Cited	Serious games No AI
Haptic Knob [32,35]	2	End-effector (parallelogram mechanism)	Forearm—PS Wrist—FE	DC Motors	Impedance Control	Load cell, encoders	Not Cited	Serious games No AI
Open Wrist [36–38]	3	Exoskeleton (3-RPS (revolute–prismatic–spherical) parallel mechanism)	Wrist—FE, RU, PS	DC Motors	PD Trajectory Tracking	Joint Angles (encoders) and Forces	mechanical stops	No Serious games No AI
UHD [39]	3	End-effector	Wrist—FE, RU, PS	DC Motors	Impedance Control	Linear Potentiometer	Not Cited	No Serious games No AI
IIT Genova Robot [41]	3	Exoskeleton	Wrist—FE, RU, PS	DC Motors	Impedance Control	Load cell, encoders	Not Cited	Serious games No AI
SCRIPT Prototype 1 [42]	1	Exoskeleton	Wrist—FE	Springs	Not provided	Rotary potentiometer	Not Cited	Serious games No AI
Harvard University Robot [30]	2	Exoskeleton (wearable soft robot)	Wrist—FE, PS	Pneumatic actuator	Not provided	Not provided	Not Cited	No Serious games No AI
WRES [43]	3	Exoskeleton	Wrist—FE, RU, PS	DC Motors	Not provided	Load cell, encoders	Not Cited	No Serious games No AI
Kocaeli University [10]	1	Exoskeleton	Wrist—FE	DC Motor	Impedance Control	Load cell, encoder	emergency stop	No Serious games No AI
CR2-Haptic [44,45]	1	End-effector	Wrist—FE, RU, PS	DC Motor	Impedance Control	Current sensor Pulse oximeter Encoder	mechanical stops emergency stop	Serious games No AI
Kyushu Robot University [46]	2	Exoskeleton	Wrist—FE, RU	Linear Motors	Not provided	Load cell, camera	Not Cited	No Serious games No AI
WReD [31]	1	End-effector	Wrist—FE	DC Motor	Impedance Control	Torque sensor, encoder	mechanical stops emergency stop	No Serious games No AI
Free University Berlin Robot [12]	1	End-effector	Wrist—FE	DC Motors	Impedance Control	encoder	Cited	No Serious games No AI
UFU wrist robot [24]	1	End-effector	Wrist—FE, RU, PS	Servomotor	Impedance Control (AAN)	Torque Sensor	Cited	Serious games No AI

RU—radial/ulnar deviation; FE—flexion/extension; PS—pronation/supination. Assist-As-Needed (AAN).

Table 3. Outcomes of wrist rehabilitation devices selected and used with patients.

Device Name	Experimental Evaluation	Outcomes
MIT wrist robot [33,34]	36 stroke participants	Improvements in motor impairment scales
Haptic Knob [32,35]	15 stroke participants	Significantly improved hand and arm functions
Open Wrist [36–38]	spinal cord C3-5 level	Improvements in hand function test
UHD [39]	1 stroke participant	Reliable and repeatable performance was achieved
IIT Genova Robot [41]	9 stroke participants	Improvements in motor function and range of motion
SCRIPT Prototype 1 [42]	23 stroke participants	Possibility of using device in home care
CR2-Haptic [44,45]	7 stroke participants	Improvements in motor function and range of motion
Free University Berlin Robot [12]	12 stroke participants	Reduction in spasticity and pain relief
UFU wrist robot [24]	3 stroke and 14 healthy participants	Significant gains in motion amplitudes

5. Wrist Robot Device Control System

The MIT wrist robot [33,34], Haptic Knob [32,35], UHD [39], IIT Genova Robot [41], WReD [31], and the UFU wrist robot [24] are robots based on the impedance controller that modulates how the robot reacts to the mechanical disturbance of a patient or doctor, ensuring smooth and compliant behavior. Impedance control refers to the use of a control system (actuators, sensors, controllers, and computers) capable of imposing a desired behavior on the attachment of the robot to the patient's hand [24,48]. This control system has been successfully applied in multiple robotic applications involving human–motor interaction. For robots that interact with humans, the most important feature of the controller is stability. The stability of most robot controllers is vulnerable when coming into contact with objects with unknown dynamics. However, dynamic interactions with highly variable and poorly characterized objects (i.e., patients with neurological impairments) do not destabilize the impedance controller. This is essential for safe operation in a clinical setting [22].

