Mechanical Design of an Assistive Robotic System for Bilateral Elbow Tendinopathy Rehabilitation

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Abstract: Diseases related to upper limb mobility are increasingly common among the actual population. For this reason, robotic physical assistive systems have been proposed to support therapy processes and improve the functional capabilities of people. However, there are still open issues related to mechanical design, such as joint coupling and bidirectional configurations. In this work, we present a novel design of a 7 DoF robotic assistive system with anthropometric adjustment, arm change configuration for elbow tendinopathies rehabilitation to use it in both arms. The design is supported by the analysis of the upper limb pathophysiology and the exercises required to treat elbow tendinopathies.

1 INTRODUCTION

Currently, physical disabilities are a public health problem, affecting people's quality of life and limiting the development of physical activities (Jabeen et al., 2016). According to the World Health Organization (WHO), more than one billion people worldwide have a disability, of which 16.5% suffer from mobility-related impairments (WHO, 2011). Some of the causes of this kind of impairments are injuries related with neurological, vascular, infectious or degenerative agents. Moreover the impairments can be caused by high level of demand in the performance of repetitive activities, occupational or domestic accidents, etc. (Jabeen et al., 2016; Dick et al., 2010; Fagher and Lexell, 2014). These injuries usually occur in the tendon structures of the upper limb, especially in the shoulder and elbow becoming into tendinitis or tendinopathies (Occhionero et al., 2014; Costa et al., 2015), which consequently results in pain, difficulty in the mobility and low strength. In these cases, a physical rehabilitation process is required to restore the functionality of the affected joint (Ritchie, 2003; Hillman, 2012; Kessler, 1950; ACP, 1932). Patients undergo treatments that include exposing muscle tissues to progressive stress, increasing range of motion and muscle strength, and preventing the onset of chronic pain (Ritchie, 2003; McHugh et al., 2013; Wattchow et al., 2018; Bruder et al., 2017; Milicin and Sîrbu, 2018; Contributors, 2003; Gates et al., 2015). As part of the rehabilitation process, assistive robotics can be used to support physiotherapy, providing technological tools to assist an appropriate intervention depending on the level of impairment (Linda et al., 2018; Olanrewaju et al., 2015). The use of these technologies has increased due to the ease of quantifying assessment variables such as range of motion, velocities, muscle activity and strength (Ballantyne and Rea, 2019). However, the development of robotic devices naturally involves mechanical design to a large extent, which is the focus of our work.

Assistive systems are designed according to the biomechanical characteristics of the required joint. From the anatomical viewpoint, in exoeskeletons it is complex to design a system that shares perfect coupling with the joint preserving the range of motion. The limitation remains in the loss of mobility ranges, usually to avoid the collision of the robotic system with the patient; for example, when shoulder adduction-abduction exercises are performed (Islam et al., 2020; Zimmermann et al., 2019).. In the literature, there are some works that seek to improve the conditions of mechanical coupling, such as (Lessard et al., 2018) where tensegrity is proposed

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to approximate real movements more accurately, or in (Liu et al., 2018) where mechanical postural synergies are developed to reduce complexity of transmission mechanisms. In addition, in (Zimmermann et al., 2019) the exoskeleton ANYexo has been developed, where the range of motion (ROM) is optimized to mimic the interaction of the specialist. Another example is the system TTI-Exo designed by (Ugurlu et al., 2015), which has adjustable link lengths to partially align the human and exoskeletal joints to avoid uncontrolled forces caused by hyperstaticity.

On the other hand, systems have been designed bilaterally or with an option to switch arms. For end-effector based systems, bilateral design and implementation is much simpler because the anchor point between the system and the upper limb is usually through the hand grip. Work such as (Miao et al., 2018; Miao et al., 2020a; Miao et al., 2020b; Sheng et al., 2019; Zhang et al., 2020; Sun et al., 2021) have implemented bilateral training in end-effector based systems. For the case of exoskeletons the design is more complex, and some authors opt to duplicate the robotic system by adapting it for the opposing limb as (Ugurlu et al., 2015; Kumar et al., 2019). Alternatively, the same system for one limb can be adapted for the opposite limb by means of an arm-switching configuration. However, it reduces costs and adds attributes in terms of adaptability, especially if used in physical rehabilitation applications. The best known system with this configuration is the Armeo Power system by Hocoma (HOCOMA, ; Wu et al., 2018). Nevertheless, to the best of our knowledge, in the literature there are no designs with this quality apart from the Armeo Power.

In this paper we propose a mechanical design of an assistive robotic system of 7 degrees of freedom to support the therapy of elbow tendinopathies. The criteria of a medical specialist has been considered as part of the formulation and the development of the mechanical design, as suggested by (Cruz Martínez et al., 2020). We present a novel design of anthropometric adjustment and arm change, avoiding the need to duplicate the arm. For this, initially we perform an analysis of the physiopathology of the upper limb, from this, qualitative and quantitative design criteria are defined, determining the degrees of freedom and torques required according to specifications obtained from these criteria. Subsequently, we develop the mechanical design, showing the preliminary version together with the arm-switching configuration; then, we present some conclusions of this work.

2 PHYSIOLOGY, BIOMECHANICS AND PATHOLOGIES OF THE UPPER LIMB

In this section, we analyze concepts related to the anatomy, physiology, pathologies and physiotherapy of the upper limb. It is mandatory to know how the articular system of the upper limb works in order to understand the biomechanics and subsequently develop a mechanical analogy that will allow us to establish design criteria according to the problem to be addressed.

