www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

TWO-DEGREE ADJUSTABLE EXOSKELETON FOR ASSISTANCE OF THE HUMAN ARM USING A MECHANICAL SYSTEM OF FAST ASSEMBLY AND UPGRADABILITY

Julio Restrepo-Zapata[1], Carlos Gallego-Duque[2], David Marquez-Viloria[3], Juan Botero-Valencia[4]
[1,3,4]Instituto Tecnológico Metropolitano, [2]Universidad Autónoma Latinoamericana,
{[1]juliorestrepo, [3]davidmarquez, [4]juanbotero}@itm.edu.co,
[2]carlosjulian.gallego@unaula.edu.co

Submitted: May 21, 2017 *Accepted: July 17, 2017* *Published: Sep. 1, 2017*

Abstract- Stroke affects about 975,000 people annually. Currently different robotic systems are used, such as exoskeletons that support motor rehabilitation, where they sometimes increase the patient's possible recovery rate. But these systems are expensive and often require adequate locations for therapy routines. This article offers the mechanical design of an exoskeleton concept for human upper limbs that allows the attachment to the arm and forearm, offering protection, torque, and movement, plus the possibility to adapt to different arm sizes. The biomechanics of the human arm, the kinematics required by the exoskeleton, different design criteria for this type of system, the CAD model, and the simulation of a robotic exoskeleton with an active and passive degree of freedom are considered. As a main result, the exoskeleton includes the biomechanics of the human arm so that its kinematics allow for adequate human arm movements for providing mechanical assistance, data acquisition and analysis, but also safety.

Index terms: Active orthosis, Exoskeleton, Interactive adaptation, Wearable-robot

I INTRODUCTION

As indicated by [1] stroke affects 795,000 people annually. In general, these patients are left with injuries and motor impairments, such as hemiplegia and residual hemiparesis, which drastically reduces the quality of life of the affected individuals, as well as affecting their respective families. Usually, these people require rehabilitation processes that can last for most of their lives, where the patient must travel to a specialized place with professionals in the area, which generates high costs. At present, for this rehabilitation process robotic exoskeletons are used, which in turn allow increasing the possible percentage of recovery and facilitate the process of the therapies [2]. Studies have been carried out, such as [3, 4, 5, 6, 7, 8] who offer exoskeletons for rehabilitation assistance, but their non-mobile system, price or operational complexity prevents them from being easily used by patients without professional staff, nor can they use it without going to a specialized place. It is necessary to improve the rehabilitation assistance so that the exoskeletons used in this application area, are easy to use, inexpensive and meet design criteria that also allow easy maintenance and repair, as well as portability. This article offers a concept of a low-cost anthropomorphic system with adaptability as an exoskeleton for the human arm and forearm, with variable size. It presents a system of two degrees of freedom, one active and one passive; the first assists the movement of the elbow and the second mechanically attaches to the forearm without impeding or restricting the movement of pronation and supination. There are different mechanisms used for exoskeletons of the arm and forearm, always looking for that it is suitable for the application and meets the requirements of the connection including the kinetics of the human arm. So, it is in the case of [9], where its exoskeleton 5 DOF is attached to the arm and forearm, using a hinge-like articular system looking for movements in parallel with the exoskeleton. Similar to [10] who use in their investigation a non-portable exoskeleton for the analysis of electromyographic signals during the performance of muscular resistance exercises exerted by the exoskeleton. Different from the previous ones, [11] uses linear actuators for the different movements of the shoulder, having these located in the section of the back and a connection to the arm. Also [12] presents an exoskeleton used in rehabilitation, but this uses rotational actuators in the shoulder section. Its mechanism is attached to the arm and forearm, but is manipulated from the user's hand, where it has a grip section and allows support in rehabilitation. The electromechanical system of [13] is guided by Bowden cables on a non-movable platform which also requires a holding in the hand to be directed. For the rehabilitation of the hand, similar to [14] who use an exoskeleton that uses Bowden cables for the stabilization of the human arm when it operates firearms, [15] use a non-portable exoskeleton that is directed by the user and used in therapies with virtual environments.

Considering the electromechanical system systematically as an analogy of the human body, an exoskeleton can be divided into three sections. Bones, which mechanically support the body can be compared with mechanical components, thus allowing a section of the exoskeleton to be denoted as the support of the same. Tendons and joints can be compared to the joints of the electromechanical system and the coupling of energy transmission between one link and another. In addition, actuators, such as the muscular system, in the exoskeleton these can be reconfigurable, adaptable to a new design; External parts can be added, with quick coupling, without the need for a generic system. In such a way, this one receives improvements easily, allows easy intervention of maintenance, tolerates changes in the system of contribution of mechanical energy and is easy to assemble and disassemble. Thus, an integral system that provides adequate information for control is achieved. Either solely as an anthropomorphic system or used as a garment, as well as an exoskeleton, for the control of an external system, of the same, or only for the acquisition of biomechanical information, as the authors have proposed in previous works [16, 17].

