RESEARCH ARTICLE

Diseño mecánico de un exoesqueleto para rehabilitación de miembro superior

Mechanical design of an exoskeleton for upper limb rehabilitation

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Resumen

El ritmo de vida actual, tanto sociocultural como tecnológico, ha desembocado en un aumento de enfermedades y padecimientos que afectan las capacidades físico-motrices de los individuos. Esto ha originado el desarrollo de prototipos para auxiliar al paciente a recuperar la movilidad y la fortaleza de las extremidades superiores afectadas. El presente trabajo aborda el diseño de una estructura mecánica de un exoesqueleto con 4 grados de libertad para miembro superior. La cual tiene como principales atributos la capacidad de ajustarse a la antropometría del paciente mexicano (longitud del brazo, extensión del antebrazo, condiciones geométricas de la espalda y altura del paciente). Se aplicó el método BLITZ QFD para obtener el diseño conceptual óptimo y establecer adecuadamente las condiciones de carga de servicio. Por lo que, se definieron 5 casos de estudio cuasi-estáticos e implantaron condiciones para rehabilitación de los pacientes. Asimismo, mediante el Método de Elemento Finito (MEF) se analizaron los esfuerzos y deformaciones a los que la estructura está sometida durante la aplicación de los agentes externos de servicio. Los resultados presentados en éste trabajo exhiben una nueva propuesta para la rehabilitación de pacientes con problemas de movilidad en miembro superior. Donde el equipo propuesto permite la rehabilitación del miembro superior apoyado en 4 grados de libertad (tres grados de libertad en el hombro y uno en el codo), el cual es adecuado para realizar terapias activas y pasivas. Asimismo, es un dispositivo que está al alcance de un mayor porcentaje de la población por su bajo costo y fácil desarrollo en la fabricación.

Palabras clave: MEF, Blitz QFD, exoesqueletos, diseño mecánico.

Abstract

The pace of modern life, both socio-cultural and technologically, has led to an increase of diseases and conditions that affect the physical-motor capabilities of persons. This increase has originated the development of prototypes to help patients to regain mobility and strength of the affected upper limb. This work, deals with the mechanical structure design of an exoskeleton with 4 degrees freedom for upper limb. Which has the capacity to adjust to the Mexican patient anthropometry (arm length, forearm extension, geometry conditions of the back and the patient's height) BLITZ QFD method was applied to establish the conceptual design and loading service conditions on the structure. So, 5 quasi-static cases of study were defined and conditions for patient rehabilitation were subjected. Also by applying the finite element method the structure was analyzed due to service loading. The results presented in this work, show a new method for patient rehabilitation with mobility deficiencies in the upper limb. The proposed new design allows the rehabilitation of the upper limb under 4 degrees of freedom (tree degrees of freedom at shoulder and one at the elbow), which is perfect to perform active and passive therapy. Additionally, it is an equipment of low cost, which can be affordable to almost all the country population.

Key words: FEM, Blitz QFD, exoskeletons, mechanical design

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Introduction

Cerebrovascular disease (CVD) is a growing world health problem. According to data from the World Health Organization (WHO), CVD is one of the largest causes of disability and seriously affects the individual's quality of life, having a very broad spectrum of effects. Additionally, it is associated with emotional disorders and depression (Secretary of Health, 2009). The effects of CVD can be sensory or motor, the latter being the ones that generate a greater degree of disability. Among Mexican patients who have motor effects, it was found that 81% of the stroke victims suffered some complication. The most frequent effects are depression, shoulder pain and osteoarticular contractures (Cabrero-Rayo *et al*. 2008).

Rehabilitation of adult patients with CVD is a process aimed at achieving a functional, physical and social level to facilitate their independence and reintegration into the family, social and work environment (Secretary of Health, 1992). Physical rehabilitation can be mainly divided into two kinds:

1. Active - The patient is responsible for moving their limb.
2. Passive - The physiotherapist starts the movement of the patient's limb.

The use of robots and/or exoskeletons in rehabilitation has two fundamental applications (Sabater *et al*. 2007):

- During the patient's active movements, the robot stores information on executing the movement (including position, speed and force) for viewing the progress and optimizing the exercise routines.
- Additionally, passive or resistive movements may be produced in the patient's limb held by the robot, thus replacing the physiotherapist.

The devices used for rehabilitation of the upper limb are mainly classified into two groups: exoskeletons and end-effectors (Rodríguez-Prunotto *et al*. 2014). An exoskeleton is defined as a biomechatronic system where the mechanism is adapted to the physical structure of the human body. It has a control that can be connected to the same signals as the brain and actuators that analogously generate or reproduce the body's functions. The exoskeleton acts as a single integrated system that can develop varied activities (Pons, 2008).