The upper limb is composed of three parts: the arm, the forearm and the hand. In the proximal part of the arm is the joint complex called the shoulder (Fierro, 2015), which is the most mobile joint in the entire human body since it allows the orientation of the upper limb in the three anatomical planes (sagittal, frontal and transverse), which allows flexion-extension, adduction-abduction, internal-external rotation, horizontal flexion-extension and complementary movements such as protraction-retraction (Keith L. Moore and Agur, 2013; Knudson, 2007). The elbow is located in the distal part of the arm and proximal part of the forearm (Palacios, 2015). This joint allows flexion and extension movements, as well as distributing the load bearing forces and transmitting pronation and supination movements to the wrist. In the proximal part of the hand we find the wrist joint, which allows movements of pronation-supination, flexion-extension and radial-ulnar deviation (Fierro, 2015; Keith L. Moore and Agur, 2013). Note that in the schemes of elbow therapy exercises, it also involves the mobility of the other joints of the upper limb. (Knudson, 2007; Taboadela, 2007; Chaurand et al., 2007)

The normal joint ranges are shown in the Table 1, where the measurement methods of the AAOS (American Academy of Orthopaedic Surgeons) of the United States are used.

2.1 Tendinopathies and Physiotherapy

The elbow joint is frequently exposed to different conditions or pathologies. Among the most common are traumas such as fractures, dislocations, simple contusions, sprains and strains (Med,). There are also elbow tendinopathies produced mainly by activities or work that require constant and repetitive use of the elbow (Ruiz, 2011). The tendinopathies of the elbow are divided into lateral epicondylitis (tennis elbow) (Sanchez,), and medial epicondylitis (golfer's elbow)

Table 1: Joints and ranges of mobility. AAOS: American Academy of Orthopaedic Surgeons.

Joint	Movement	Angles
Shoulder girdle	Protraction - Retraction	Protraction: 0° – 25°/30°, Retraction: 0° – 25°/30°
Shoulder (gleno-humeral)	Abduction - Adduction	Abduction: 0° – 180°, Adduction: 0°
	Flexion - Extension	Flexion: 0° – 180°, Extension: 0° – 60°
	Internal - External rotation	Internal: 0° – 70°, External: 0° – 90°
	Horizontal Flexion - Extension	Flexion: 0° – 135°, Extension: 0° – 40°/50°
Elbow	Flexion - Extension	Flexion: 0° – 150°, Extension: 0°
Wrist	Pronation - Supination	Supination: 0° – 80°, Pronation: 0° – 80°
	Flexion - Extension	Flexion: 0° – 80°, Extension: 0° – 70°

(Grupo, 2011; SportMe,). In these cases of trauma, a physical rehabilitation process is necessary to restore the person physically, socially and occupationally (ACP, 1932; Kessler, 1950; Ritchie, 2003; Hillman, 2012).

The main goal of physical rehabilitation is the prevention of stiffness and restoration of the joint. Once mobility, stability and pain are controlled, speed and strength are restored later, essentially to prevent chronic pain (Vulliet et al., 2017). Within physical therapy, the specialist uses some tests to validate the diagnosis of tendinopathy as Maudsley, Mills, Cozen, inverted cozen, golfer's elbow sign, etc. And then uses other exercises for rehabilitation as stretching, mobility and isometric exercises (Kessler, 1950; ACP, 1932; Henning, 2010). As mentioned before, the exercise schemes used in the diagnosis and rehabilitation of tendinopathies require the use of the elbow joint, and also the shoulder and wrist joints (Cortés Rojas and Ramos Moreno, 2017). Therefore, the mechanical design must respond to the minimum specifications of movement of the joints included in the different diagnostic and rehabilitation protocols. This leads to the selection of joints, ranges of mobility and degrees of freedom in the design of the robotic system.

3 DESIGN CRITERIA

Based on the anatomy, physiology, and biomechanics of the upper limb, and considering the diagnostic and rehabilitation exercises for elbow tendinopathies, the anatomical-mechanical model and the design specifications of the assistive system are determined. The starting point is an anatomical and functional parametric definition of the upper limb. Then, a first approach is made to design the device based on the biomechanics of the upper limb. In Fig. 1 an analogy of the mechanical model approach is presented.

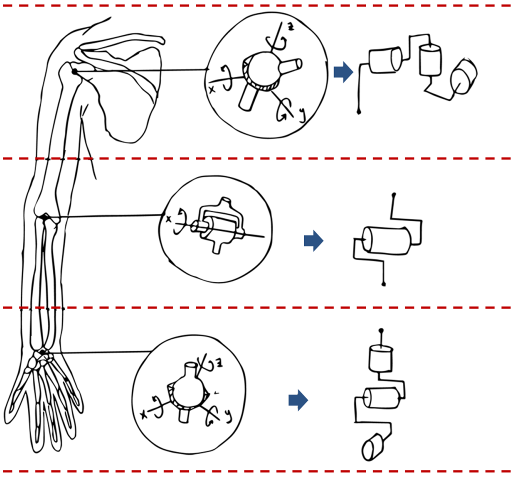


Figure 1: Anatomical-Mechanical analogy.

Anatomically, it is complex to design an active system that shares a perfect coupling with the joint and preserves maximum working space, and the system design must guarantee a perfect coupling between the robotic system and the human limbs in order to avoid discomfort or collisions (Islam et al., 2020; Zimmermann et al., 2019), but preserving to a greater extent the ranges of mobility.

