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THE REVIEW OF RESEARCH ON WRIST REHABILITATION ROBOTS

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Abstract. *Stroke is the main cause of disability among adults worldwide, resulting in a high number of individuals with motor and cognitive deficits. The main consequence of this brain injury is the loss or weakening of human body movements, especially the upper limbs. Thus, the use of robotic devices can help in the rehabilitation process by providing improvements in motor and functional performance and providing quantitative evaluations of movement. One of the applications of robotics in medicine is the development of devices to assist in the rehabilitation of the human wrist. The human wrist is a joint with three degrees of freedom that connects the hand to the forearm, developing radial-ulnar deviation, flexion-extension, and pronation-supination movements. This review paper aims to report the leading research on robotic devices to aid the wrist rehabilitation process. Another goal is to classify the surveyed devices according to the number of degrees of freedom, the movements associated with the wrist, the type of actuator, the control method, the feedback signal, and the experimental evaluation. The method consists of researching the main articles at Scopus with "wrist rehabilitation robot" as keywords since 2012. Results showed a variety of wrist rehabilitation devices that could be classified and presented as a table to ease the reader's analysis. The table contains all the essential attributes necessary to develop wrist devices for rehabilitation. This paper presents a review of the main robotic devices for wrist rehabilitation found in the literature in the last few years. The primary highlight is the classification of each of these robotic devices according to their main attributes and features. In addition, it is a way for health professionals, such as physiotherapists and physicians, to apply this scientific knowledge to patients who are victims of stroke and have lesions in the wrist region. Finally, it serves as a guide for wrist rehabilitation researchers who wish to compare different robotic manipulators based on many aspects and characteristics and provides an outlook on their future development direction. Another important aspect reported in the article is the importance of serious games in conjunction with a simple wrist rehabilitation device. These ideas will be implemented in a new robotic wrist rehabilitation device made by the Laboratory of Automation and Robotics at UFU (Federal University of Uberlândia).*

Keywords: *wrist, rehabilitation, robotics, review, classification*

1. INTRODUCTION

Stroke is the leading cause of disability among adults worldwide, causing high numbers of individuals with motor and cognitive deficits. The main consequence of this brain injury is the loss or weakening of the movements of the human body, especially of the upper limbs. Soon after the stroke, the brain goes through several stages of recovery, where the Central Nervous System (CNS) can reorganize neural circuits through neuroplasticity. Neuroplasticity is defined as the ability of the nervous system to restructure itself by forming new connections so that another part of the brain takes over the function of the damaged part (Cramer et al., 2011). The basic condition for functional improvement after stroke is increased neuroplasticity. Considering that neuroplasticity begins to develop immediately in the first months after stroke, the type and intensity of interventions in the acute period gain great importance (Coskunsu et al., 2022). This restructuring of the nervous system, responsible for the learning and stimulation processes, occurs both spontaneously and with the help of rehabilitation and non-invasive brain stimulation (Auriat et al., 2015).

Thus, the use of robotic devices can assist in the rehabilitation process, providing improvements in motor and functional performance, by providing quantitative evaluations of movement. The possibility of using robotic devices as a more efficient means of providing therapy has been the subject of research involving post-stroke rehabilitation (Hesse et al., 2003; Gonçalves & Siqueira, 2014; Rodrigues & Gonçalves, 2022). Currently, rehabilitation devices for upper limbs have had great advances in recent years, but it is still necessary to conduct a lot of studies related to the theme, mainly due to the complexity of human hand movements (Silva, 2011) and (Thomazoni, 2015). 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 (Payedimarri et al., 2022).

One of the applications of robotics in medicine is the development of devices to assist in the rehabilitation of the human wrist. The human wrist is a joint with three degrees of freedom that connects the hand to the forearm, developing radial-ulnar deviation, flexion-extension and pronation-supination movements (Kapandji, 2007).