As the main contributions to this branch of technology, in 1992, *MIT-MANUS* was designed, which is an exoskeleton used to generate physiotherapy and occupational therapy routines. It executes visual and auditive activities with tactile, proprioceptive and kinesthetic extension, carries out rehabilitation routines and has a virtual environment. The mechanism is of five degrees of freedom (DOF) mounted on a parallelogram managed by a gear box (Hogan, 1992). In 2003, a soft-actuated, exoskeleton of seven degrees of freedom appeared capable of generating shoulder flexion/extension, abduction/adduction and internal/external rotation, elbow flexion/extension, forearm pronation/supination, and wrist flexion/extension and radial/ulnar deviation. The original characteristic is the use of pneumatic muscles as an antagonistic pair. It has a light mass and an excellent force to weight ratio (Tsagarakis and Caldwell, 2003). Likewise, in 2004, the *ASSIST* (*Active Support Splint*) device was produced, which is an exoskeleton of one degree of freedom that is driven by smooth pneumatic actuators. Two variants of this system were developed. One with the aim to increase the range of movement and the second with the aim to increase muscular resistance. Physically, this device is an interface manufactured in plastic with the palm and arm of the user and it has two kinds of soft rotatory actuators placed between both sides. The greatest advantage of the device is the minimal sensation of restriction when the device is not working (Sasaki *et al.* 2004). In the same year, devices that combine virtual reality and rehabilitation had the greatest drive. This was the case of the 7 DOF exoskeletons, through which the human user can interact with a virtual environment. The shoulder joint is spherical and generates shoulder adduction/abduction and elevation and turning of the upper part of the arm. The elbow manages flexion/extension and turning of the forearm. The wrist has flexion/extension and abduction/adduction. The structure weighs a total of 2.3 kg (Chou *et al.* 2004). *Sarcos Master* is a lightweight 7 DOF exoskeleton, which minimizes inertia due to gravity and the *Coriolis* effect so that the user's arm movements are not affected.

By 2005, torque motion could be individually applied to any or all of the degrees of freedom, resulting in a dynamic new environment, so that subjects could adapt to the system (Mistry *et al*. 2005). Additionally, in 2005, an exoskeleton was presented in Latin America, specifically created in Colombia. Said device has 3 DOF with the internal/external rotation of the humerus, flexion/extension of the elbow and pronation/supination of the wrist. A biomechanical analysis was conducted for this prototype, where 5 DOF of the upper limb were identified (Gutiérrez *et al.* 2005). In 2006, the device designed by the Rice University focused on rehabilitation in virtual environments in active and passive mode. It uses robotic manipulators to generate flexion/extension movement in the elbow, pronation/supination of the forearm, flexion/extension of the wrist and radial/ulnar deviation. It is comprised of a revolving joint in the elbow, a revolving joint for rotation of the forearm and three spherical/prismatic/revolving joints in series/parallel for the wrist (Sledd and O'Malley, 2006; Gupta and O'Malley, 2006). In 2007, the Saga University developed a 4 DOF exoskeleton with a mobile center of rotation for the shoulder joint, which assists in the rehabilitation of vertical and horizontal shoulder flexion/extension, elbow flexion/extension and forearm pronation/supination movements. It is installed in a wheelchair where people with physical weaknesses can use it. Also, the user does not bear the weight of the exoskeleton (Kiguchi, 2007). Additionally, the *CADEN-7* device was made, which using a man/robot attachment aperture for upper and lower arm segments, generates flexion/extension, abduction/adduction and internal/external rotation of the shoulder, flexion/extension of the elbow and pronation/supination, flexion/extension and radial/ulnar deviation of the forearm. Safety is implemented in three levels: mechanical design, electric design and the control program (Perry *et al.* 2007).

Another device on which its researchers have worked for a lot of time is *RUPERT*, and four versions have been developed. The first version included four pneumatic muscles, shoulder elevation, elbow extension and supination and wrist extension. After considering the patients' functional conditions, the structure was restricted to the abduction of the shoulder in a single plane (15° laterally). The maximum elevation was limited to 45°. It also has a platform that stabilizes the shoulder blade. In the second version, the center of rotation and length of each segment was altered. However, this feature generated the problem of increasing the total weight and increased the demand for energy in the shoulder and elbow joints. The third version was a structure made from carbon fiber. It was developed to reduce the weight of the previous version while maintaining its rigidity. The mechanism permitted flexing of the shoulder, bending of the elbow, supination and pronation, as well as wrist flexion/extension. The fourth version is of 5 DOF, increasing the humeral rotation to the previous degrees of freedom. It also has an adaptive closed loop control system, which helps the users to calmly carry out their tasks in a 3D environment (Chen and Liao, 2006; Sugar *et al.* 2007; Wei *et al.* 2008 and Balasubramanian *et al.* 2008).

ARMin was a project that involved a long research process for its development. The first version was of 6 DOF, four active and two passive, with the aim to permit elbow flexion/extension and the spatial movements of the shoulder. It focused on rehabilitation therapies with the aim to recover the capacity of carrying out activities in daily life. It is adjustable in five parameters. The second version was of 7 DOF, with two of them being connected. It has sensors which allow the forces of interaction between the patient and the exoskeleton to be measured. Additionally, a force/torque sensor was placed in the section that supports the forearm. Furthermore, to complement the measurements, the hand lever was set with effort indicators, as well as the inclusion of a screen where the therapist indicates the routine to follow. The third version has six active degrees of freedom with three for the shoulder, one for elbow flexion/extension, one for forearm pronation/supination and the final one for wrist flexion/extension (Nef *et al.* 2006, Mihelj *et al.* 2007; Brokaw *et al.* 2011).

Recently, the *Hocoma* Company has managed a project called *Armeo®*, which is comprised of three devices for rehabilitation of the upper limb. The project is aimed at patients with brain injuries and neurological disorders and it is designed for progressive rehabilitation. Destaca *Power®* was a joint development between the *ETH Zúrich* Hospital and the Balgrist University Hospital. It permits early rehabilitation of motor skills, as well as providing intelligent support of the upper limb in a long 3D space. The other devices are called *Spring®* and *Boom®* (Hocoma Catalog, 2012).