In the OpenWrist [35,36], passive and active assist modes are implemented using PD control, while the restricted mode is implemented via an impedance controller. In the case of restricted mode, the patient moves the arm against the viscous field to a desired position, and a movable virtual wall prevents the patient from retracting the arm. Proportional-Derivative (PD) Control was used as a controller, using position and force as input parameters. In the version of RiceWrist-S Robot [37], an Assist-As-Needed (AAN) controller was developed. This control system estimates the lowest sensor strength based on a model to determine the patient's capability.

SCRIPT Prototype 1 (SP1) [42] is a wrist, hand, and finger orthosis that assists post-stroke individuals suffering from disabilities caused by spasticity and abnormal synergies. SP1 can compensate for these unwanted effects of torques, but it cannot actively generate or control motion. It refers to a passive mechanism of action.

The basis of a variety of robot-assisted rehabilitation devices is trajectory tracking control [43]. This method can be applied directly to passive training for patients with impaired active motor skills. The accurate tracking of desired trajectories is not only simple but also an effective approach for rehabilitation applications. Incorporating adherence into trajectory tracking control can result in greater comfort and safety during training, as well as allowing for active engagement for more effective rehabilitation [31].

The objective of this review article is not to delve into the details of the control of structures that are already detailed in the literature, as in [1,4,48].

Safety

One of the main requirements for a rehabilitation robot is safety. For this, there is the IEC 80601-2-78:2020 standard (The International Electrotechnical Commission (IEC) [18] is the main global organization that prepares and publishes International Standards for all electrical, electronic, and related technologies) regarding medical electrical equipment. For a wrist rehabilitation device, three aspects significantly affect safety, such as operating ranges, operating modes, and operating forces/torques [24]. Data on desired operating modes, speed, acceleration, and trajectories should be pre-defined by the physiotherapist based on the patient's needs and limited by software or a physical device to avoid unwanted damage to the already affected wrist.

The [18] is detailed about the necessary requirements for medical devices that apply to wrist devices, like protection against electrical hazards, protection against mechanical hazards, protection against unwanted and excessive radiation, and protection against excessive temperatures. The [18] also presents good practices for the construction of the device, considering the hazardous situations and fault conditions of programmable electrical devices, electromagnetic compatibility and electromagnetic disturbances of the device, usability, and the requirements for medical electrical equipment used in the home healthcare environment. Devices for wrist rehabilitation need to predict emergency stopping mechanisms.

It is noted that most of the devices listed in Table 2 do not reference the IEC 80601-2-78:2020 standard [18] because they were developed before 2020 or did not take security requirements into account. According to this standard, specific basic and essential safety requirements are established, as well as performance requirements for medical robots that physically interact with patients with a disability, for the purpose of supporting or performing rehabilitation, assessment, compensation, or relief related to the patient's movement functions. Thus, it is believed that safety in a robotic device is indispensable for patient safety and to attest to the quality of the device. Figure 14 shows a drawing of the wrist robot device's interaction with a patient. The patient's neurological/musculoskeletal systems and the controller of the wrist device interact with each other through the measurement of the interaction force in the actuated wrist. This force directly influences the movement of the patient's wrist and the physical structure of the device, together with a feedback signal to the wrist device.