This review article aims to report the main research on robotic devices to aid the wrist rehabilitation process. In addition, these researched devices are classified according to the number of degrees of freedom, the movements associated with the wrist, the type of actuator, the control method, the feedback signal, and experimental evaluation. The method consists of searching the top Scopus articles with the keywords "wrist rehabilitation robot" since 2012. According to the *Scorpus* statistical graph, the demand for articles on the topic is greatest between the years 2012 and 2022. During this period, there are articles with high impact and great scientific relevance. In the research, more than 300 related articles were shown, but only 40 articles were used. The reduced use of cited articles is the result of research based on wrist rehabilitation devices with three degrees of freedom, whose characteristics are similar to the device under construction by the Laboratory of Automation and Robotics at UFU (Federal University of Uberlândia). Thus, this literature review will help in the construction of this future device, with more adaptive and better characteristics for voluntary patients.

This paper presents a review of the main robotic devices for wrist rehabilitation found in the literature in recent years. In addition, it is a way for health professionals, such as physical therapists and physicians, to apply this scientific knowledge to stroke patients with wrist injuries, as well as a guide for wrist rehabilitation researchers who want to compare different robotic manipulators based on many aspects and characteristics.

Another important aspect reported in the article is the importance of serious games in conjunction with a wrist rehabilitation device. This idea will be implemented in a new robotic wrist rehabilitation device made by the Laboratory of Automation and Robotics at UFU (Federal University of Uberlândia), as previously mentioned.

2. LITERATURE REVIEW

This section reports on major research on robotic devices to aid the wrist rehabilitation process. These researched devices are classified according to the number of degrees of freedom, the movements associated with the wrist, the type of actuator, the control method, the feedback signal, and the experimental evaluation. The method consists of searching the main Scopus articles with the keywords “wrist rehabilitation robot” since 2012. In addition, with bibliographic reference research, it is possible to develop a new device with more advantageous and efficient characteristics for the rehabilitation of the wrist. Serious games are also mentioned to allow a playful environment for the patient, as well as to quantify the patient's evolution and the efficiency of the device.

2.1 Fundamentals of Robotic Rehabilitation

Medical rehabilitation is a process of maximizing the physical, social, vocational, psychological, and educational capacities of individuals who find themselves with significant material and moral damages, inadequate and incompatible with family and social aspects (Mayetin et al., 2018). Thus, the goal of the rehabilitation process is to minimize these negative effects of an individual’s inability to integrate into society. Physical therapy and rehabilitation are important for the recovery of daily activities of patients with motor problems.

Thus, the use of robotic devices can assist in the rehabilitation process, providing improvements in motor and functional performance by providing quantitative evaluations of movement. The possibility of using robotic devices as a more efficient means of providing therapy has been the subject of research involving post-stroke rehabilitation (Hesse et al., 2003) and (Gonçalves & Siqueira, 2014).

Currently, with the advancement of technologies, the study methodologies related to robotic rehabilitation have grown considerably, expanding new research and studies in this field of science. As an example, there are injuries involving the wrist. These lesions are complex and challenging in their treatment, but they have been gaining notoriety through the latest studies because it is an extremely important region for the human body (Brito, 2019).

The wrist is a distal joint of the upper limb with two degrees of freedom, connecting the hand to the forearm. He can develop radial-ulnar deviation and flexion-extension movements. There's also the rotation. Hand rotation does not occur specifically in the wrist but rather in the joints referring to the elbow and forearm. Then one has a third degree of freedom on the wrist corresponding to pronation and supination. Considering the existence of three degrees of freedom, the wrist can be compared to a spherical joint, mechanically restricted by the ranges of motion associated with the wrist (Kapandji, 2000). Wrist flexion/extension movements occur in the sagittal plane. During flexion, the palm heads to the anterior surface of the forearm and in extension, the dorsal surface of the hand heads to the posterior surface of the forearm (Brito, 2019). The range of motion, measured from the reference position, is 85°, Fig. 1.