3.1 Qualitative and Quantitative Criteria

An qualitative and quantitative criteria are established by analyzing the advantages and disadvantages of parameters such as the type of device (exoskeleton, end-effector), type of chain (open, closed), type of transmission (rigid, elastic), and above all, to seek the greatest inclusion of the population through a parametric analysis of anthropometry based on anthropometric indices of the Latino and U.S. population (Avila-Chaurand et al., 2007; Gordon et al., 1989). In Table 2 the criteria considered in the design of the robotic assistive system are shown where qualitative criteria as type of device, type of chain, type of transmission, and quantitative criteria as dimensional parameters and functional parameters are considered.

The first three aspects listed in Table 2 (type of

Table 2: Qualitative and quantitative design criteria.

		Advantages	**Disadvantages**
Type of device	Final effector	Does not depend on the length of the human arm, more people inclusion	Limited movement according to dimensions
		Easy to manufacture	Cannot move each joint independently
			Joint position estimation needed, can not be directly measured
	Exoskeleton	The movement occurs directly in the patient's joints.	Depends on anatomical lengths of patients, exclusion criteria
		Independent movement for each joint	Increased manufacturing complexity
		Independent control of each junction, independent measurements	
Type of chain	Open	Wide movement regardless of device dimensions	Increased susceptibility to external forces and inertia
	Closed	Major stability against external forces	Movement limited by the dimensions of the device
Type of transmission	Rigid	Direct connection with drive shaft, avoids losses for friction or elasticity.	Possible fractures in the structure due to unforeseen shocks
		Space optimization	
	Elastic	Quieter movements	Possible sliding under forces greater than supported
		Absorbs shocks in the transmission	Large dimensions
		Easy disengagement and maintenance	
		Min	**Max**
Dimensional parameters	Height	1.47 m	1.93 m
	Body mass	46.7 Kg	124.7 Kg
	Upper limb weight	2.335 Kg	6.235 Kg
	Arm length	0.27 m	0.41 m
	Arm perimeter	0.23 m	0.34 m
	Forearm length	0.21 m	0.33 m
	Forearm perimeter	0.21 m	
	Side arm length	0.65 m	0.82 m
	Elbow width	0.055 m	0.074 m
	Elbow to elbow width	0.34 m	0.7 m
	Hand length	0.15 m	0.19 m
	Wrist width	0.045 m	0.06 m
	Hand width	0.069 m	0.091 m
	Joint and movement	**Approx. torque + standard deviation (N) in women**	**Approx. torque + standard deviation (N) in male**
Functional parameters	Shoulder adduction	28.4 ± 7.5	51.3 ± 17.7
	Shoulder flexion	30.4 ± 8.7	55.0 ± 17.6
	Shoulder extension	34.3 ± 11.2	73.5 ± 27.9
	Shoulder internal rotation	19.4 ± 4.6	41.1 ± 10.1
	Shoulder external rotation	20.7 ± 5.2	38.3 ± 9.1
	Elbow flexion	39.4 ± 7.7	70.9 ± 15.9
	Elbow extension	22.0 ± 4.7	44.3 ± 9.8
	Hand grip	250.4 ± 54.8	411.3 ± 73.5

device, type of chain and type of transmission) are based on the number of advantages versus the number of disadvantages. The other criteria are delimited specifications according to the application. First, for the type of device an exoskeleton is more appropriate, the most important reason is that the motion is applied directly at the joint and reduces the need to estimate positions and velocities. Second, for the type of chain is indifferent if design specifications and workspaces are retained. In our case, an open chain configuration was chosen because of the design complexity of the whole upper limb, and also, the selection of a closed chain limits the range of joint amplitude and singularities may appear (Romero-Acevedo et al., 2018; Guatibonza et al., 2018). Third, the type of transmission also depends on the application and the amount of stress that will be applied to the actuator and to the mechanical structure. In our case, the motion studies and the technical characteristics of the actuators define the necessary load to satisfy the requirement torque. Finally, the dimensional parameters define to a large extent the design specifications of the robotic system, since they are based on anthropometric studies of the target population. These dimensional criteria have maximum and minimum values that the robotic system must achieve. This is an aspect of adaptability and generalization within the framework of the target population. Similarly, the functional parameters define the specifications in terms of maximum torques and the need of transmission systems. Whether using them or not depends on the technical characteristics of the motors and the effort requirements.

In this work, the option of bilateral handling without the need to duplicate the robotic system for the opposite arm is proposed. This is possible through an arm switching configuration. This feature reduces costs and adds attributes in adaptability, especially if it is used in physical rehabilitation applications (HOCOMA, ; Wu et al., 2018).

3.2 Degrees of Freedom

Based on the mobility ranges defined in Table 1, the workspace of the entire upper limb is defined by identifying the maximum lenghts that the upper limb can achieve in the frontal, transverse and sagittal planes.

The design of the robotic system must then be adjusted to the defined workspace. The challenge now is to define a design that preserves spatial specifications, adaptability to people with different anthropometric proportions, collision avoidance with the robotic system and configuration for arm-switching. The following aspects play a very important role in the design to guarantee the working space: 1. Number of degrees of freedom, 2. Optimization of the space in the design constrained by the type of actuator used, and 3. The order in the location of each of the actuation axes. The validation of points 1 and 3 requires heuristic strategies that can be obtained by means of physical scale models or simulation models. In our case, we verified this strategy using both methods, focused mainly on the elbow joint, because it is a compound joint where several movements are generated on the same point (flexion-extension, adduction-abduction, flexion-horizontal extension, internal-external rotation and protraction-retraction (scapulohumeral)) (Keith L. Moore and Agur, 2013; Knudson, 2007).