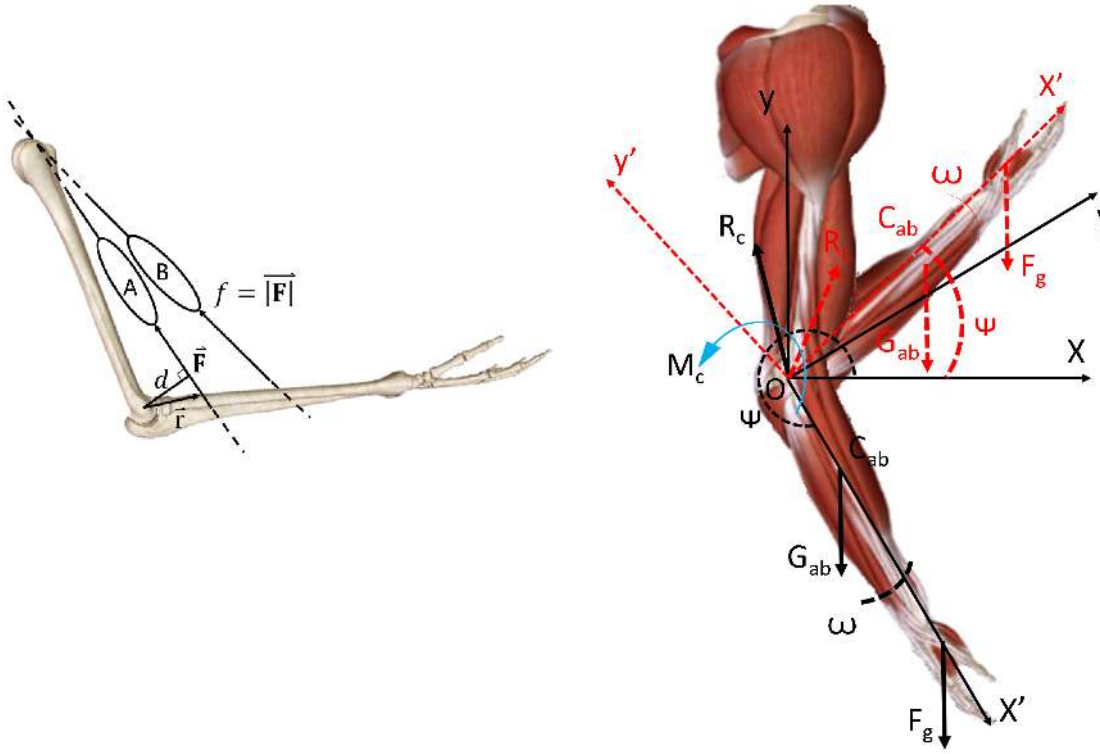
II PRELIMINARY CONSIDERATIONS

a Human arm movement

The study of forces generated due to muscle contraction is presented in the review of [18] who evaluate the strength-length relationship of the muscle, including the force generated by a single fiber, where long-lasting forces are observed. Also, as the authors indicate, the forces exerted by the muscles create a moment around the joint, where the force-length relationship is a static property of the skeletal muscle. To evaluate the potential of a muscle to generate motion, [18] indicates two factors to consider illustrated in Figure 1 a, in such a way that the moment in any mechanical system, the moment of the arm, is given by: ($\vec{M}_j = \vec{r} X \vec{F}$) where $\vec{r}$ is a vector that determines the distance from the center of the joint to any point on the line of action of the muscular force and $\vec{F}$ is the muscular force. Although the muscles A and B are identical, the latter has greater torque due to its position with respect to the forearm. [19] offers a mathematical function of the rotation efficiency, based on the geometric relation of the muscular connections for three rotations of the human arm, from a biomechanical model, where they show the variation of this function throughout the pronation movement. They also evidence that "pronation efficiency derives from a greater radius of curvature of the axis, a large medial epicondyle of the humerus and a round tester closer to radial fixation".

For the analysis of forearm rotation for pronation and supination, [20] provide a biomechanical model and 3D imaging techniques that observe strength components and extension and flexion ranges using bone rests. [21] evaluate maximal torsional stresses for the right forearm with respect to pronation and supination, where each muscle has a unique function with respect to the articular movement, where the flexor muscles contract and pull the bone, causing flexion in the joint, in comparison to the extensors, which extend and straighten the joint.

Then, for the dynamic model, [22] determined the resulting moment in the elbow joint through the model present in the equation 1, where the forearm motion is expressed and the authors compare it with a mobile reference system. Their model is presented in Figure 1 b, then, thanks to the respective considerations offered by the authors, the equation 2 of [22] indicates the resulting torque of the elbow. Similarly, in [23] optimized design parameters of an exoskeleton of the upper limbs in their research, seeking to obtain a correct biomechanical simulation, where they use a dynamic model, looking for their exoskeleton to assist the user when he holds something in his hands.