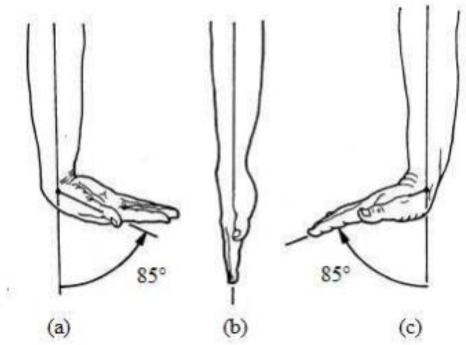

Figure 1. (a) Flexion at 85°, (b) Anatomical position at 0°, (c) Extension at 85° (Kapandji, 2000).

Abduction movement (radial deviation) and adduction (ulnar deviation) in the wrist occur around the anteroposterior axis in the frontal plane, Fig. 2. The abduction or radial deviation of the wrist has an amplitude of movement of 15°, in relation to the reference position. The adduction or ulnar deviation has different amplitudes according to the adopted reference. For the angle on the line joining the center of the wrist with the distal portion of the third finger, the amplitude is 45°. Referencing the axis of the hand, the amplitude is 30°. In relation to the axis of the middle finger, the amplitude is 55° (Brito, 2019).

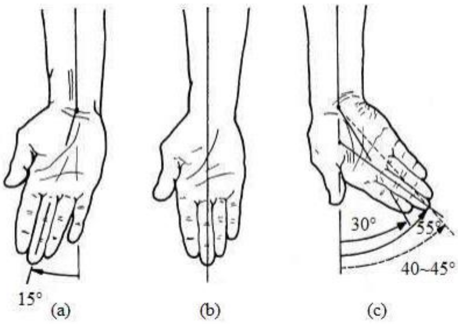

Figure 2. (a) Abduction or radial deviation at 15°, (b) Anatomical position at 0°, (c) Adduction or ulnar deviation, conventionally at 45° (Kapandji, 2000).

The pronation and supination movement consist of the rotation of the radius around the ulna, allowing the rotation of the forearm, and consequently of the wrist, around the axis itself. The supination position is performed when the palm of the hand is directed upwards with the thumb outward, and the pronation position is performed when the palm of the hand is oriented downwards with the thumb inwards. The supination range of motion is 90° and the pronation range of motion is 85°, as shown in Fig. 3 (Brito, 2019).

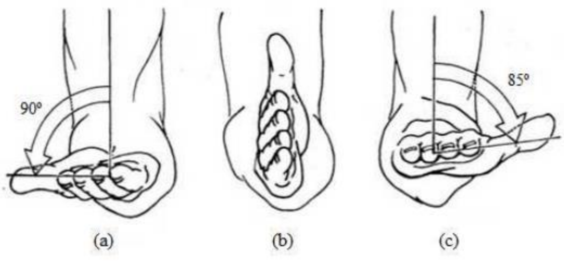

Figure 3. (a) Supination at 90°, (b) Intermediate position, (c) Pronation at 85° (Kapandji, 2000).

2.2 Wrist Rehabilitation Devices

Initial studies on rehabilitation robots are based on the early 1990s. These studies are basically divided based on the upper and lower limbs. In upper extremity rehabilitation studies, shoulder, elbow, wrist, hand, and finger rehabilitation are the main foci, as well as some combination of these (Mayetin et al., 2018).

Robots for wrist rehabilitation can be divided into two types: effectors and exoskeletons. Effector-type rehabilitation robots move the upper extremity, holding the patient's hand or forearm from a certain point. This type of robot uses the designs of serial architecture robots in robotic technology. The main objective is the realization of the movement as a whole. While exoskeleton-type robots consist of shafts placed at the joints of the upper limb. The structure of these axes produces a movement associated with the joints, so each joint can be measured and tracked (Mayetin et al., 2018).