The design of the system suggests a minimum of 6 degrees of freedom (DoF), since the exercise schemes defined in both diagnosis and rehabilitation of tendinopathies indicate not only the use of the elbow joint, but also the other joints of the upper limb. In our case, we consider the protraction-retraction movements as a complement of the flexion-extension horizontal shoulder movements to reach the full range of amplitude in the transverse plane. Consequently, the design is oriented to a redundant 7 DoF robotic system. The procedure is as follows: We start from a conceptual design where an initial order of the axes of actuation is defined. Subsequently, we transfer the concept to a physical scale model so that the options of the order and alignment of the axes with the shoulder can be visually analyzed. Finally, the configuration on the scale model suggests an organization of the axes of action as defined here: 1. protraction - retraction (scapulo-humeral), 2. flexion - horizontal extension (gleno-humeral), 3. flexion - extension (gleno-humeral), 4. adduction - abduction (gleno-humeral), 5. elbow flexion - extension, 6. wrist pronation - supination, and 7. wrist flexion - extension. With these configurations, a simple CAD model is constructed to confirm the range of the system in the previously described workspace.

In Fig. 2 a simple conceptual design of the 7 DoF system is shown in the limit positions of the workspace. The proposed configuration satisfies the workspace of the upper limb and no collisions are generated in maximum amplitudes of the movements such as abduction, extension and horizontal flexion of the shoulder.

3.3 Motion Analysis

The motion analysis allow to determine the maximum torque required for each joint. In shoulder joint, actuators must provide necessary torque to move both

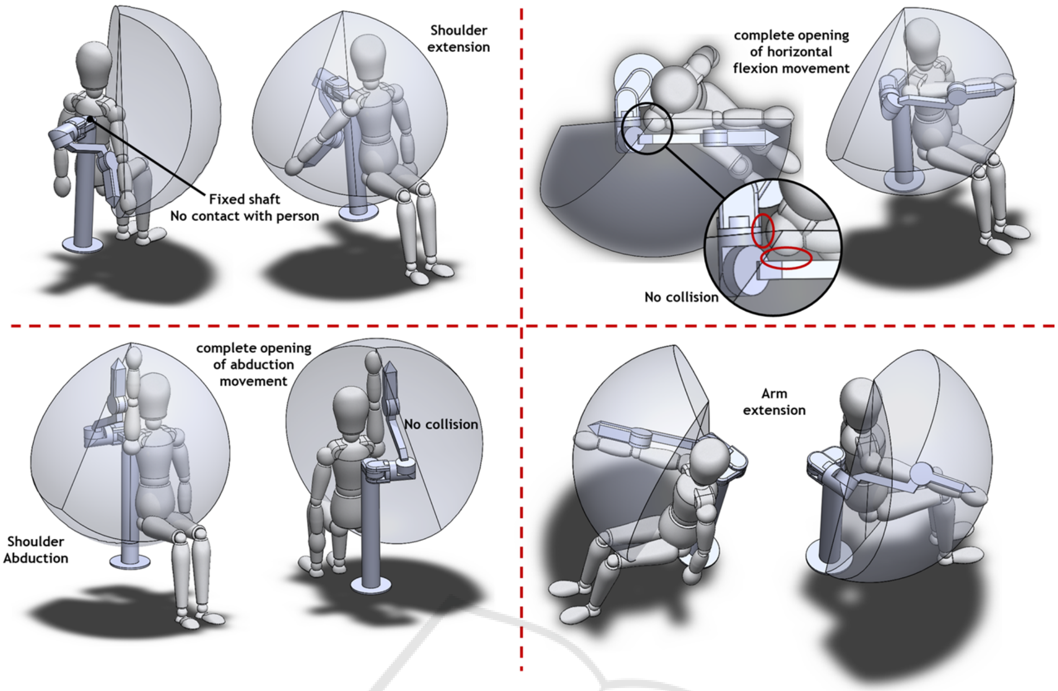
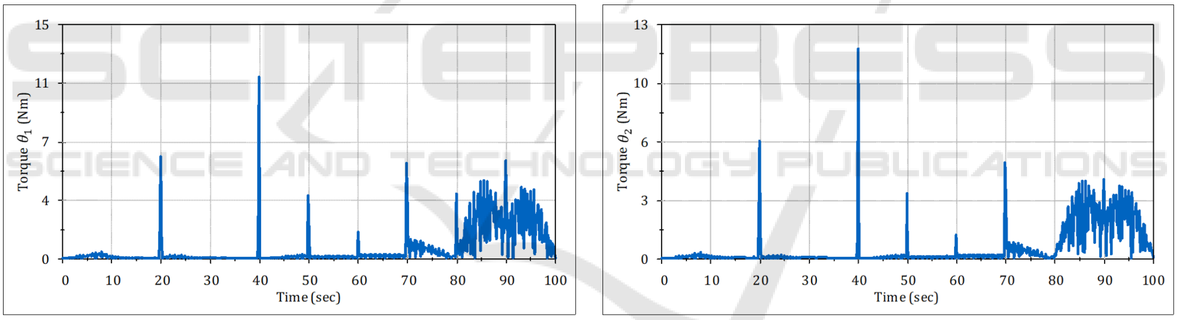
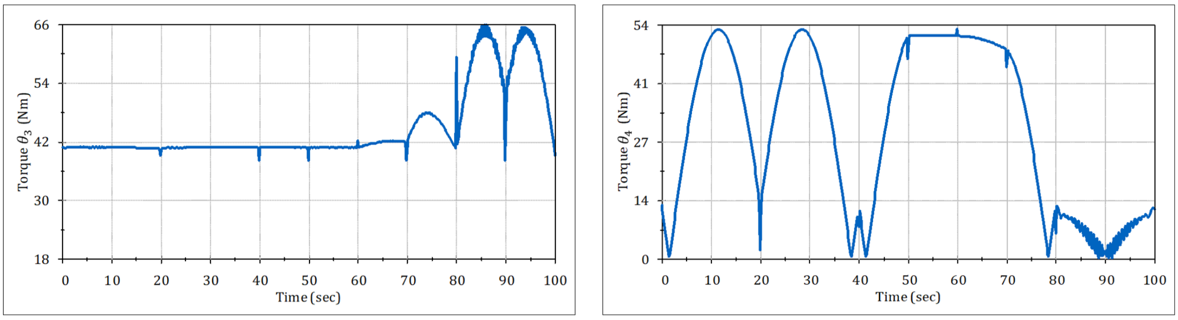