This work presents the development of the design of the mechanical structure of a exoskeleton-type rehabilitation device that is adjusted to the longitudinal dimensions of the upper limbs and is designed for patients of the Mexican population. This new device is capable of reproducing the active/passive movements carried out by a physiotherapist during physical rehabilitation therapies through four degrees of freedom (three in the shoulder and one in the elbow). The rehabilitation equipment was designed by applying *Blitz QFD®*. *Blitz QFD®* is a practical and synthetic tool that does not require sophisticated computer systems or specific tools (like the house of quality) to produce positive results. It aims to obtain the adequate features for the patient's rehabilitation and it is comprised of seven small steps for its operation by the patient: desired specifications, classification of specifications, structuring of needs, analyzing the structure of needs, prioritizing the needs, listing the needs in order of importance, and analyzing only the priority needs in detail (González-Bosch and Tamayo-Enríquez, 2002). The numerical analyses are also presented, which are generated in a computer program with an algorithm that applies the finite element method (FEM) to validate the structural competence of the new device. The new device is capable of generating movement routines of active, passive and combined rehabilitation. Additionally, the segmental longitudes can be personalized and the routines can be individualized according to the deficiencies of the Mexican patient. The routine can also be monitored and optimized according to the individual's progress.

Materials and Methods

The development of the new rehabilitation device was divided into two stages. The first is focused on *Blitz QFD®* for the development of the conceptual mechanical design. While the second stage displays the quasi-static analysis through the application of the FEM on the device structure.

Conceptual Design (*Blitz QFD®*)

Blitz QFD® is a quality management method that is based on transforming the user's needs into the quality of the design and contributing greater quality indexes with respect to the specific elements of the manufacturing process. From its beginning as a technique, *QFD* has implemented methodologies to reduce the development period and decrease the group efforts required. The design parameters were established for the proposal presented in this work. These were divided into dimensional and functional parameters as presented in Table 1 and they were obtained from the anthropometric dimensions of the Mexican population (Avila-Chaurand, 2001).

Table 1. Design parameters.

Dimensional	Functional
Arm varies between 29 and 40 cm.	Shoulder flexion/extension in the sagittal plane around the transverse axis: 45 to 50° extension and 180° flexion.
Forearm varies between 21 and 30 cm.	Abduction of the shoulder in the frontal plane: 0 to 180°.
Distance between shoulders: 39 to 55 cm	Horizontal flexion/extension of the shoulder around the vertical axis: 30 to 40° extension and 140° flexion.
Height from seat to feet: 34 to 45 cm.	The device can continuously execute the three shoulder movements.
The shoulder height in sitting position varies from 85 to 108 cm.	Elbow flexion: 140-145° (160° passively).
	Pronation/supination of the upper limb: 90° supination and 85° pronation.
	Device for a person with a maximum weight of 90 kg.

To fulfill the needs proposed in the design parameter, 1,620 possible concepts were generated. Four filters were applied to reduce them. The first filter (feasibility) reduces them to 128 possibilities. After the second filter, (technological availability), 32 possible solutions are left. No combination is eliminated with the third filter and the most appropriate concept is obtained with the fourth filter (Decision Matrix).

A conceptual design is obtained when completing the implementation of *Blitz QFD*®. In this particular case, it is as follows:

- To adjust the length of the arm and the forearm, manually moved telescopic bars were proposed.
- To adjust the thickness of the upper limb, adjustable padded straps were used.
- The modification of the mechanism's dimensions related to the shoulder width was established through a linear bearing unit.
- For the height of the telescopic column, the sliding elements were limited using two-position buttons.
- The rotation movement was produced by servomotors.
- The position control is established through an encoder.

The prototype that meets the described resulting characteristics can be seen in Figure 1. Additionally, the passive and active degrees of freedom that the device has are indicated (the active DOF are labeled AD and the passive DOF are labeled PD). AD1 corresponds to flexion/extension of the forearm and AD2 is flexion/extension of the shoulder in the sagittal plane. AD3 corresponds to shoulder abduction in the coronal plane and AD4 represents horizontal flexion/extension of the shoulder in the transverse plane. PD1 indicates the adjustment of the longitude section of the forearm and PD2 fulfills the function in the arm part. PD3 is used to longitudinally place the device in the coronal plane and PD4 in the transverse plane. PD5 is applied to adjust the back and position of the chair. These last three degrees of freedom were developed with the aim to place the shoulder in a correct spatial position. Figure 2 shows the general assembly, dividing it into specific parts. Table 2 indicates the key and name of the parts.

The device is divided into four subsystems for better development. These are:

1. Forearm subsystem - It is comprised of Q, P and N (Figure 2). Its purpose is to support the patient's forearm. The length is modified through the rail with holes of Part Q. The button is used to keep it in place and to prevent it from moving.
2. Arm subsystem - The structure, comprised of O, N and M (Figure 2), was designed to permit the adjustment of the arm length. The mechanism is similar to that of the forearm with the difference that it is longer. The servomotor is placed in O, which executes the AD1 movement.
3. Shoulder subsystem - Comprised of subassemblies G, H, I, J, K and L (Figure 2), it is a structure that allows the independent and individual execution of shoulder movements. For this section, the external forces already established in the two previous sections will be considered. The FEM analysis was carried out in two stages. The first stage corresponds to the structure to generate the AD2 and AD3 movements. The second stage corresponds to the structure that executes the AD4 movement and that is comprised of the parts that join the exoskeleton at the base, as well as those that transmit movement from the servomotor to the rest of the exoskeleton, and at the same time, it supports the whole structure. To execute this movement, the structure of the arm and forearm have to be unlocked from the structure that supports the ab-