These robots are also classified into different types of motion assistance, among them: active, passive and haptic. Active devices refer to active motion assistance and have at least one actuator. Thus, these active devices are able to produce movement in the upper limb. Typically, they are devices used by patients quite debilitated to perform exercises. In the case of passive devices, they are equipped with actuators that provide only resistive force. This type of device is unable to move the limbs, but can resist movement when exerted in the wrong direction. They are devices used in the rehabilitation of individuals who are able to move their limbs. Haptic devices, on the other hand, constitute another type of assistance, interacting with the user through the sense of touch. They can be classified as assets or liabilities, depending on the type of actuator. Used in virtual environments, their main function is not to cause or resist movement, but rather to provide a tactile sensation to users (Brito, 2019).

The evolution of robotic rehabilitation of the human wrist is mainly due to several studies and research done over the last few years, in Table 1. In (Krebs et al., 2007) a rehabilitation robot with three degrees of freedom called MIT-MANUS was developed. In the handle of the robot was added a load cell and a direct force control scheme to minimize the interaction forces between the user and the robot (Tagliamonte et al., 2010).

Haptic Knob was designed at the National University of Singapore to train hand opening/closing as well as forearm pronation/supination (Lambercy et al., 2007). This device has two Degrees Of Freedom (DOFs), parallelogram mechanism, a linear bearing, belt driven mechanism in combination with DC motors.

Gupta and O'Malley (2006) created a device called RiceWrist, an electrically driven haptic forearm-wrist exoskeleton. This work presents an impedance-based position and force controller for the device. Subsequently, the RiceWrist-S was developed, a serial robot mechanism for wrist and forearm rehabilitation. The device has a grip strength sensing handle. The RiceWrist-S is designed to provide high torque output and cover the entire working space of the human wrist (Pehlivan et al., 2014).

The UHD (Universal Haptic Drive) was developed for wrist rehabilitation (Oblak et al., 2010). UHD can provide actuation for three DOFs of the wrist joint, with flexion/extension movements, pronation/supination, and abduction/adduction movements. The UHD actuation mechanism works on the basis of elastic series actuation.

Northwestern University's robotic exoskeleton features a DOF to provide the flexion/extension movements for patients' wrist joint. This exoskeleton is powered by a DC motor in conjunction with a zero-clearance harmonic gear. The evaluation provided encouraging evidence for the usefulness of the robotic exoskeleton for physical therapy (Ren et al., 2013).

IIT Genova presents three DOFs, with abduction/adduction, flexion/extension and pronation/supination movements of the human wrist. The robotic system is powered by four DC motors. Two motors are used to enable abduction/adduction movement and gravity compensation and the other two motors are used to power flexion/extension and pronation/supination movements (Masia et al., 2014).

A robotic pulse exoskeleton has been developed at the University of Sheffield with the aim of providing physiotherapy to stroke survivors. We evaluated 23 patients with chronic stroke for six weeks. The robotic exoskeleton provides flexion/extension to the wrist joint using an electromagnetic actuator (Amirabdollahian et al., 2014).

The Harvard University robotic device was used to evaluate a healthy participant, with the aim of validating the design and performance of the capability in terms of range of motion and torque. Experimental evaluation with a healthy participant provided the results intended by the research (Bartlett et al., 2015).

RiceWrist is a rehabilitation exoskeleton with four DOFs for the wrist and forearm. RiceWrist is designed based on the serial-in-parallel mechanism and is composed of three prismatic-spherical revolutions, supporting abduction/adduction, flexion/extension, and forearm pronation/supination movements. The fourth DOF is the vertical translation of the platform, and provides less alignment of the anatomical axes of the wrist with the robotic platform (Pehlivan et al., 2015). Subsequently, the RiceWrist-S was developed, a serial robot mechanism for wrist and forearm rehabilitation. The device has a grip strength sensing handle. The RiceWrist-S is designed to provide high torque output and cover the entire working space of the human wrist (Pehlivan et al., 2014).