Figure 2: Composition of upper limb workspace based in AAOS.



(a) Torque acquisition from pronation-supination movements.

(b) Torque acquisition from horizontal flexion-extension movements



(c) Torque acquisition from flexion-extension movements

(d) Torque acquisition from abduction-adduction movements

Figure 3: Theoretical torques from motion analysis.

robotic and human arm. Therefore, an analysis is carried out to determine the last design criteria: choice of the actuator and type of transmission (elastic, rigid).

To perform the simulation, an initial weight is assigned to the links of the CAD model using an average weight per link of $1.5Kg$ taken from Table 2. The weights are then oversized by at least an additional 40 % or 50 %. Additionally, the weight of the human arm is incorporated taking as a reference the maximum dimensional parameters of Table 2. Flexion-extension, abduction-adduction and horizontal shoulder flexion-extension movements are considered for the simulation. From the motion studies an approximation of the maximum torques is obtained. These values are used as a reference for the choice of the actuators and dimensional design of the assistive robotic system. The results obtained are shown in Fig. 3a-3d

Notice that the θ_1 Protraction - retraction (scapulohumeral) and θ_2 Flexion - horizontal extension (glenohumeral) joints reach maximum values of $12Nm$. While θ_3 Flexion - extension (glenohumeral) and θ_4 Adduction - abduction (gleno-humeral) joints, the required torques reach values of $66Nm$ and $54Nm$, respectively. This implies that the actuators chosen must satisfy these torques or, alternatively, use torque multiplication drives if they are not commercially available.

The torques obtained are purely theoretical and will involve a reduction of the design dimensions of the robotic system to reduce the demand of the motors on the physical therapy routines, the weight of the patient's arm, and the weight of the robotic assistive system itself. With the results obtained from Figs. 3a-3d we analyzed commercial aspects of the actuators such as weight, continuous and maximum torques, controller card included, transmission box included and prices. Finally, we are using the RMD-X8 pro brushless actuators for their weight-quality-price ratio. The actuators will be for the shoulder and elbow joints, and following the same line the RMD L-5015 actuators are intended for the wrist joint. These actuators are equipped with a transmission box. However, the theoretical torque results obtained in Figs. 3a-3d suggest adding an additional transmission stage that can either be elastic or rigid. The choice does not imply any advantage or disadvantage of one over the other, as long as the same dimensional design conditions and torque multiplication factor are preserved. With these considerations, we proceed to the mechanical design of the upper limb assistive robotic system.

4 MECHANICAL DESIGN OF THE ROBOTIC ASSISTIVE SYSTEM

For the design of the assistive robotic system, we start by placing in the design software all the commercial components required. In the structural development of the arm, the actuators are the main components since from there, we start to design drawers, housings, supports, bases.

We start designing from the distal to the proximal part of the upper limb. The actuator is placed in the same orientation of the movement to be executed. Considering the design criteria in Table 2, we design the wrist joint starting with the grip, subsequently, the first joint movement (wrist flexion-extension), and then, the second joint movement (wrist pronation-supination). We implement handgrip adjustable to different hand sizes, using a manual gear. To perform the wrist flexion-extension movements, the axis of movement between the robotic system and the wrist are aligned.

Subsequently, the forearm section and the second wrist movement are designed. The forearm has two support points. One is located in the proximal part of the forearm, and the other in the distal part. The actuator for the wrist protraction-retraction movements is located on the distal part of the forearm. The designed system has a semicircular rail propelled by a belt. A carriage is connected to the rail, which slides and rotates concentrically with the midpoint of the semicircle of the rail. This connection aligns it with the axis of movement of wrist pronation-supination.

The proximal part of the forearm has two support rods for length adjustment. These rods work as a linear rail by means of a worm screw. This mechanism allows the operator to set up the length of the robotic forearm according to the length of the patient's forearm. Finally, a setup gear is designed to make the arm change. This allows the operator to rotate the forearm-wrist-grip complement in 180° around the elbow joint. This option is similar to the Hocoma's Armeo Power system (HOCOMA,), but it reduces weight and size, without decreasing robustness.