(a) (b)

Figure 1: (a) Image based in [18]. The moment of the arm due to the muscle, and the trajectory of it, determine the moment $\vec{M}_j$ of the joint due to the muscular contraction. (b) Image based in [22]. The torque of the joint depends on the size of the individual and the conditions of the load attached to the body.

$$\begin{cases} -m_{ab}y'_{C_{ab}}\dot{\omega}\bar{i}' + m_{ab}x'_{C_{ab}}\dot{\omega}\bar{j}' + \begin{vmatrix} \bar{i}' & \bar{j}' & \bar{k}' \\ 0 & 0 & \omega \\ -m_{ab}y'_{C_{ab}}\omega & m_{ab}x'_{C_{ab}}\omega & 0 \end{vmatrix} = \\ G'_{ab_x}\bar{i}' + G'_{ab_y}\bar{j}' + G'_x\bar{i}' + G'_y\bar{j}' + F'_{eb_x}\bar{i}' + F'_{eb_y}\bar{j}' + R'_{ab_x}\bar{i}' + R'_{ab_y}\bar{j}', \\ \\ -\dot{\omega}I'_{xz}\bar{i}' - \dot{\omega}I'_{yz}\bar{j}' + \dot{\omega}I'_{zz}\bar{k}' + \begin{vmatrix} \bar{i}' & \bar{j}' & \bar{k}' \\ 0 & 0 & \omega \\ -\dot{\omega}I'_{xz} & -\dot{\omega}I'_{yz} & -\dot{\omega}I'_{zz} \end{vmatrix} = \\ M_f\bar{k}' + M'_Q(F_{eb})\bar{k}' + M'_Q(G_{ab})\bar{k}' + M'_Q(G)\bar{k}' \end{cases} \tag{1}$$

$$\Im(R_c) = \begin{cases} R_c = \sqrt{R_c^2} \\ M_c = I'\dot{\omega} + cos\varphi(L_{C_{ab}}G_{ab}L_{ab}F_g) \end{cases} \tag{2}$$

b Kinematics of the human arm

The presented kinematic model of the human arm in figure 2 considers each joint only as rotational, where 7 degrees of freedom similar to [24] are used. For this, Table 1 shows the parameters Denavit Hartenberg.

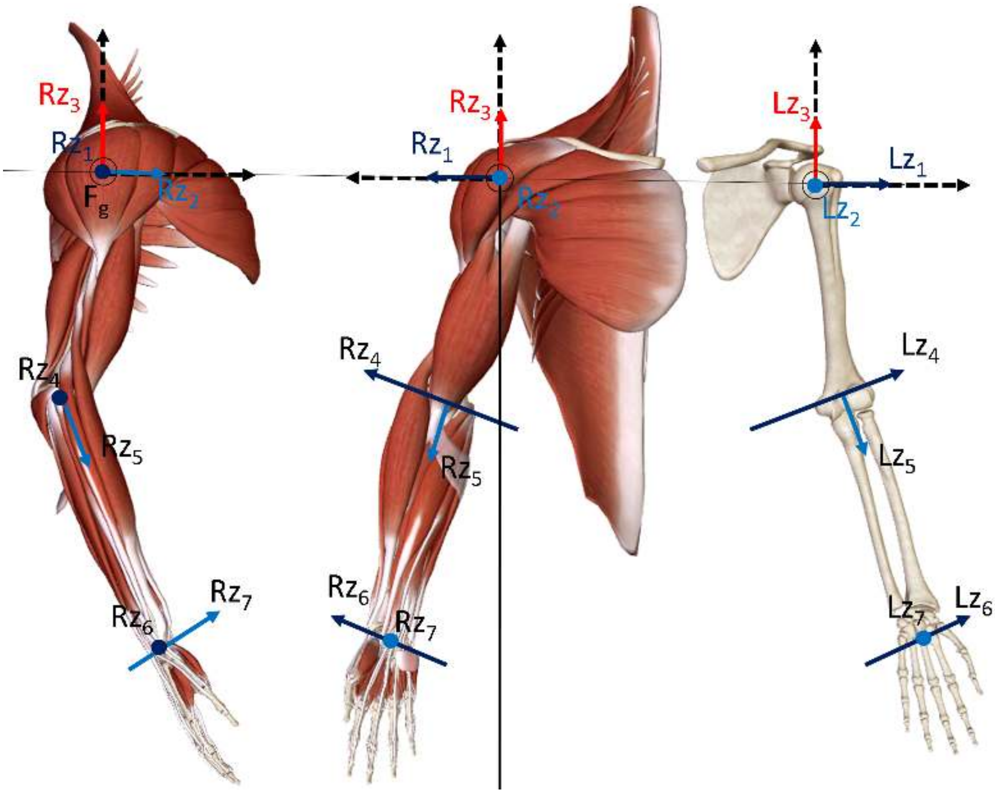


Figure 2: Illustrations generated in [25]. The kinematics of the human arm can be represented by considering only the rotational movements (the elasticity of the joint is neglected, since it can be considered 0) [24].

For figure 2 and table 1 we have the following representation, where the kinematic model of the human arm is given by $T_0^7 = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4 \cdot T_4^5 \cdot T_5^6 \cdot T_6^7$ where T_0^7 represents the position and final orientation of the arm.

Joint	b_i	θ_i	a_i	α_i
1	0	θ_1	0	90
2	0	θ_2	0	90
3	0	θ_3	0	90
4	b_4	θ_4	0	90
5	0	θ_5	0	90
6	b_6	θ_6	0	-90
7	0	θ_7	0	90

Table 1: DH parameters of the human arm.