The UTM Robot is a robotic exoskeleton with a DOF, designed at Seoul National University (SNU). This robot provides flexion/extension movements to the wrist joint of stroke survivors. The exoskeleton is powered by a brushless DC motor. The SNU robot also used torque sensors to measure human-robot interaction (Khor et al., 2017).

Pezent (2017) developed OpenWrist. This robotic device is the evolution of the RiceWrist-S. A fourth degree of passive linear freedom between the third joint and the human interface point allows for small misalignments between the user's and robot's joints.

WRES is a two-DOF-robotic wrist exoskeleton developed by researchers at Kyushu University, Fukuoka, Japan. This robot provides three DOFs for abduction/adduction, flexion/extension, and pronation/supination movements. WRES provides the actuation for the handle using DC gear motors (Buongiorno et al., 2018). The Kyushu Robot used a load cell for human-robot interaction with torque feedback and a camera-based motion analysis system for online position determination (Higuma et al., 2018).

The Omega.7 effector robot is powered by servo motors and provides three DOFs for the wrist joint. This robot was used in seven patients with stroke and three patients with traumatic brain injury. The quantitative assessment provided encouraging results for the use of Omega.7 rehabilitation (Liu et al., 2019).

WReD is a wrist rehabilitation robot with a single DOF, providing flexion/extension movement. This robot was developed at Tongji Zhejiang College, Jiaxing, China, and is powered by a DC motor (Xu et al., 2019).

The robotic rehabilitation device, made at the Laboratory of Automation and Robotics of UFU (Federal University of Uberlândia) is directed to wrist rehabilitation movements. The developed robotic structure has a base for hand support and is coupled to a servomotor. For the use of this mechanism, a game was developed as a graphical interface. Together with the structure control system, an impedance control was implemented, allowing the patient the intention to resist the movement performed by the platform or assist him with the necessary movement required. Fourteen volunteers without injury and three volunteers after stroke participated in the case study (Brito, 2019).

Table 1. Literature review of wrist rehabilitation devices

Device Name	References	DOF	Joint(1)	Actuation Type	Control Method	Feedback Signal	Experimental Evaluation
MIT-MANUS robot	Krebs et al (2007)	3	Wrist – FE, AA, PS	Servo motors	Impedance control (AAN)	Load cell, encoders	36 Stroke participants
Haptic Knob	Lambercy et al (2007)	2	Forearm – PS wrist – FE	DC motors	Impedance control (AAN)	Load cell, encoders, BCI	15 Stroke participants
RiceWrist	Gupta et al (2008)	4	Forearm – PS, wrist – FE, AA	DC motors	PD Trajectory Tracking	Joint angles and forces	Not Provided
UHD	Oblak et al (2010)	3	Wrist – FE, AA, PS	SEA	Impedance control (AAN)	Linear potentiometer	1 Stroke participants
Northwestern University Robot	Ren et al (2013)	1	Wrist – FE	DC motors	Impedance control (AAN)	Load cell, potentiometer	3 Stroke participants
IIT Genova Robot	Masia et al (2014)	3	Wrist – FE, AA, PS	DC motors	Impedance control (AAN)	Load cell, encoders	9 Stroke participants
Sheffield University Robot	Amirabdollahian et al (2014)	1	Wrist – FE	DC motors	Not Provided	Rotary potentiometer	23 Stroke participants
Harvard University Robot	Bartlett et al (2015)	3	Wrist – FE, AA, PS	PMA	Not Provided	Not Provided	1 Healthy participant
Rice Wrist	Pehlivan et al (2015)	3	Wrist – FE, AA, PS	DC motors	MPC control (AAN)	Load cell, encoders	5 Healthy participants
SNU Robot	Beom et al (2016)	1	Wrist – FE	DC motors	Not Provided	Torque sensor	20 Stroke participants
UTM Robot	Khor et al (2017)	3	Wrist – FE, AA, PS	Not Provided	PD Trajectory Tracking	Not Provided	7 Stroke participants
Open Wrist	Pezent et al (2017)	3	Wrist – FE, AA, PS	DC motors	PD Trajectory Tracking	Torque sensor	Not Provided