The next joint (elbow flexion-extension) is then designed. In the same way, the actuator is positioned to align the movement of the motor with the elbow. Next to the output shaft, the support is connected to other linear guide to correct the length of the robotic arm according to the length of the patient's arm. We then proceed to design the joints associated with the gleno-humeral shoulder joint (flexion-extension, horizontal flexion-extension and abduction-adduction). There are three actuators

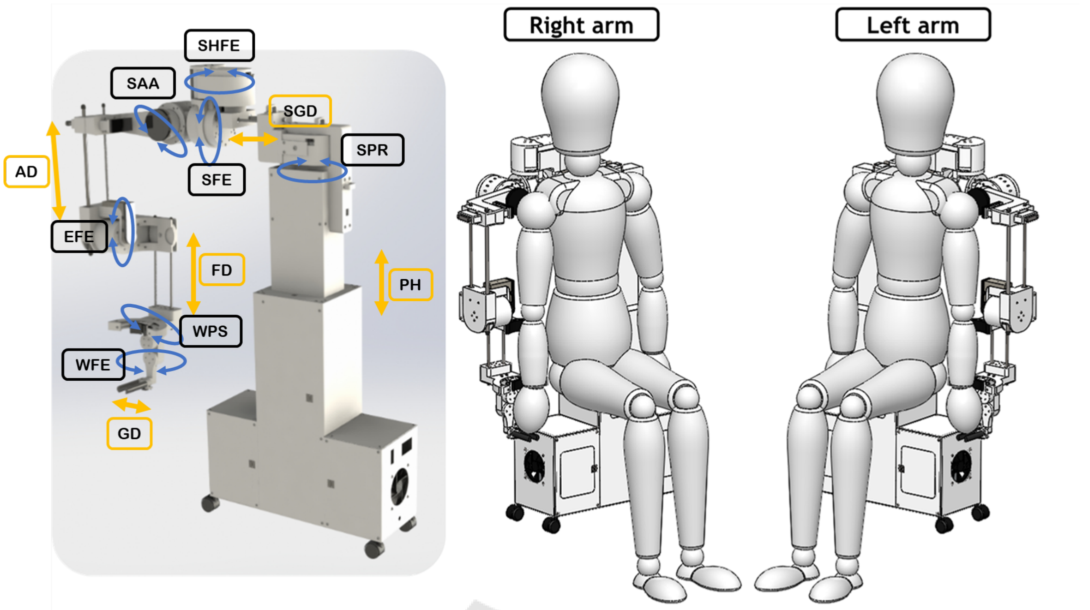


Figure 4: complete robotic assistive system design and arm switch configuration. SPR: shoulder protraction-retraction, SHFE: shoulder flexion-extension, SFE: shoulder flexion-extension, SAA: shoulder adduction-abduction, EFE: elbow flexion-extension, WPS: wrist pronation-supination, WFE: wrist flexion-extension, PH: patient height, SGD: scapulo-humeral to gleno-humeral distance, AD: arm distance, FD: forearm distance and GD: grip distance

share the same frontal plane, and a locking mechanism to execute the arm change configuration. This mechanism allows to release the shoulder arm on an axis to rotate it 180°. The actuators associated to the flexion-extension and abduction-adduction movements require planetary transmission. This is because with this configuration a higher torque multiplication factor is obtained than with a belt transmission (see the results in Figs. 3c and 3d). The planetary transmission has a 1:8 ratio, which means a significant increase of the joints torque. As it is a rigid transmission, helical gears are used to reduce noise compared to spur gears. On the other hand, the actuator that performs the horizontal flexion-extension movements does not require a substantial increase in torque. Therefore, a belt drive is enough, since this movement is performed in the horizontal plane, so gravity does not affect.

Finally, the shoulder motion in the scapulo-humeral part (pronation-supination) is an extension of the horizontal flexion-extension movements of the shoulder. So, in a similar way we have a belt transmission, which is enough because the movement is also performed in the horizontal plane. This joint is important as it supports the weight of the whole robotic arm and the human arm. A reinforcement support is directly connected to the main base of the assistive system. The base is composed of a structural system of beams in the shape of an inverted T where the robotic arm is housed in the upper part and this base functions as a rail to correct the alignment height with respect to the height of the patient. Rail guides are driven by linear bearings and the movement is driven by linear actuators. The electronics, power supplies, control systems and ventilation are located in the lower part, to give more stability and robustness to the base of the system. Finally, beaver-type wheels are included to move the robotic system as needed. We present the complete assistive robotic system in configuration for left arm and right arm, and a render in Fig. 4.

5 CONCLUSIONS

This paper presents the procedure for the mechanical design of a robotic assistive system for the rehabilitation of elbow tendinopathies. We present a series of guidelines for the design of this type of systems starting from an analysis of the physiological, biomechanical and technological components associated with the pathology, supported also by motion simulation studies where we consider joint mobility ranges. Subsequently, we identified some qualitative and quantitative design criteria that are of great importance in the design of systems for physical rehabilitation, and we determined the complete workspace of the upper limb, built the conceptual and mathematical models of the system. We consider practical aspects of performance selection, and in addition, we propose a never-before-seen arm switching configuration.

These criteria are a starting point in the systematization of the mechanical design processes of robotic systems for physical assistance or rehabilitation. Future work will be oriented to the construction of the robotic assistive system, and the improvement of the system as observed in practice.