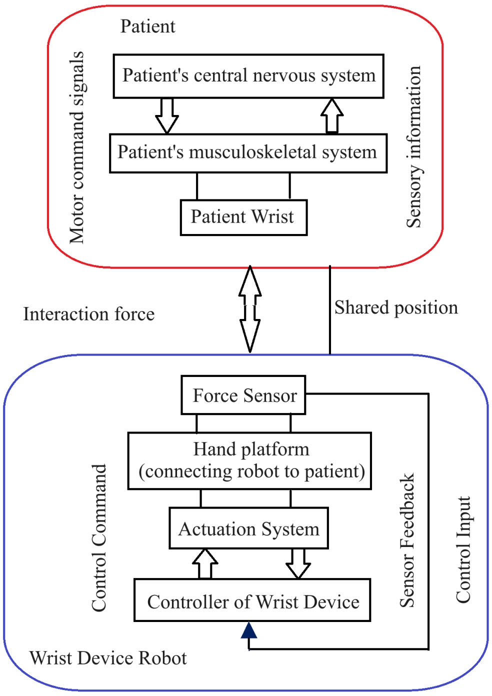


Figure 14. Safety drawing for wrist rehabilitation devices (adapted from standard [18]).

In addition to safety, another key aspect is the use of serious games/virtual reality games. These games can make physiotherapy less boring and are a fundamental instrument for the quantification of the patient's evolution and the efficiency of the device.

6. Serious Games and AI in Wrist Rehabilitation Devices

The use of serious games in robotic rehabilitation has emerged as a promising approach to address the challenges associated with the monotony and repetition of therapy sessions [41,48]. Serious games or virtual reality games designed for rehabilitation offer a means of increasing engagement, motivation, and adherence to treatment in the context of robotic rehabilitation [49].

Serious games can provide a motivating and engaging environment for patients undergoing robotic rehabilitation. The interactive and goal-oriented nature of games can make therapy sessions more enjoyable. Additionally, the introduction of interpersonal rehabilitation games, where patients can compete or cooperate with another person, adds a social element to the rehabilitation process. The choice between competition and cooperation can be tailored to individual patient preferences [50]. Another key aspect is the fact that serious games provide a quantitative means to assess the patient‘s progress and the efficiency of the robotic rehabilitation device. In summary, integrating serious games into robotic rehabilitation not only introduces an element of pleasure and motivation but also improves the overall patient experience. The gamification of therapy sessions can lead to increased patient compliance, better outcomes, and a more comprehensive assessment of the device‘s progress and effectiveness [49,51].

However, not all serious games are equally effective for all patients. Each individual has specific characteristics and needs that should be considered when choosing games and defining the level of difficulty. To solve this problem, the use of artificial intelligence techniques has been added, which allow for a further personalization of serious games for each patient [52–54]. It can be seen that devices such as the MIT wrist robot [33,34], RiceWrist [36], UHD [39], ITT Genova Robot [41], SCRIPT 1 prototype [42], and UFU wrist robot [24] use virtual reality capable of quantifying the efficiency of the device and the evolution of the patient. However, they do not use the artificial intelligence associated with these virtual games. The Harvard University Robot [30], for example, does not mention the presence of the games. Currently, the use of artificial intelligence in any research is indispensable. However, in practice, the research and application of AI in wrist rehabilitation robots are still not significant. Therefore, the use of AI in rehabilitation would be extremely relevant for robotic devices. AI would provide more concrete data on the patient's evolution and the efficiency of the device, allowing for a further customization of the serious games for each patient.

7. Discussion

Highlighting the main research related to robotic devices for the rehabilitation of the human wrist, it can be seen that there are several characteristics found, namely as follows: the number of degrees of freedom, wrist movements, type of actuator, control system, experimental evaluation, safety, and presence of AI associated with serious games or virtual reality games. The referenced articles come from research focused on wrist rehabilitation devices using the PRISMA methodology.

In most of the devices surveyed, serious games are integrated to create a playful environment for patients in rehabilitation and quantify the efficiency of the device. It can be seen that research on the robotic rehabilitation of the human wrist should still associate serious games with artificial intelligence, providing a more personalized and dynamic experience for each patient. As previously discussed, not all serious games are equally effective for all patients. Considering that each individual has specific characteristics and needs, it is crucial to take these aspects into account when selecting games and determining the level of difficulty. In addition, regarding the safety of the devices, it was shown that the devices urgently need to comply with the IEC 80601-2-78:2020 standard [18] regarding medical electrical equipment. Safety should be the priority of research related to the rehabilitation of the human wrist, which focuses on the human being themselves.