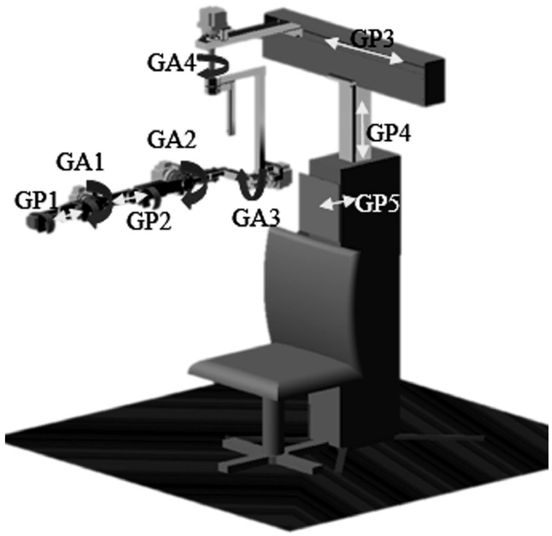

Figure 1. Prototype (degrees of freedom).

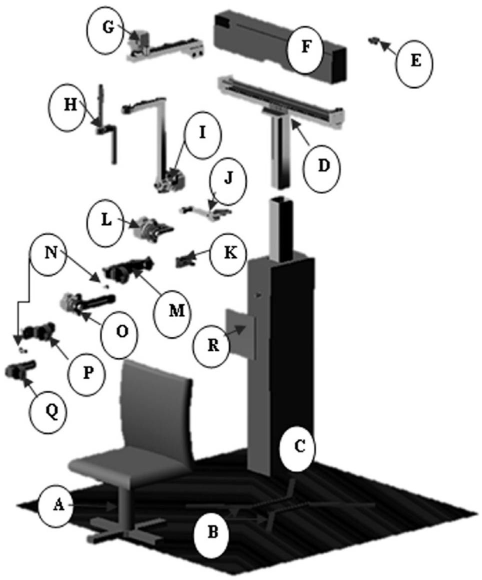

Figure 2. Design parts.

duction servomotor (*FHA-11C® Model, Harmonic-Drive* Brand) to be able to freely carry out said turn. The bar that is used for reconfiguration will have the capacity to join the structure only when this movement is made and to remove it when not, through adjustment by nut and screw; as well as the 90° movement of the two parts that join the frontal abduction structure.

4. Base subsystem - Formed by the B to F subsystems (Figure 2). This section is used to modify the width of the back or distance from the shoulder. It is executed through movement of the mobile car (which supports the structure that is in contact with the upper limb, the linear bearing unit *LQBR 12-2LS® Model, SKF* Brand is selected) on a rail. This also serves to start the change of settings from left-handed to right-handed, or vice versa. The patient's position is given through the back which has a back support where straps that secure the patient can be attached, preventing the patient from slipping from the seat or moving their trunk during rehabilitation. The latter is common in rehabilitation devices, because they do not secure the patient, which can cause a spinal injury, as well as reducing the benefits of the device by incorrectly carrying out the rehabilitation.

Numerical Analysis (FEM)

A quasi-static analysis of the structure was conducted with the aim to obtain the load ranges that the structure supports for its own weight and that of the patient, as well as the minimum torque required to maintain the static balance of the system. The loads that are applied during the finite element method analysis were established through a study of the upper limb (arm, forearm and hand) (Figure 3). The analysis is elastic, isotropic and homogeneous. Discretization was carried out in a controlled manner with elements gener-

Table 2. Keys and numbers of the parts.

No.	Part	No.	Part	No.	Part
A	Chair	G	AD4 support	M	Fixed arm
B	Base support	H	AD4 axis	N	End button
C	Fixed base	I	AD3 support	O	Mobile arm
D	Elevator	J	AD3 movement	P	Fixed forearm
E	Back handle	K	AD2-AD3 connection	Q	Mobile forearm
F	Upper shell	L	AD2 support	R	Back

ally of 10 mm and, in the areas of interest, of 1 mm. The element used had 6 kept degrees of freedom. The convergence was carried out on movement, rotation, force and time.

Figure 3. Contact areas (securing) of the exoskeleton with the upper limb.

In the case of numerical analysis using the mechanical structure, it was developed with different materials and its characteristics for evaluation are shown in Table 3:

- Aluminum 6061 - It was applied in the general structure.
- Grade A Type 8 Steel - It was used for all the nuts and bolts.
- Bronze SAE 62 - It was used as the material for all the axle boxes.

The structural analysis of the mechanism is divided into five cases, because the behavior of the section in contact with the upper limb is similar to that of a beam in a cantilever (it only has support at one end, while the other one is free). Therefore, the free end may undergo movement generated by the system's own physical characteristics (weight of the elements), which affects the optimum operation of the system. As well as analyzing each of the device's sections, the proposed cases are the most common in the development of rehabilitation for patients with ailments in the upper limb.

Case 1 Structural Analysis of the Forearm

The fastening straps support the weight of the forearm and hand. For this reason, the loads are applied to the structure in these areas. The scale is established by considering a beam with double support. The first corresponds to the forearm fastening strap (CC) and the second is the wrist fastening strap (CM). Table 4 presents the data that were taken as a basis to establish the border conditions of the numerical analyses. The biomechanical data were based on the research work of Lissner and Williams (1991). Additionally, the resulting forces were indicated. These are applied to the structure itself, as well as to the border conditions for analysis in the FEM program (Figure 4). The support and the movement restrictions were placed around the axis of the GA1 movement.