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REFERENCES

U.s. national library of medicine. elbow injuries and disorders. https://medlineplus.gov/elbowinjuriesanddisorders.html. [Online; accessed March-2022].

ACP (1932). Physiotherapy: Its principles and practice. *Annals of Internal Medicine*, 6(2):298.

Avila-Chaurand, R., Prado-León, L., and González-Muñoz, E. (2007). *Dimensiones antropométricas de la población latinoamericana : México, Cuba, Colombia, Chile / R. Avila Chaurand, L.R. Prado León, E.L. González Muñoz.*

Ballantyne, R. and Rea, P. M. (2019). A game changer: 'the use of digital technologies in the management of upper limb rehabilitation'. In *Advances in Experimental Medicine and Biology*, pages 117–147. Springer International Publishing.

Bruder, A. M., Shields, N., Dodd, K. J., and Taylor, N. F. (2017). Prescribed exercise programs may not be effective in reducing impairments and improving activity during upper limb fracture rehabilitation: a systematic review. *Journal of Physiotherapy*, 63(4):205–220.

Chaurand, R. Á., León, L. R. P., and Muñoz, E. L. G. (2007). *Dimensiones antropométricas de población latinoamericana*. Universidad de Guadalajara, CUAAD.

Contributors (2003). Rehabilitation of the hand & upper limb. In Prosser, R. and Conolly, W. B., editors, *Rehabilitation of the Hand & Upper Limb*, pages vii – viii. Butterworth-Heinemann, Oxford.

Cortés Rojas, M. F. and Ramos Moreno, I. R. (2017). Revisión documental de los métodos diagnósticos y de tamizaje en desórdenes músculo esqueléticos en miembros superiores de etiología laboral. http://hdl.handle.net/10554/39988.

Costa, J. T. D., Baptista, J. S., and Vaz, M. (2015). Incidence and prevalence of upper-limb work related musculoskeletal disorders: A systematic review. *Work*, 51(4):635–644.

Cruz Martínez, G. M., Z-Avilés, L., et al. (2020). Design methodology for rehabilitation robots: Application in an exoskeleton for upper limb rehabilitation. *Applied Sciences*, 10(16):5459.

Dick, F. D., Graveling, R. A., Munro, W., and and, K. W.-B. (2010). Workplace management of upper limb disorders: a systematic review. *Occupational Medicine*, 61(1):19–25.

Fagher, K. and Lexell, J. (2014). Sports-related injuries in athletes with disabilities. *Scandinavian Journal of Medicine & Science in Sports*, 24(5):e320–e331.

Fierro, G. (2015). "anatomía del hombro," guido fierro ortopedia y traumatología - cirugía de hombro y codo. https://www.guidofierro.com/diagnostico-y-tratamiento.

Gates, D. H., Walters, L. S., Cowley, J., Wilken, J. M., and Resnik, L. (2015). Range of motion requirements for upper-limb activities of daily living. *American Journal of Occupational Therapy*, 70(1):7001350010p1.

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., Corner, B., Carson, J., Venezia, J. C., Rockwell, B. M., Mucher, M., and Kristensen, S. (1989). 2012 anthropometric survey of u.s. army personnel: Methods and summary statistics.

Grupo, d. t. d. o. d. c. o. d. B. (2011). Epicondilitis y epitrocleítis. revisión. *Farmacia Profesional*, 25(6):49–51.

Guatibonza, A. F., Solaque, L., and Velasco, A. (2018). Kinematic and dynamic modeling of a 5-bar assistive device for knee rehabilitation. In *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*. IEEE.

Henning, T. (2010). Clinical tests for the musculoskeletal system: Examinations-signs-phenomena. *JAMA*, 303(15):1541.

Hillman, S. K. (2012). Core concepts in athletic training and therapy with web resource. *Annals of Internal Medicine*.

HOCOMA (-). Hocoma products overview. Online, accessed August-2020.

Islam, M. R., Brahmi, B., Ahmed, T., Assad-Uz-Zaman, M., and Rahman, M. H. (2020). Exoskeletons in upper limb rehabilitation: A review to find key challenges to improve functionality. *Control Theory in Biomedical Engineering*, pages 235–265.

Jabeen, T., Kazmi, S., Rehman, A., and Ahmed, S. (2016). Upper and lower limbs disability and personality traits. *Journal of Ayub Medical College, Abbottabad: JAMC*, 28:348–52.

Keith L. Moore, A. F. D. and Agur, A. M. R. (2013). Moore, anatomía con orientación clínica. Wolters Kluwer Health, S.A., Lippincott Williams & Wilkins.

Kessler, H. H. (1950). The principles and practices of rehabilitation. *Physical Therapy*, 30(3):126–127.

Knudson, D. (2007). *Fundamentals of Biomechanics, Second edition*. Springer US.

Kumar, S., Wöhrle, H., Trampler, M., Simnofske, M., Peters, H., Mallwitz, M., Kirchner, E. A., and Kirchner, F. (2019). Modular design and decentralized control of the RECUPERA exoskeleton for stroke rehabilitation. *Applied Sciences (Switzerland)*, 9(4).

Lessard, S., Pansodtee, P., Robbins, A., Trombadore, J. M., Kurniawan, S., and Teodorescu, M. (2018). A Soft Exosuit for Flexible Upper-Extremity Rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(8):1604–1617.