III MATERIALS AND METHODS

a Design Criteria

An anthropomorphic electromechanical system with adaptive capacity as exoskeleton for the upper limbs is required. It has a degree of freedom similar to flexion and extension of the arm relative to the elbow and one similar to pronation and supination, in such a way that the first degree of freedom offers mechanical energy to the system in assisting the movement or contributing to the torque, while the second allows for the proper coupling to the forearm ensuring the centered fastening of the exoskeleton. It is also necessary to include a safety system to protect the elbow without affecting the range of motion. The mechanical system must have the proper weight, easy assembly, easy replacement of parts and maintenance. The mechanical system must be able to adjust its size and be portable. The Exoskeleton should provide relevant information for the biomechanical analysis and control of the system for the contribution of movement or torque.

b Description of the electromechanical system

The electromechanical system of the exoskeleton was built under the concept of similarity to the human body, where it was divided into three sections. The first is similar to the bone system, which is the largest section of the system. It is composed of fifteen pieces presented in Figure 3. This section has the possibility of adapting to different sizes, as well as easy assembly to replace parts, easy maintenance and modification of the mechanical system, which allows easy adaptation under different configurations.

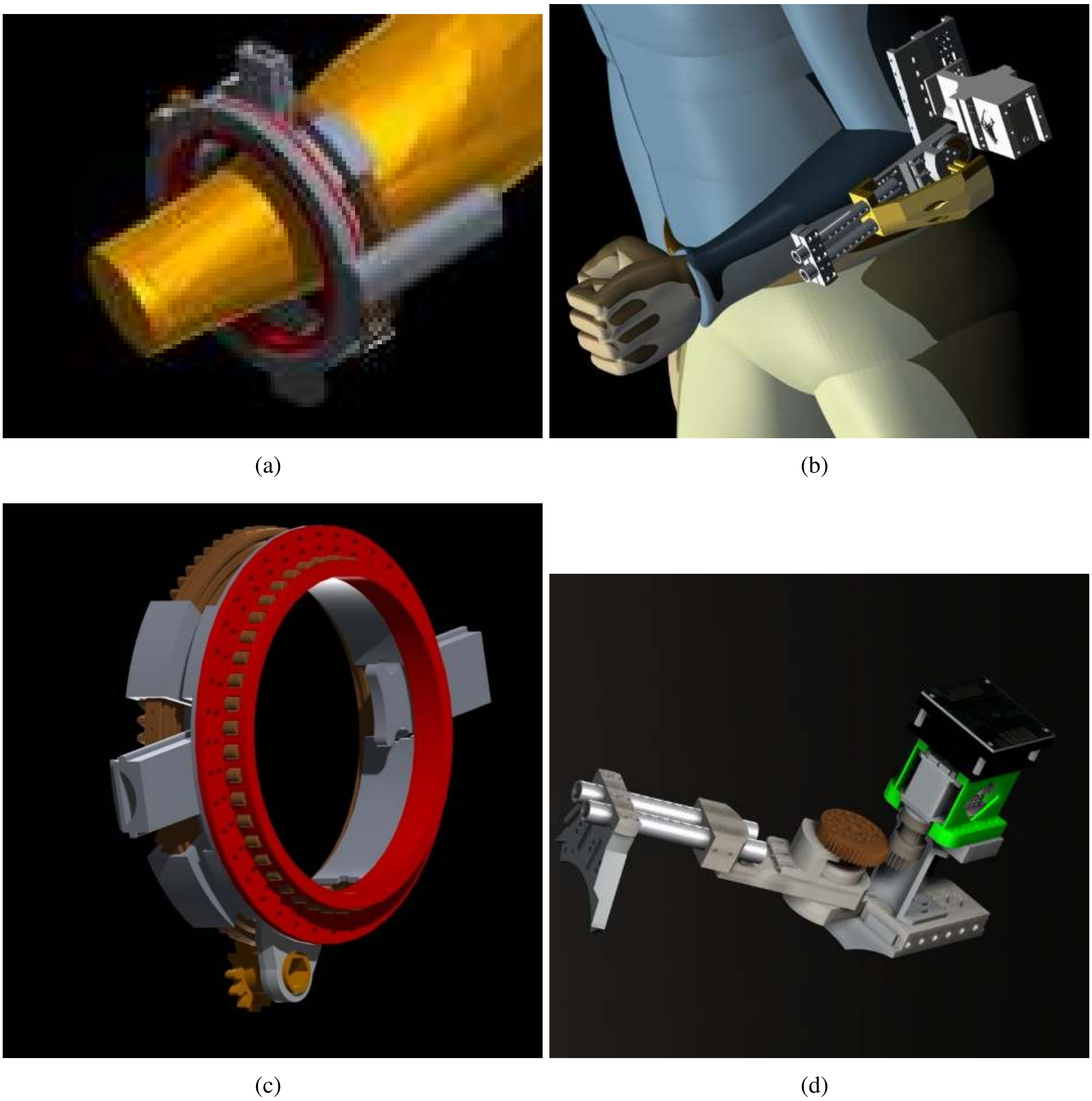


Figure 3: (a) and (b) contain the size adjustment mechanism for fastening the forearm. It consists of three sub sections (Rolling bearing that allows pronation and supination, support of the mechanism, and an adjustment system based on linear movement with a base fixed on a spiral structure). (c) and (d) present the complete electromechanical system. Its parts are presented in detail in Table 2.