Table 4. Forearm and hand parameters.

Initial Parameters	Parameters for FEM
Forearm-hand section, mass 2.07 kg and center of gravity at 307.52 mm (measured from the elbow). Forearm structure, mass 0.844 kg and center of gravity at 131.442 mm (measured from the elbow axis).	The CM strap supports 23.098 N. The CC strap is subjected to 2.79 N. A torque of 7.33 Nm and force of 28.5863 N is obtained in the elbow joint.

Case 2 Structural Analysis of the Arm

In this section, the structure has a single strap with which the patient's arm is secured (CB). Additionally, the servomotor (*FHA-14C®* Model) was connected, which generates the AD1 movement. The data that are considered for this case are established from the total weight of the upper limb analogously with the previous case. These data are shown in Table 5 and are applied to the structure to generate the border conditions in the analysis through the FEM program (Figure 5). The support and movement restriction were placed around the DA2 movement axis.

Table 3. Materials used for analysis (Hibbeler, 2006).

Material	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's Ratio	Yield Strength (MPa)
Aluminum 6061	69.5	2700	0.33	240
Grade A Type 8 Steel	200	7850	0.3	600
Bronze SAE 62	103.4	8820	0.34	520

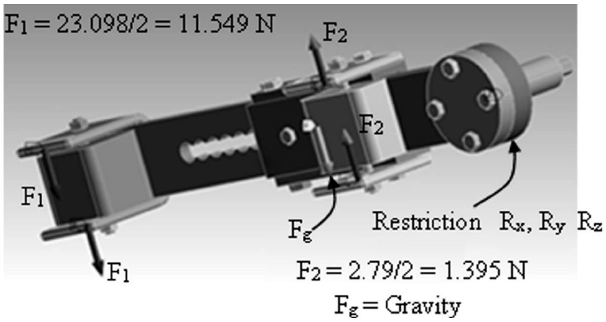

Figure 4. Forearm in loading position.

Table 5. FEM analysis parameters of the arm.

Entry Parameters	Parameters for the FEM Analyses
Complete upper arm, mass 4.41 kg and center of gravity at 368.09 mm (measured from the shoulder). Forearm and arm structure, mass 2.923 kg and center of gravity at 353.985 mm (measured from the shoulder).	The arm fastening strap is subjected to 22.956 N. A torque of 26.07 Nm and force of 71.9364 N is obtained in the shoulder joint (Figure 5).

Case 3 Structural Analysis of the Shoulder

The analysis of the structure's section focused on the shoulder joint was divided into two stages:

- Stage one - The structure is analyzed from the forearm section to the AD3 movement axis. The forces that are applied as border conditions are those obtained in Cases 1 and 2. The support and restriction are placed in the AD3 movement axis (Figure 6).
- Stage two - Up to the AD4 movement axis. The border conditions are similar to those of the previous stage. Movement is restricted in the AD4 axis (Figure 7).

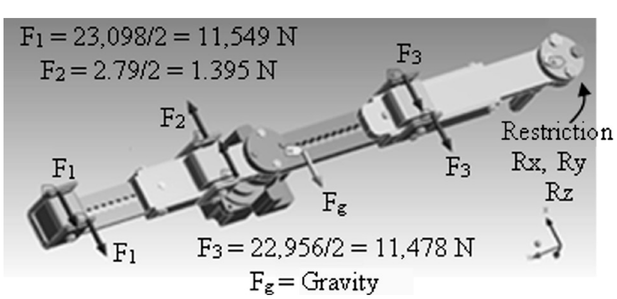

Figure 5. Arm and forearm in loading position and consideration for connection.

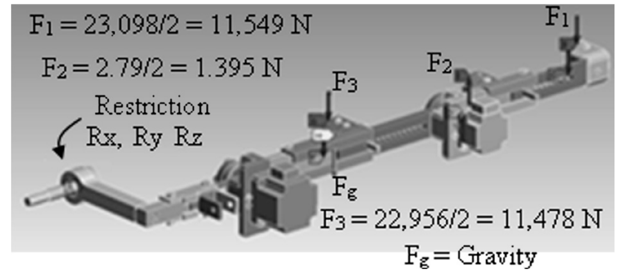

Figure 6. Shoulder in first loading position.

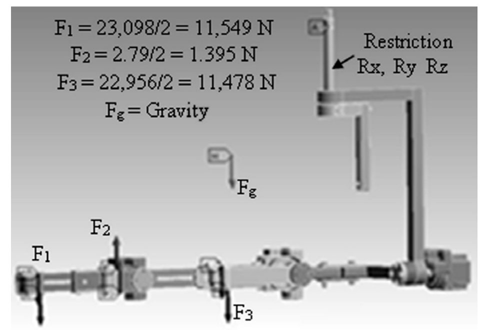

Figure 7. Shoulder in second loading position.

Case 4.- Analysis of the Upper Section

An analysis was conducted on the whole upper section. This is comprised of the forearm section to the upper support of the telescopic lifting column. The movement restrictions on said part were proposed for the analysis and the same loads induced by the weight of the upper limb were used (Figure 8).

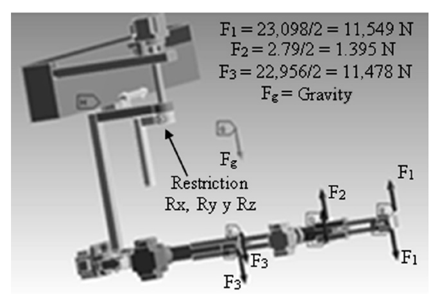

Figure 8. Upper section in loading position.