Although there are several devices developed for the rehabilitation of the human wrist, few are commercially available. In addition, several are in the prototype construction phase, and some present experimental results with patients, as shown in Table 3. In most cases, the experimental tests were conducted with few patients, but they presented unambiguous evidence of the effectiveness of using this equipment to improve patient outcomes.

Another aspect observed refers to the fact that the most efficient robotic rehabilitation devices tend to be the least complex [10]. The development of a low-cost robotic rehabilitation device for the human wrist, focusing on the utilization of individual degrees of freedom, represents an innovative approach in the field of rehabilitation [24]. This concept is grounded in the idea that simplicity and the targeted treatment of specific movements can increase the efficiency of robotic rehabilitation devices [50]. The devices proposed in [24,45] allow for the rehabilitation of the human wrist by individually addressing its three degrees of freedom. This approach diverges from traditional methods that simultaneously work all movements, providing a more focused and potentially more effective rehabilitation strategy.

The aspects that need to be addressed in the development of a new wrist robot for rehabilitation are summarized as follows:

- ➢ Movements: They need to be in the function of the traditional physiotherapeutic concepts and reproduce the rehabilitation protocols. It is desirable that the center of rotation of the device coincides with the rotational axis of the human joint;
- ➢ Safety: In addition to robots being developed to be safe to use, with mechanisms to prevent accidents and injuries, the need complies with the IEC 80601-2-78:2020 standard [18];
- ➢ Cost: Especially for developing countries, the issue of cost is fundamental for the inclusion of this equipment in wrist rehabilitation procedures. In addition to the cost of the equipment, one must also think about the easy replacement of parts that are widely used commercially and their maintenance, which should preferably be carried out by the users themselves;
- ➢ User-friendly device: Wrist robot devices need to be patient-friendly and easy to adjust, allowing for the quick attachment and removal of the patient's hand/forearm. The equipment also needs to be user-friendly for healthcare professionals, allowing for easy use;
- ➢ Adaptability: Wrist robot devices need to adapt to different patients at the anthropometric level and the difficult level. The control systems need to adapt to the needs of patients, and the use of serious games together with AI can potentially enhance the rehabilitation process.

In reference [4], it is discussed if the next therapist will be a robot, and the answer is no for the next decade. We are experiencing an aging population, which leads to a greater number of health problems that require physiotherapists to rehabilitate the human wrist [55]. On the other hand, the number of physiotherapists available has decreased [56]. The use of robotic devices can help healthcare professionals serve more patients. We emphasize that the robotic devices for wrist rehabilitation to be developed should be seen as tools for health professionals/physiotherapists and not as equipment that will replace them.

8. Conclusions

This paper presents a comprehensive literature review focusing on robotic devices designed for wrist rehabilitation. The review reveals a diverse range of such devices, which have been categorized and summarized in a tabular format for enhanced readability and analysis. These tables encapsulate key attributes essential for wrist rehabilitation device development, including degrees of freedom, wrist movements, actuator types, control systems, experimental evaluations, safety features, and the integration of artificial intelligence with serious games or virtual reality. Furthermore, an analysis of these devices' application with patients demonstrates their potential efficacy in motor wrist rehabilitation. Therefore, it is recommended that healthcare professionals, particularly physiotherapists and physicians, leverage this scientific knowledge in treating patients with conditions such as strokes and wrist injuries. Additionally, this paper serves as a valuable resource for researchers in the field, offering insights into comparing different robotics wrist based on specific characteristics, such as the incorporation of serious games with artificial intelligence. Moreover, it underscores the importance of adhering to safety standards, notably the implementation of the IEC 80601-2-78:2020 standard [18] in robotic devices to ensure patient safety.

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