For the section similar to the muscular system, the embedded servomotor and the articulation, assembly and bearing parts, as well as gears that allow movement between the arm and the forearm, are used. Driven gear in phosphor bronze and a 12L14 steel conductor are used. The driven gear only has its serrated section at 154 degrees, which allows that in case of failure the system only moves in the range of the motion of the elbow.

The second joint ensures that the user's forearm remains centered regardless of its dimensions, allowing adequate calculations and easy coupling. In conjunction with the main section, it allows the system to be adapted to the user's arm without affecting its range of motion. In total, 64 screws m3, 21 screw m2.5 and 35 m2 are used. The other pieces and their quantities are shown in Table 2. The third section is the one that allows the connection with the user. For this case it contains hypoallergenic material and elastic fiber with strap fastening, too. The protection of the servomotor and the forearm attachment were built in ABS with a 3D printer and the other parts were made of standard aluminum. A generic rolling bearing with an outer diameter of 30 mm and an inner of 9.5 mm was used.

b.1 Servomotor

The electromechanical system has a digital servo motor (MX 64) of high resolution (0.088) and low cost. Its Stall Torque is 7.3 Nm. It contains embedded an M3 cuts processor of 72 MHZ, transmission ratio 200 1 and a chassis in aluminum with the capacity of internal temperature, Torque, position and speed measurement. Its performances are suitable for the use in exoskeletons [26].

b.2 Safety

In portable robotics it is necessary to ensure that the wearer is not damaged or injured due to the electromechanical system. For this, it is necessary to consider different mechanical, electrical or electronic safety systems and in control even though these may be redundant. In the case of the proposed exoskeleton, it is known that its stall torque is 7.3Nm and that it has for its angular displacement 360 degrees - higher than the range of the human elbow movement. For this reason, it is necessary to ensure that the system does not affect this articulation; so it is considered, both mechanically and on the software level, the mechanical regulation of the range of motion, achieving similarity with the kinetics of the human elbow. For the arm and forearm, the passive articulation does not contain the same drawback. It also allows full movement for pronation and supination.

	List of parts		
	part	**volume** mm^3	**quantity**
arm	coupling	89328.1	1
	bone arm 1	44796.9	1
	bone arm 2	25115.4	1
	servomotor holder	46080.2	1
	axes aligner	30991.8	1
	servomotor protection	46080.2	1
	separators	266.306	1
	electronic coupling	311.773	1
	power shield	51612.0	1
	embedded system	13132.8	1
	feeding system	25950.96	1
	main gear	9194.82	1
	gear holder	9157.69	1
forearm	bone forearm 1	32156.9	1
	prismatic guide support	20812.8	1
	diameter forearm tube 15 mm	10142.2	2
	holder of the pronator	5326.9	1
	holder of the rod pronator	39478.2	1
	pronator bearing	93131.2	1
	forearm support	9990.0	4
	adjustment system for the forearm	46848.4	1
	forearm holder	9980.2	2
elbow	bearing	5669.79	1
	dent gear	6047.54	1
	rotation axis	4757.43	1
	gear support	12831.5	1
	gear only in 154	13635.3	1
actuator	digital servomotor MX 64	60612.4	1
fabric	hypoallergenic fabric		1
fixing to the arm	fabric straps		2
nuts and bolts	M3		64
	M2.5		25
	M2		21
Total		985572,836	35

Table 2: List of exoskeleton parts

IV RESULTS

a Electromechanical exoskeleton system

a.1 Exoskeleton kinematics

The exoskeleton must have the ability of elbow movement. For this reason, both in its mechanical components and at the programming level, using the Denavit-Hartenberg standard the kinetics of the system is described under the parameters of Table 3. Then, equation 3 describes the movement of the exoskeleton elbow, in a range of 0 to 154 degrees. Equation 4 contains the behavior of the forearm relative to the elbow. To this section, being a passive articulation, it was not necessary to apply a movement limiter to protect the forearm, where T = t1 t2.

	d	θ	a	α
1	0	θ_1	0	0
2	k	θ_2	0	90

Table 3: DH parameters

$$T1 = \begin{Bmatrix} Cos\theta_1 & -Sen\theta_1 & 0 & 0 \\ Sen\theta_1 & Cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{Bmatrix} \quad (3)$$

$$T2 = \begin{Bmatrix} Cos\theta_2 & 0 & Sen\theta_2 & 0 \\ Sen\theta_2 & 0 & -Cos\theta_2 & 0 \\ 0 & 1 & 0 & k \\ 0 & 0 & 0 & 1 \end{Bmatrix} \quad (4)$$

a.2 Connection with the user

It is necessary that the exoskeleton is properly coupled with the user, in such a way as to ensure an adequate biomechanical analysis, in addition to allowing the correct support in assistance or control. Therefore a connection using hypoallergenic material used in commercial orthoses is used on the arm, avoiding allergic reactions and displacement of the system when different actions are performed. But the material has the necessary flexibility to not affect volume changes during flexion and extension of the arm. It is also used as support for fixing the exoskeleton to the body. An arrangement of flexible belts for the torso ensures that the system remains in its location even in the case of strong movements. The attachment system for the body can be seen in Figure

4, where the exoskeleton base piece to which the system is coupled in the arm section is also shown. In figure 6 in section a, b and in figure 5 the clamping mechanism is shown with the forearm, thus guaranteeing the same distance of the articulation of the pronation and supination movements, letting the user's hand free and furthermore the mechanism has the possibility of adding mechanisms.