Case 5 Analysis of Transmission Axes

For this case, the AD1 movement axis was analyzed, where Aluminum 6061 was used. The motor selected was a *Harmonic Drive FHA-11C®* Model, which generates a torque of 11 Nm to the structure. Only the case in which the axis was subjected to twisting was analyzed and the cutting effect was not considered, because the stress is applied directly to the axle boxes. Under these considerations, the border conditions were established and applied for numerical analysis. The movement and rotation restrictions were placed on the holes where the attachment tubes are located (Figure 9). The AD2 and AD3 movements were analyzed for the second axis. There the border conditions were obtained in a similar way to the previous axis. However, for the second axis, there is the variation of the motor used, which is *Harmonic Drive FHA-14C®*, generating a torque of 28 Nm (Figure 10).

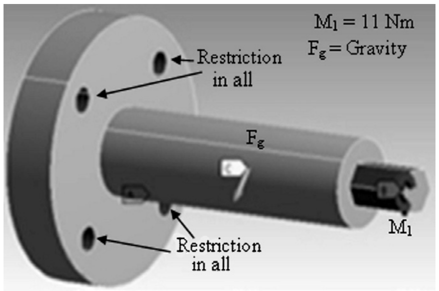

Figure 9. Loading position and movement restriction for AD1 axis.

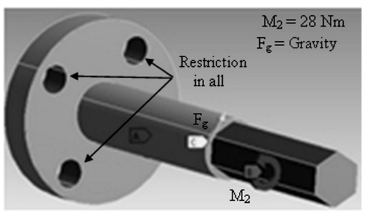

Figure 10. Loading position and movement restriction for axis AD2.

The AD4 axis is important, because it transmits torque and joins the mobile structure to the base. The servomotor selected for this movement is *Harmonic Drive FHA-14C®*, which generates a torque of 28 Nm. Therefore, the previously mentioned torque is applied to this analysis at a strength of 147.15 N (which subjects the tension stress to the axis and originates from the weight of the structure (Figure 11)).

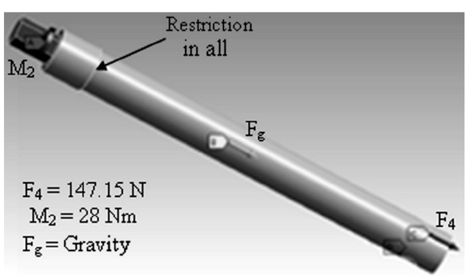

Figure 11. Loading position and movement restriction for axis AD4.

Results

The results from the numerical simulation (FEM) are displayed below. It is important to mention that the von Mises yield criterion was used. The results obtained for von Mises stress and movement for the forearm section are presented in Figures 12 and 13.

The numerical results obtained for von Mises stress and movement for the arm section are presented in Figures 14 and 15.

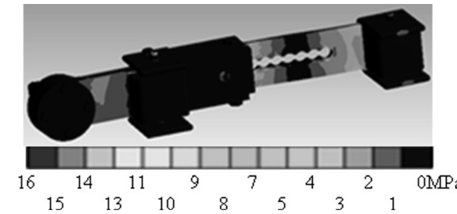

Figure 12. Forearm (von Mises stress).

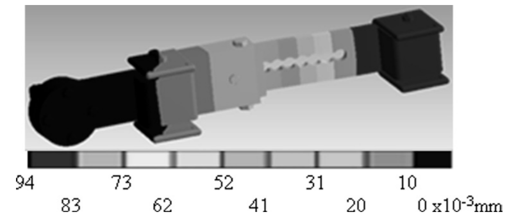

Figure 13. Forearm movement in z.

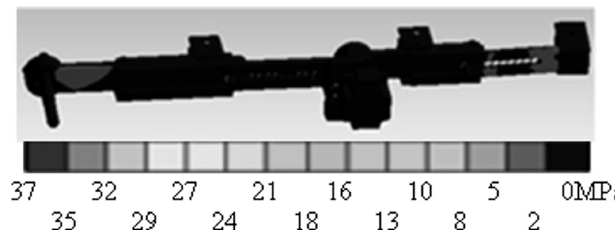

Figure 14. Arm-forearm (von Mises stress).

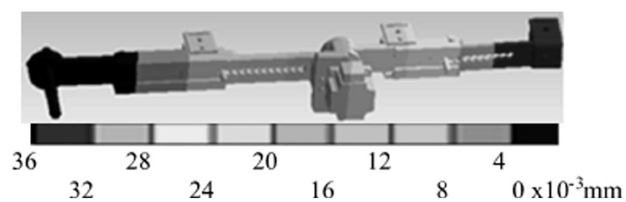

Figure 15. Arm-forearm movement in z.

The results obtained for von Mises stress and movement for the first stage of loading on the shoulder are presented in Figures 16 and 17.

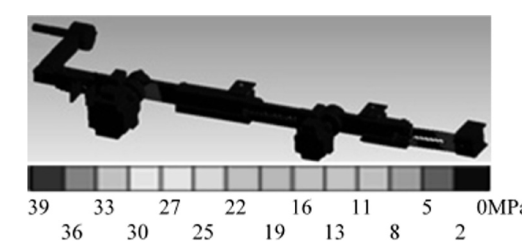

Figure 16. First stage of shoulder loading (von Mises stress).

