Hand Exoskeleton Design for the Rehabilitation of Patients with Rheumatoid Arthritis

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Abstract. Starting in 2015, various exoskeleton designs have been developed to facilitate interventions in the rehabilitation of patients with movement disabilities aimed primarily at flexing and extending the finger joints. This article covers the review and generation of a device for the physical rehabilitation of people diagnosed with rheumatoid arthritis (RA). Among the determining aspects for its manufacture, it has been detected that most have been designed with different technological tools with limited degrees of freedom (GDL) and the application of mechanical systems without studies of interaction with the user. The applied methodological framework for the development of exoskeletons of the hand includes a systematic review of the devices, referring to their mechanical, electronic and functional attributes according to the technological trends of the last five years. The information analyzed in this article allows the generation of an exoskeleton with the use of rapid prototyping techniques within user-centered digital manufacturing processes.

Keywords: Rheumatoid arthritis · Hand · Exoskeleton · Physical rehabilitation · Systematic review

1 Introduction

Knowledge about rheumatoid arthritis, RA, is transforming, as currently there are more problems due to inflammatory diseases within immunological pathogenesis and more frequent nature that affects the joints of patients. These types of complications critically affect quality of life but can be transformed with more frequent treatment [13, 15].

The hand is crucial in carrying out the daily activities necessary. One's functional disability demands the assistance of third parties, thus causing a socio-economic impact due to the limitations of the patient's productive capacity, therefore causing family income decreases whilst having increased medical expenses [18].

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1. Analysis of the current situation of the patient's hand: Physical limitations, postures, movement capacity, strength, power, flexibility, among others;
2. The patient is asked to perform certain finger flexion-extension movements, grasping movements, while the exoskeleton control system analyzes the sensor signals and determines the expected movement;
3. Movement capture [20]: the control system selects a movement pattern and adjusts it to the current position of the patient, thus allowing movement with its own force;
4. After repeating the movement, the system analyzes the situation again, then prepares to anticipate the following movements of the user.

Therefore, the design of a portable hand rehabilitation device [17] with programmable movement functions may be important for the periodic rehabilitation of the patient. The device must be able to assess the state of the motor functions of the hand, such as stiffness of a finger, independence of the finger, articulation angles and/or external force of the hand. In addition, it should help the voluntary movement of the patient for both flexion and extension of the fingers, allowing force to be applied to each finger joint.

In contrast to conventional prosthetics, a hand exoskeleton serves as a multipurpose, medical device because it is designed and constructed based on the anthropometry of the human hand. Furthermore, it adjusts easily to movements while minimizing patient discomfort, in addition to expanding and improving the skills selected by the user.

2 State of Art of Hand Exoskeletons Today

For the development of the device, a review was established in different databases such as Dialnet, IEEE Xplore and RedMed from 2015.

Inclusion and exclusion criteria corresponding to the requirements for the construction of the exoskeleton were applied based on the search results. The inclusion criteria for the existing information in the articles analyzed were as follows.

– The study and/or article presents a prototype or approaches to hand exoskeleton designs.
– The study applies the design of a hand exoskeleton to the rehabilitation of RA patients.
– The study exhibits mechanical, electronic and/or functional attributes of the hand exoskeleton.
– The studio features robotic finger or hand designs, pneumatic finger or hand and/or rehabilitation gloves.

The exclusion criteria were as follows:

– The study has not been published in English or Spanish.
– The device has been used for rehabilitation of patients with cerebral palsy.
– The device does not use functional components.
– The study and/or article presents a prosthetic hand device instead of an exoskeleton.

53 studies/articles on handheld devices applied in physical rehabilitation were analyzed, but in the end 45 were chosen for the study and the systematic review because some designs were used for different purposes.

Additionally, it is highlighted that, despite the similarity of prosthetic hands with hand exoskeletons, the study focused on the physical rehabilitation of RA patients with the assistance of an exoskeleton.

In the last five years, the number of studies that contribute to the development of hand exoskeletons and that are relevant for their review and analysis has increased. Many of these devices have adapted to new technologies and have evolved in the use of materials, thus overcoming the limitations within the traditional design of exoskeletons. This article presents the proposals that meet the following requirements:

– The exoskeleton allows flexion-extension movement of the fingers.
– The exoskeleton uses mechanisms that allow dynamic movement of the patient's hand.
– There is an adaptation of the exoskeleton to the variety of anthropometric hand measurements.
– The patient can control the exoskeleton in relation to degrees of freedom (DOF).