WRES	Buongiorno et al (2018)	3	Wrist – FE, AA, PS	SEA	Trajectory Tracking	Encoders	1 Healthy participant
Kyushu University Robot	Higuma et al (2018)	2	Wrist – FE, AA	Linear motors	Not Provided	Load cell, camera	1 Healthy participant
Omega.7	Liu et al (2019)	3	Wrist – FE, AA, PS	Servo motors	Virtual Reality (AAN)	Not Provided	7 Stroke and 3 TBI participants
WReD	Xu et al (2019)	1	Wrist – FE	Servo motors	Impedance control (AAN)	Torque sensor, encoder	1 Healthy participant
Federal University of Uberlândia	(Brito, 2019)	1	Wrist – FE	Servo motors	Impedance control (AAN)	Torque sensor	3 Stroke and 14 Healthy participants

(1) AA – adduction/abduction, FE – flexion/extension, PS – pronation/supination.

2.3 Serious Games

Digital games can be used for fun and entertainment, as well as for other purposes. The term "serious games" denotes digital games that serve serious purposes such as education, training, advertising, research, and health. In this paper, serious games will be used in order to assist in robotic rehabilitation (Wiemeye & Kliem, 2012).

Serious games have the potential to address the competencies illustrated in Fig. 4 more directly and systematically, without neglecting players' gaming experiences such as fun, motivation, flow, immersion, presence, challenge, curiosity, and other emotions (Wiemeye & Kliem, 2012). One of the main problems with robotic rehabilitation is that therapy sessions can be tedious due to the repetition of exercises. Thus, serious games can motivate, engage, and increase patient adherence to treatment (González González et al., 2019; Alves et al., 2022; Gonçalves et al., 2023).

One possible way to improve motivation in motor rehabilitation is through the use of interpersonal rehabilitation games, which allow the patient to compete or cooperate with another person. The fact that the game allows the patient to compete or cooperate refers to the personality of each patient, but according to the literature, the favorite game chosen is competition (Andrade et al., 2013). Serious games are also a quantitative way to assess patient evolution and device efficiency.

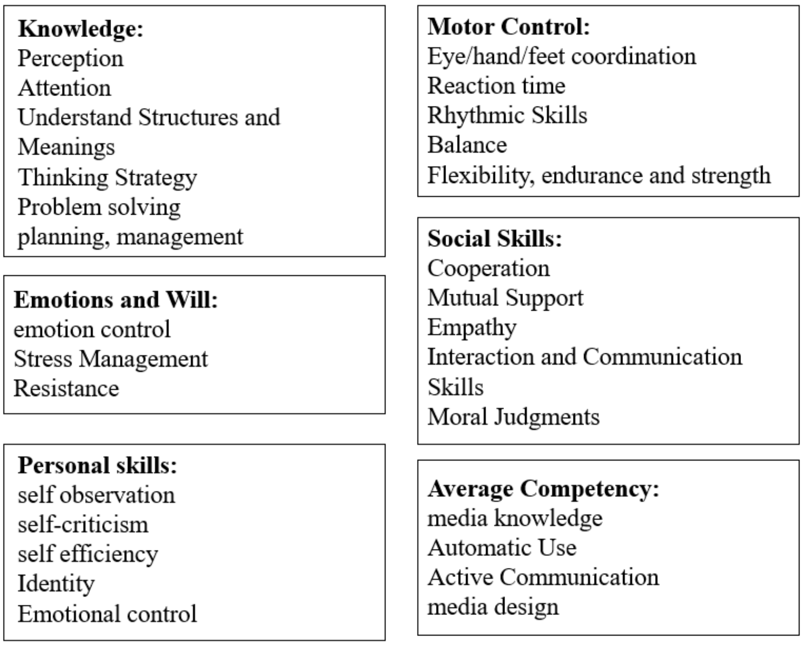

Figure 4. Skills that can be improved by playing digital games (adapted Gebel et al., 2005).