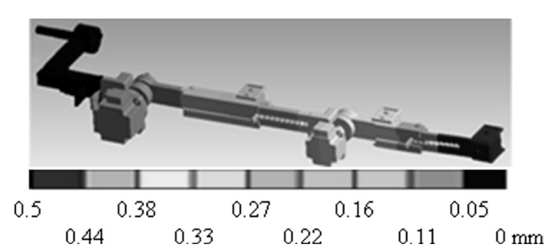

Figure 17. First stage of shoulder loading (movements in z).

The von Mises stress and movement for the second stage of loading on the shoulder are presented in Figures 18 and 19.

Finally, the numerical results obtained for von Mises stress and movement in axes AD1, AD2 and AD4, respectively, are presented in Figures 20 to 25.

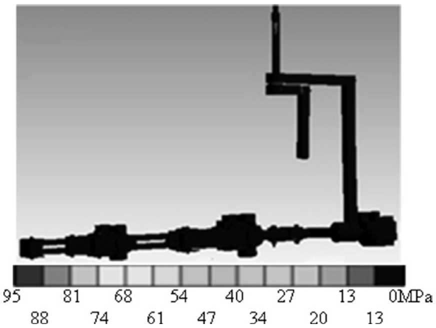

Figure 18. Second stage of shoulder loading (von Mises stress).

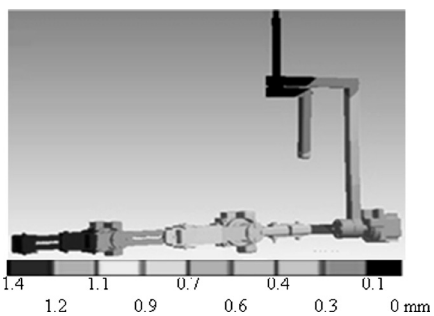

Figure 19. Second stage of shoulder loading (movements in z).

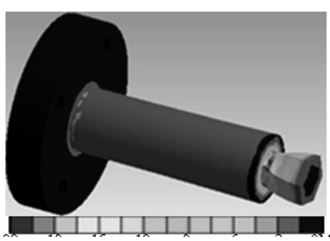

Figure 20. AD1 axis (von Mises stress).

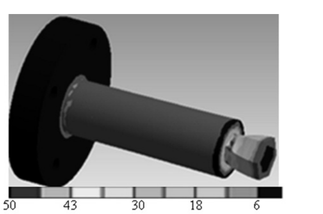

Figure 21. AD1 axis (movement in x).

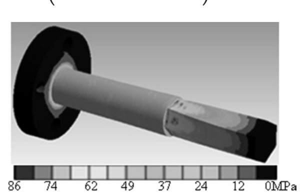

Figure 22. AD2 axis (von Mises stress).

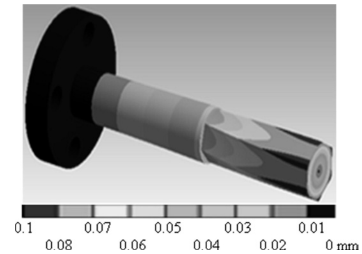

Figure 23. AD2 axis (movement in x).

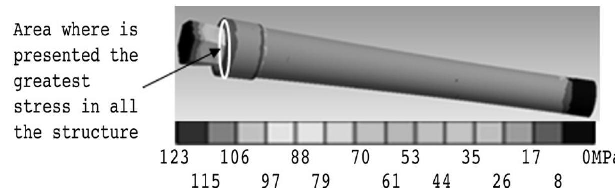

Figure 24. AD4 axis (von Mises stress).

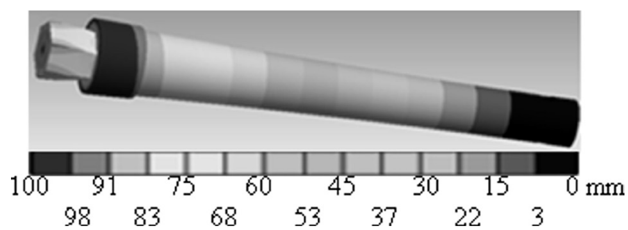

Figure 25. AD4 axis (movement in x).

Discussion

The deformations shown in some cases (both stages of the shoulder and AD2 and AD4 axes) are considerable compared to the other cases. However, the results found on scale are not significant to cause damage to the structure. The above is due to the fact that they are accumulated movements of the previous sections.

For Case 1 of the forearm, where the resulting maximum deformation was 94 x 10^{-3} mm, it is the only one where this correction of position is not going to be possible. From a mechanical perspective, the resulting deformations obtained in the analysis are not considered to be worrying regarding the development of an operational failure.

The complexity of the geometry and joining interfaces of the exoskeleton hinder the development of numerical analysis. The above is due to the interaction between all of the parts, which results in it being necessary to apply a large amount of nodes and elements. Additionally, because of the loads applied, it was only necessary to apply the elasticity concepts of the material and the theory of failure (von Mises). With these, it is possible to establish the value of the efforts (ductile materials) and the critical areas. Through the previous figures, it is possible to visualize the possible points of failure, which are found in the stress concentrators (as was to be expected). However, the stress values are not close to the value of yield strength, because they are not relevant.

The greatest stress values presented in Cases 1 and 2 are located on the button (Part N of Figure 2). This is due to the limitation function of movement, because due to this, they undergo flattening. The prototype obtained by the application of *Blitz QFD®* adequately supports the load conditions that were estimated.