Linda, N., Maia, M., Hennen, L., Wolbring, G., Bratan, T., Kukk, P., Cas, J., Capari, L., Krieger-Lamina, J., and Mordini, E. (2018). Assistive technologies for people with disabilities - part ii: Current and emerging technologies.

Liu, K., Xiong, C. H., He, L., Chen, W. B., and Huang, X. L. (2018). Postural synergy based design of exoskeleton robot replicating human arm reaching movements. *Robotics and Autonomous Systems*, 99:84–96.

McHugh, G., Swain, I. D., and Jenkinson, D. (2013). Treatment components for upper limb rehabilitation after stroke: a survey of UK national practice. *Disability and Rehabilitation*, 36(11):925–931.

Miao, Q., McDaid, A., Zhang, M., Kebria, P., and Li, H. (2018). A three-stage trajectory generation method for robot-assisted bilateral upper limb training with subject-specific adaptation. *Robotics and Autonomous Systems*, 105:38–46.

Miao, Q., Peng, Y., Liu, L., McDaid, A., and Zhang, M. (2020a). Subject-specific compliance control of an upper-limb bilateral robotic system. *Robotics and Autonomous Systems*, 126:103478.

Miao, Q., Zhang, M., McDaid, A., Peng, Y., and Xie, S. Q. (2020b). A robot-assisted bilateral upper limb training strategy with subject-specific workspace: A pilot study. *Robotics and Autonomous Systems*, 124:103334.

Milicin, C. and Sîrbu, E. (2018). A comparative study of rehabilitation therapy in traumatic upper limb peripheral nerve injuries. *NeuroRehabilitation*, 42(1):113–119.

Occhionero, V., Korpinen, L., and Gobba, F. (2014). Upper limb musculoskeletal disorders in healthcare personnel. *Ergonomics*, 57(8):1166–1191.

Olanrewaju, O. A., Faieza, A. A., and Syakirah, K. (2015). Application of robotics in medical fields: Rehabilitation and surgery. *Int. J. Comput. Appl. Technol.*, 52(4):251–256.

Palacios, J. R. (2015). Sistema locomotor extremidad superior. https://www.infermeravirtual.com/esp/actividades_de_la_vida_diaria/ficha/extremidad_superior/sistema_locomotor.

Ritchie, P. (2003). Sports injuries: Mechanisms, prevention, treatment. second edition. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 19(4):448.

Romero-Acevedo, M., Guatibonza, A., and Velasco-Vivas, A. (2018). Modular knee-rehabilitation device: Configuration and workspace of assisted physical therapy routines. In *2018 IEEE 2nd Colombian Conference on Robotics and Automation (CCRA)*. IEEE.

Ruiz, D. M. C. (2011). Epicondilitis lateral: conceptos de actualidad. revisión de tema. *Revista Med de la Facultad de Medicina*, 19(1):9.

Sanchez, D. M. Epicondylitis, arthroscopic surgery unit. https://www.ucaorthopedics.com/patologias/codo/epicondilitis/. [Online; accessed March-2022].

Sheng, B., Xie, S., Tang, L., Deng, C., and Zhang, Y. (2019). An Industrial Robot-Based Rehabilitation System for Bilateral Exercises. *IEEE Access*, 7:151282–151294.

SportMe. “las tendinitis del codo. epicondilitis y epitrocleitis” medical center sportme. https://clinicabernaldez.com/tendinitis-del-codo-dolor-de-codo-epicondilitis-epitrocleitis/. [Online; accessed March-2020].

Sun, J., Shen, Y., and Rosen, J. (2021). Sensor reduction, estimation, and control of an upper-limb exoskeleton. *IEEE Robotics and Automation Letters*, 6(2):1012–1019.

Taboadela, C. H. (2007). Goniometria una herramienta para la evaluacion de las incapacidades. *Medicine. ASOCIART SA ART*, pages 1–130.

Ugurlu, B., Nishimura, M., Hyodo, K., Kawanishi, M., and Narikiyo, T. (2015). Proof of Concept for Robot-Aided Upper Limb Rehabilitation Using Disturbance Observers. *IEEE Transactions on Human-Machine Systems*, 45(1):110–118.

Vulliet, P., Chervin, J., Pierrart, J., Bourdillon, E., and Masmejean, E. (2017). Patologías del codo y rehabilitación. *EMC - Kinesiterapia - Medicina Física*, 38(2):1 – 18.

Wattchow, K. A., McDonnell, M. N., and Hillier, S. L. (2018). Rehabilitation interventions for upper limb function in the first four weeks following stroke: A systematic review and meta-analysis of the evidence. *Archives of Physical Medicine and Rehabilitation*, 99(2):367–382.

WHO (2011). World report on disability. Technical report, World Health Organization.

Wu, W., Fong, J., Crocher, V., Lee, P. V., Oetomo, D., Tan, Y., and Ackland, D. C. (2018). Modulation of shoulder muscle and joint function using a powered upper-limb exoskeleton. *Journal of Biomechanics*, 72:7–16.

Zhang, L., Guo, S., and Sun, Q. (2020). Development and assist-as-needed control of an end-effector upper limb rehabilitation robot. *Applied Sciences*, 10(19):6684.

Zimmermann, Y., Forino, A., Riener, R., and Hutter, M. (2019). ANYexo: A Versatile and Dynamic Upper-Limb Rehabilitation Robot. *IEEE Robotics and Automation Letters*, 4(4):3649–3656.