3. ROBOTIC WRIST REHABILITATION DEVICE

The most efficient robotic rehabilitation devices are the least complex (Mayetin et al., 2018). Based on this premise, it was proven that the treatment of only one movement at a time proved to be better and more efficient, compared to the traditional method, in which all movements are simultaneously worked (Andrade et al., 2013). Thus, a new wrist rehabilitation device from the Federal University of Uberlândia (UFU) proposes the development of a low-cost robotic device for the rehabilitation of the human wrist, in which it uses the three degrees of freedom individually. The proposed new device has as its starting point the prototype developed in the master's thesis Brito (2019), at the Laboratory of Automation and Robotics at UFU. The prototype built allows individual movements with the use of serious games, Fig. 5 (Brito, 2019; Gonçalves et al., 2020).

Thus, we propose for future work the development of a low-cost robotic device for the rehabilitation of the human wrist, in which it uses the three degrees of freedom individually. In addition, serious games will be implemented in conjunction with the device to allow a playful environment for the patient, as well as quantify the evolution of the same and the efficiency of the device. The serious games implemented will have as their main scope the competition/cooperation between two patients or between a patient and the physiotherapist. These serious games will be associated with the use of artificial intelligence techniques. In addition, for the validation of the robotic wrist rehabilitation device in conjunction with the serious games, experimental tests with healthy volunteers and patients will be done.

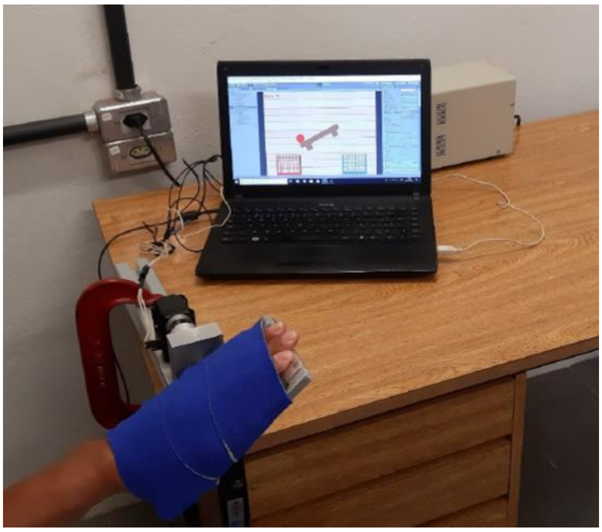

Figure 5. Use of the human wrist rehabilitation device in patients (Brito, 2019).

4. DISCUSSION AND CONCLUSIONS

The results of the literature review showed a variety of wrist rehabilitation devices that could be classified and presented in table form to facilitate the reader's analysis. The table contains all the essential attributes needed to develop wrist devices for rehabilitation. This paper presented a review of the main robotic devices for wrist rehabilitation found in the literature in recent years. The main highlight is the classification of each of these robotic devices according to their main attributes and functionalities. In addition, it is a way for health professionals, such as physiotherapists and doctors, to apply this scientific knowledge to stroke patients with injuries in the wrist region. It also serves as a guide for wrist rehabilitation researchers who wish to compare different robotic manipulators based on many aspects and characteristics and provides insight into their future development direction.

Another important aspect reported in this article is the importance of serious games in conjunction with a low-complexity wrist rehabilitation device. These characteristics will be implemented in a new robotic wrist rehabilitation device manufactured by the Laboratory of Automation and Robotics at UFU (Federal University of Uberlândia).

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