Rehabilitation Movements

The (active and passive) rehabilitation movements for elbow flexion/extension are executed when there is flexion of the shoulder in the sagittal plane to 90° (Figure 26a). With these settings, it is possible to execute the maximum flexion movement, which varies between 140°-145° (according to the patient's characteristics (Figure 26b)), when the extension movement for the elbow is zero. For shoulder flexion/extension in the sagittal plane, it is started from the neutral position, that is, 0° (Figure 26c). Extension is executed with an amplitude of 45°-50° (Figure 26d), while flexion is executed at values of 180° (Figure 26e). Implementation of the device with a user executing elbow flexion is observed in Figure 26f. Finally, the patient executes shoulder flexion in the sagittal plane in Figure 26g.

Future Work

It is highlighted that this work only reports on the part corresponding to the structural analysis (mechanical). It is important to mention that the control design stages would need to be considered, which include routines for the correction of posture through the sensors and motors that are used. Furthermore, the electric/electronic control stage and the stage of the interface to a 3D environment that generates greater user motivation to perform rehabilitation therapies with this device will be conducted as the following stage of development of the overall project. These activities are carried out based on the electromyographic signals obtained from electrodes that are placed on the patient's upper limb (Torres-San Miguel *et al.* 2011).

Conclusions

A mechanical design was made of an exoskeleton for rehabilitation of the upper limb using the methodology called *Blitz QFD®*. The new device was implemented according to the specifications of patients with a Mexican anthropometry. The configuration displayed by this equipment is four active degrees of freedom, which are the minimum needed to develop rehabilitation patterns in patients' with deficiencies in the upper limb. Passive degrees of freedom were necessary to longitudinally adjust the segments of the device's structure. It is important to highlight that the holed rail system is the most appropriate for the Mexican phenotype, which is used to make the longitudinal

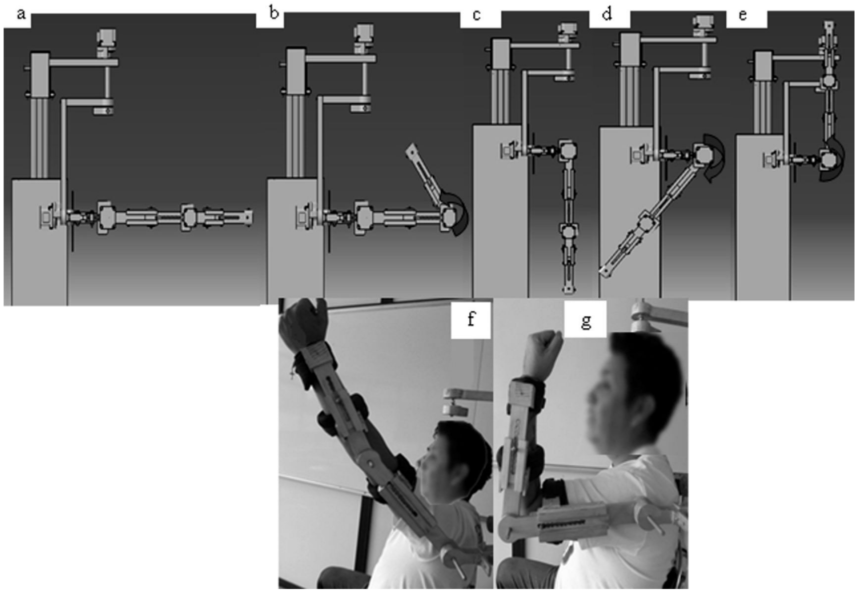

Figure 26. Rehabilitation movements: a) Elbow flexion to 0°. b) Maximum elbow flexion. c) Shoulder flexion in the sagittal plane to 0°. d) Maximum shoulder extension. e) Maximum shoulder flexion. f) Patient flexing elbow. g) Patient flexing shoulder.

adjustment and is capable of achieving a connection between the structure and the individual's forearm and arm. It is important to mention that the devices mentioned in the introduction to this work were not designed for the Mexican population (with respect to segmental longitudes), which generates considerable imbalances between the centers of rotation of human and mechanical joints. While it does not cause harm to active therapies, it does to passive therapies.

Within the analyses using the FEM, it could be proven that the structural system of the new rehabilitation system is within the ranges to support the service loads. However, the result where the maximum stress value is 123 MPa (Figure 24) only affects one part. Therefore, the rest of the structure supports less stress and the design is considered to be acceptable. Regarding movements presented in the structure, Cases 3 (first stage) and 4 are considerable. However, it is emphasized that the problem is corrected in the positioning and control stage, combined with the structure of the forearm sections presenting a movement in the hundredths of a millimeter range. No geometric optimization technique has been considered, because the results are acceptable and the dimensions are made to be able to provide support and comfort to the user.

The rehabilitation equipment presented herein was designed with the aim to support physical rehabilitation through the generation of variable routines of continuous movement, where this equipment is capable of aiding the flexion/extension movements of the shoulder in the sagittal plane and in the horizontal plane, and abduction in the coronal plane, as well as the flexion/extension movement of the elbow. With these movements, this device is capable of providing a numerous amount of routines for the patient. Likewise, through angular position sensors, it can collect data to provide feedback to the user on the progress or setbacks that occur. Additionally, this equipment could be used from an early stage of injury (where the recovery of mobility and strength is required) to the stages where recovering fine movements is desired. This is achieved through the combination of active/passive movements. The above is a great advantage compared to the other devices, which only act in the fine adjustment stage (like the case of the *Armeo Spring®* device).

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