Figure 4: Attachment system to fix the exoskeleton to the body of the user.

The coupling to the forearm is constructed entirely of thermoplastic material, to facilitate its construction and reduce costs. But this system can also be built with standard metals that allow greater mechanical persistence, but sacrificing the low weight of this section. It has a main support section responsible for supporting all the structural section, coupled in the back section to a set of parts that function as a bearing, achieving the movement of pronation and supination, in addition to supporting different loads that are transmitted by the arm of the user. The front section has the fixation system for the forearm, which is based on the conversion of a spiral movement to a linear movement, allowing a concentric fixation.

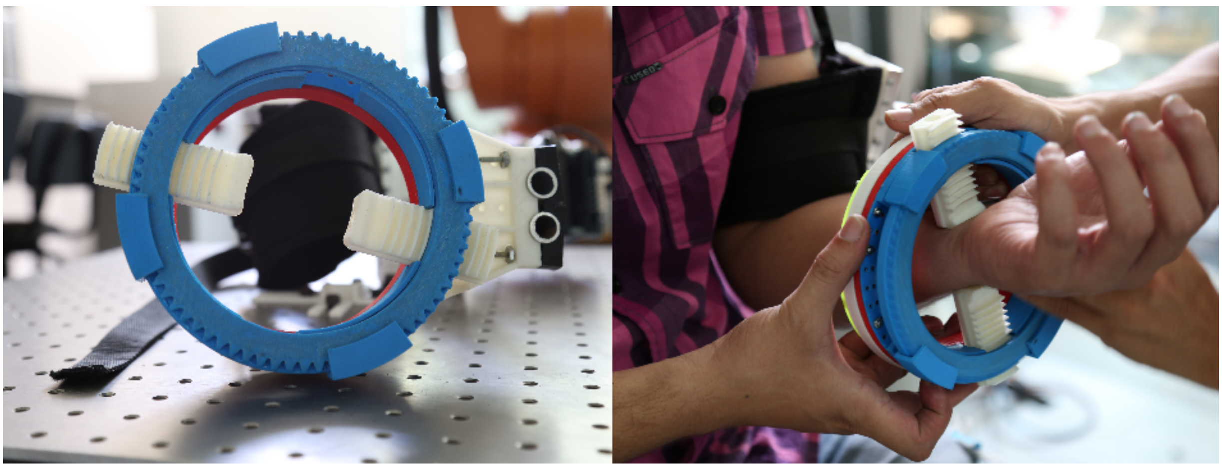


Figure 5: Attachment system to fix the exoskeleton to the user's body.

b Two degrees of freedom exoskeleton

The figure 6 shows the finished exoskeleton and its attachment to the human arm, its aligned axes have a size range of 100 mm to 210 mm allowing adjustment to different sizes of human arm.

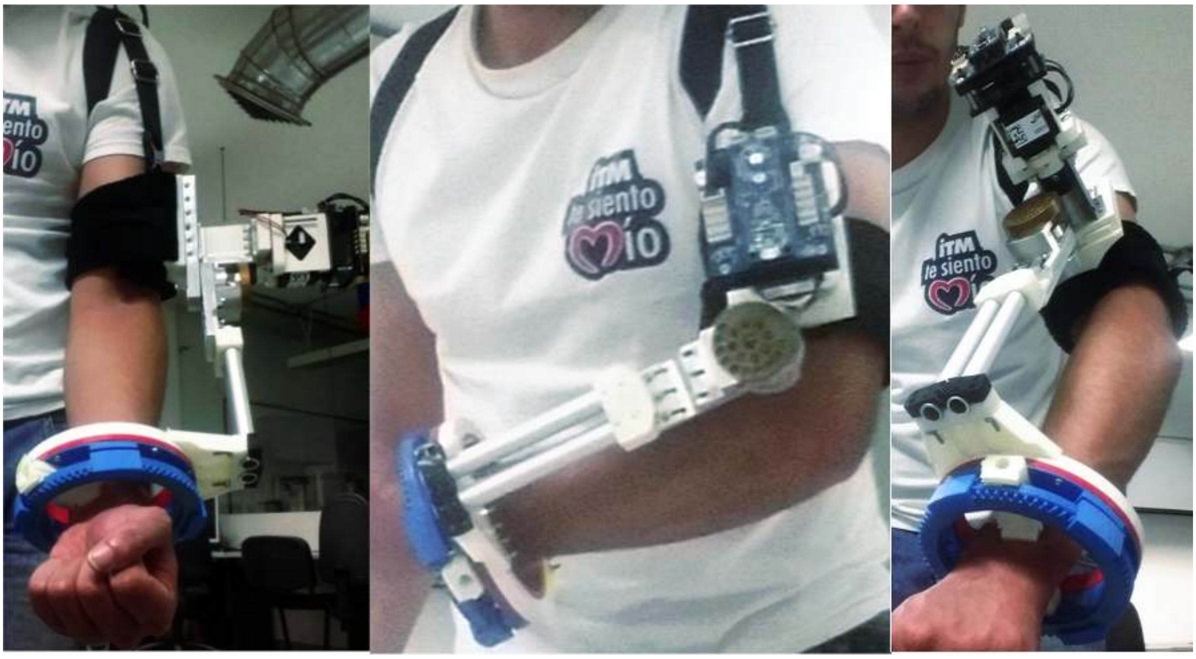


Figure 6: Exoskeleton of two degrees of freedom complete with modular electromechanical system that allows ease of assembly and adaptation of new or external parts, with a digital servomotor, useful for rehabilitation assistance.