3 Research Contributions

Thirty-six hand exoskeletons were reviewed according to the criteria de-scribed above. The devices were organized in chronological order and classified according to their attributes of mechanism, control and unit of action, described in Table 1.

Table 1. Summary of the mechanical, electrical and functional attributes of robotic hand exoskeletons since 2015 (Source: Own Elaboration, 2020).

Year	Actuation	Force of output (N)	Degrees freedom	Finger movements	Range movement	Weight	Functionality	References
2015	Hybrid tire	1.3	3	Flex	150	–	Rehab	[8–11]
	Hydraulic	8	15	Flex and Ext	250	<500 g	Rehab	[1]
	Pulley cable	680	15	Flex and Ext	–	711 g	Rehab	[5]

(*continued*)

Table 1. (*continued*)

Year	Actuation	Force of output (N)	Degrees freedom	Finger movements	Range movement	Weight	Functionality	References
	Tire	29,5	99	Flex and Ext	112	194 g	Rehab	[17]
	Tire	13	3	Flex	149	–	Rehab	[30]
	Tire	10,35	15	Flex	141,2	200 g	Rehab	[34, 35]
	Tire	9,25	12	Flex	191,2	180 g	Rehab	[36]
	Tire	2 N	3	Flex and Ext	143,5	25 g	Rehab	[19]
	Tire	–	3	Flex	165	–	Rehab	[40]
	Tire	–	–	Flex	99,7	200 g	Rehab	[33]
2016	Linear actuator	3,125 N	1	Flex	–	–	Rehab	[30]
	Tire	–	15	Flex and Ext	–	–	Rehab	[24–26]
	Tire	35 N	15	Flex	105,9	–	Rehab	[41]
	Tire	17 N	3	Flex and Ext	93	–	Rehab	[28]
	Tire	10 N	12	Flex and Ext	–	<100 g	Rehab	[38]
	Tire	5 N	3	Flex	–	–	Rehab	[37]
	Tire	2 N	3	Flex	40	–	Rehab	[4]
	Tire	2,2 N	4	Flex		–	Rehab	[31]
2017	Pulley cable	10 N	2	Flex	–	–	Rehab	[6]
	Pulley cable	16 N	15	Flex	141,2	300 g	Rehab	[22]
	Tire	11 N	14	Flex and Ext	96	85,03 g	Rehab	[32]
	Tire	35 N	44	Flex and Ext	90	–	Rehab	[16]
	Tire	–	15	Flex	–	–	Rehab	[18]
	Pulley cable	–	2	Flex and Ext	120	90 g	Rehab	[2]
	Tire	5 N		Flex and Ext	110	285 g	Rehab	[27]
2018	Tire	4 N	3	Flex and Ext	171	–	Rehab	[39]

(*continued*)

Table 1. (*continued*)

Year	Actuation	Force of output (N)	Degrees freedom	Finger movements	Range movement	Weight	Functionality	References
	Tire	–	–	Flex and Ext	–	<150 g	Rehab	[23]
	Tire	>10 N	6	Flex and Ext	–	–	Rehab	[12]
2019	Tire	4 N	–	Flex	–	75 g	Rehab	[7]
	Neumatic	–	4	Flex and Ext	106	156 g	Rehab	[14]

4 Design of the Hand Exoskeleton System

The development of the rehabilitation device consists of two parts. The first focuses on development through rapid prototyping and digitization of the hands of study subjects for the establishment of necessary measures and GDL; on the other hand, the mechanical design is established by means of actuators and resistance bands.

4.1 Control of the Exoskeleton in Relation to DOF

Control of hand strength and position is an important aspect that allows the exoskeleton to provide the patient with repetitive and precise movements [30]. Therefore, there are devices that have addressed the use of specialized sensors to obtain force and position. Among the most relevant works is [18] a glove used to measure the flexion angle of the finger using curvature sensors based on a three-layer back propagation neural network (BP). This project highlights that the most important part in the design of the mechanical system is the connection between the actuator and the glove.

Another exoskeleton analyzed was that of a robotic orthosis that becomes a functional prototype of the Exoskeleton System (HES) where the mechanism leads to the use of simple actuation systems and control algorithms, but is characterized by being able to adapt to the movement of each Finger powered with 2 DOF linear electric actuators that ensures independent movement of each finger phalanx. The novelty of these HES is the incorporation of the 1 DOF mechanism never used in this field of design and that is capable of providing precise movements of the phalanges [6].

4.2 Preliminary Study

Preliminary study starts from the verification of the GDL necessary for a correct rehabilitation considering the analysis of force, loads, and resistances according to the material; in this case the development is a printed prototype in three dimensions.

Rehabilitation is carried out through therapeutic exercises. According to the APTA, American Physical Therapy Association, therapeutic exercises are defined as the planned systematic application of physical movements, postures, or activities designed to 1) remedy or prevent impairment, 2) improve function, and 3) improve physical condition.

The development of the device will be verified in a patient in the initial state of RA, where he does not yet have symptoms of constant pain, significant deformation, or motor disability (Fig. 1).

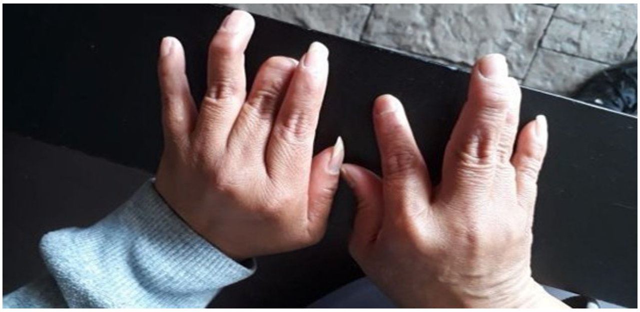

Fig. 1. Patient with rheumatoid arthritis initial stage (Source: Own Elaboration, 2020).

4.3 Final Prototype

The prototype consists of a glove-like structure that covers the hand with 3D printed actuators located at the junction of each phalanx to generate the flexo-extension action of these guided by a servomotor that exerts a contrary force.

The guides will facilitate the movement of the affected joints. The objective is to generate an organic movement of each of the phalanges, providing functional stability and correct support for the patient's hand; the pain factors net of the disease was taken into account, therefore the range of movement of the device will be predetermined by a test carried out on the patient and analyzed by photogrammetry and thus not exceed unnecessary pain limits, facilitating good performance and movement progression (Fig. 2).

In rehabilitation therapies for the hand, it must comply with international regulations, which is why the device must comply with the APTA regulations mentioned above. A maximum of 58° of range of motion will be achieved at the MCP (metacarpophalangeal) joints and at an approximate angle of 60° at PIP (proximal interphalangeal).

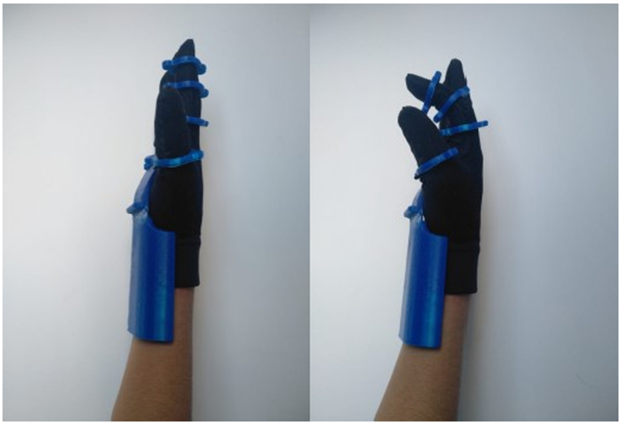

Fig. 2. Exoskeleton prototype (Source: Own Elaboration, 2020).

5 Conclusions

This article includes the development of a comparative investigation of the development of exoskeletons for rehabilitation, to take guidelines and requirements around RA, resulting in the design of a device that adjusts to the research base and real needs. from a patient; This will allow evaluating both the factors related to the device-patient interaction and the control adjustment of the programmed effort system for each patient that allows detecting the improvement of mobility through a therapeutically controlled rehabilitation.

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