V CONCLUSIONS AND FUTURE WORK

The electromechanical system of our modular exoskeleton allows easy maintenance and repair, and also offers connections for the rapid addition of new parts or the change of the current ones, under a sub-assembly concept that achieves a structurally robust mechanical section and allows changes, without affecting the application of the system. Thus taking into account the connection with the user, since it is of great importance to guarantee the reliability of the biometric information that the system requires. The digital actuator offers assistance to the individual, but restricts the speed of this, if only biomechanical signals are acquired, and also the need for the user to overcome the force required for the movement of the actuator. It is used for the arm and forearm, where for security reasons the movement of the elbow is restricted to the range of the natural operation, both mechanically and in control. For the support of the forearm, the movement is not restricted because the joint is passive so only the user is the one who generates the movement and torque. The range of adjustment for different arm sizes does not affect biomechanical analysis since the connection to the forearm is concentric.

VI ACKNOWLEDGEMENTS

This work is part of the project ”Desarrollo de un sistema electromecánico de un grado de libertad acoplable al brazo con capacidad de medición angular para aplicaciones biomédicas” with the code P16102, from the group Automática, Electrónica y Ciencias Computacionales COL0053581 from the Instituto Tecnológico Metropolitano and cofinanced by the Universidad Autónoma Latinoamericana.

REFERENCES

[1] American Heart Association, Heart Disease and Stroke Statistics (2017).
URL https://www.heart.org/idc/groups/ahamah-public/@wcm/@sop/@smd/documents/downloadable/ucm{_}491265.pdf

[2] N. Jarrasse, T. Proietti, V. Crocher, J. Robertson, A. Sahbani, G. Morel, A. Roby-Brami, Robotic Exoskeletons: A Perspective for the Rehabilitation of Arm Coordination in Stroke Patients, Frontiers in Human Neuroscience 8 (December) (2014) 1–13. doi:10.3389/fnhum.2014.00947.
URL http://www.frontiersin.org/Human{_}Neuroscience/10.3389/fnhum.2014.00947/abstract

[3] A. Frisoli, C. Procopio, C. Chisari, I. Creatini, L. Bonfiglio, M. Bergamasco, B. Rossi, M. Carboncini, Positive effects of robotic exoskeleton training of upper limb reaching movements after stroke, Journal of NeuroEngineering and Rehabilitation 9 (1) (2012) 36. doi:10.1186/1743-0003-9-36.

[4] S. Guo, F. Zhang, F. Z. Shuxiang Guo2, 3, W. Wei, F. Zhao, Y. Wang, Kinematic Analysis of a Novel Exoskeleton Finger Rehabilitation Robot for Stroke Patients, Proceedings of 2014 IEEE International Conference on Mechatronics and Automation (2014) 924–929doi:10.1109/ICMA.2014.6885821.

[5] M. Zhang, B. Lange, C. Y. Chang, A. a. Sawchuk, A. a. Rizzo, Beyond the standard clinical rating scales: Fine-grained assessment of post-stroke motor functionality using wearable inertial sensors, Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS (2012) 6111–6115doi:10.1109/EMBC.2012.6347388.

[6] M. A. Fikri, S. C. Abdullah, M. H. M. Ramli, Arm Exoskeleton for Rehabilitation Following Stroke by Learning Algorithm Prediction, Procedia Computer Science 42 (2014) 357–364. doi:10.1016/j.procs.2014.11.074.
URL http://linkinghub.elsevier.com/retrieve/pii/S1877050914015129

[7] Y. Ren, H. S. Park, L. Q. Zhang, Developing a whole-arm exoskeleton robot with hand opening and closing mechanism for upper limb stroke rehabilitation, 2009 IEEE International Conference on Rehabilitation Robotics, ICORR 2009 (2009) 761–765doi:10.1109/ICORR.2009.5209482.

[8] a. Frisoli, E. Sotgiu, C. Procopio, M. Bergamasco, B. Rossi, C. Chisari, Design and implementation of a training strategy in chronic stroke with an arm robotic exoskeleton, IEEE ... International Conference on Rehabilitation Robotics : [proceedings] 2011 (2011) 5975512. doi:10.1109/icorr.2011.5975512.
URL http://ieeexplore.ieee.org/ielx5/5961155/5975334/05975512.pdf?tp={&}arnumber=5975512{&}isnumber=5975334

[9] L. Zhou, Y. Li, S. Bai, A human-centered design optimization approach for robotic exoskeletons through biomechanical simulation, Robotics and Autonomous Systems 91 (2017) 337–347. doi:10.1016/j.robot.2016.12.012.
URL http://dx.doi.org/10.1016/j.robot.2016.12.012

[10] T.-M. Wu, C.-H. Yang, D.-Z. Chen, Muscle activation levels during upper limb exercise performed using dumbbells and a spring-loaded exoskeleton, Journal of Medical and Biological Engineering 37 (3) (2017) 345–356. doi:10.1007/s40846-017-0226-4.
URL https://doi.org/10.1007/s40846-017-0226-4

[11] J. Hunt, H. Lee, P. Artemiadis, A Novel Shoulder Exoskeleton Robot Using Parallel Actuation and a Passive Slip Interface, Journal of Mechanisms and Robotics 9 (1) (2016) 011002. doi:10.1115/1.4035087.
URL http://mechanismsrobotics.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4035087

[12] L. LIU, Y.-Y. SHI, L. XIE, a Novel Multi-Dof Exoskeleton Robot for Upper Limb Rehabilitation, Journal of Mechanics in Medicine and Biology 16 (08) (2016) 1640023. doi:10.1142/S0219519416400236.
URL http://www.worldscientific.com/doi/abs/10.1142/S0219519416400236

[13] X. Cui, W. Chen, X. Jin, S. K. Agrawal, Design of a 7-dof cable-driven arm exoskeleton (carex-7) and a controller for dexterous motion training or assistance, IEEE/ASME Transactions on Mechatronics 22 (1) (2017) 161–172. doi:10.1109/TMECH.2016.2618888.

[14] D. M. Baechle, E. D. Wetzel, S. K. Agrawal, MAXFAS: Mechatronic Arm Exoskeleton for Firearm Aim Stabilization, Journal of Mechanisms and Robotics 8 (6) (2016) 061013. doi:10.1115/1.4034015.
URL http://mechanismsrobotics.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4034015

[15] F. Grimm, A. Walter, M. Sp??ler, G. Naros, W. Rosenstiel, A. Gharabaghi, Hybrid neuroprosthesis for the upper limb: Combining brain-controlled neuromuscular stimulation with a multi-joint arm exoskeleton, Frontiers in Neuroscience 10 (AUG) (2016) 1–11. doi:10.3389/fnins.2016.00367.

[16] J.-S. Botero V., J.-P. Restrepo Z., M.-T. De Ossa J., An angle measurement system of high resolution for the upper limbs using a low-cost servomotor, IOP Conference Series: Materials Science and Engineering 138 (1) (2016) 12006.
URL http://stacks.iop.org/1757-899X/138/i=1/a=012006

[17] J.-S. Botero Valencia, J.-P. Restrepo Zapata, M.-T. De Ossa Jimenez, Design and implementation of a high-resolution angle measurement system for the upper limbs using a low-cost servomotor, International Journal on Interactive Design and Manufacturing (IJIDeM)doi:10.1007/s12008-016-0346-z.
URL http://link.springer.com/10.1007/s12008-016-0346-z

[18] F. Kinesiology, Length dependence of active force production in skeletal muscle, Applied Physiology 86 (5) (1999) 1445–1457.
URL http://jap.physiology.org/content/86/5/1445

[19] I. Galtés, X. Jordana, M. Cos, A. Malgosa, J. Manyosa, Biomechanical model of pronation efficiency: New insight into skeletal adaptation of the hominoid upper limb, American Journal of Physical Anthropology 135 (3) (2008) 293–300. doi:10.1002/ajpa.20743.
URL http:https://dx.doi.org/10.1002/ajpa.20743

[20] P. Ibanez-Gimeno, I. Galtes, X. Jordana, A. Malgosa, J. Manyosa, Biomechanics of forearm rotation: Force and

efficiency of pronator teres, PLoS ONE 9 (2). doi:10.1371/journal.pone.0090319.
URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3938685/

[21] L. W. O'Sullivan, T. J. Gallwey, Upper-limb surface electro-myography at maximum supination and pronation torques: The effect of elbow and forearm angle, Journal of Electromyography and Kinesiology 12 (4) (2002) 275–285. doi:10.1016/S1050-6411(02)00014-7.

[22] C. Paraschiv, P. Paraschiv, R. Cimpoeu, Determination of the Elbow Joint Resulting Torque and Obtaining Customized Numerical Results, Procedia - Social and Behavioral Sciences 117 (2014) 522–528. doi:10.1016/j.sbspro.2014.02.256.
URL http://linkinghub.elsevier.com/retrieve/pii/S1877042814017868

[23] L. Zhou, Y. Li, S. Bai, A human-centered design optimization approach for robotic exoskeletons through biomechanical simulation, Robotics and Autonomous Systemsdoi:10.1016/j.robot.2016.12.012.
URL http://linkinghub.elsevier.com/retrieve/pii/S0921889016301877

[24] J. Rosen, J. C. Perry, N. Manning, S. Burns, B. Hannaford, The human arm kinematics and dynamics during daily activities - Toward a 7 DOF upper limb powered exoskeleton, 2005 International Conference on Advanced Robotics, ICAR '05, Proceedings 2005 (July) (2005) 532–539. doi:10.1109/ICAR.2005.1507460.
URL http://ieeexplore.ieee.org/document/1507460/

[25] BioDigital InC, BioDigital (2016).
URL https://human.biodigital.com/index.html

[26] Robotis, Dynamixel MX 64 (2016).
URL http://support.robotis.com/en/product/actuator/dynamixel/mx{_}series/mx-64at{_}ar.htm