



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering  
December 3-8, 2017, Curitiba, PR, Brazil

## COBEM-2017-1975

# DEVELOPMENT OF THE MECHANICAL STRUCTURE OF AN ACTIVE MONOARTICULAR ORTHOSIS FOR LOWER LIMB

### **Eduardo dos Santos Caetano**

Federal Institute of Education, Science and Technology of Espírito Santo, Department of Mechanical Engineering, São Mateus, Brazil  
caet.eduardo@gmail.com

### **Douglas Ruy Soprani da Silveira Araújo**

Federal Institute of Education, Science and Technology of Espírito Santo, Department of Mechanical Engineering, São Mateus, Brazil  
douglassoprani@ifes.edu.br

### **Lorena Lucia Bastos Bandeira**

Federal Institute of Education, Science and Technology of Espírito Santo, Department of Mechanical Engineering, São Mateus, Brazil  
bastoslorenna@gmail.com

### **Antonio Carlos Basbosa Zancanella**

Federal Institute of Education, Science and Technology of Espírito Santo, Department of Mechanical Engineering, São Mateus, Brazil  
Antonio.zancanella@ifes.edu.br

**Abstract.** *In recent years, the number of people requiring motor rehabilitation treatment in the lower limbs increased. Due to the high number of patients and the long time the treatment demands, the use of robotic devices can increase the efficiency of rehabilitation treatments. In this context, we highlight the use of robotic orthoses. This work presents the development of the prototype of an active monoarticular lower limb orthosis, dedicated to perform the extension and flexion movement of the human knee. The mechanical structure of the device was developed by applying the concepts of the strength of materials for the selection of material and definition of the dimensions of the device. The device was mounted and fixed on a workbench, presenting low weight and compact dimensions, and enables the development of research in robotic rehabilitation techniques of the movement of extension and flexion of the human knee.*

**Keywords:** *orthosis, rehabilitation robotics, manufacturing, assistive technology.*

## 1. INTRODUCTION

According to the Brazilian Institute of Geography and Statistics (2012), 7% of the Brazilian population declares that they have motor deficiencies, many of them due to pathologies or accidents. In recent years, the number of people with some lower limb deficiency has been increasing, due to several reasons such as cerebral vascular accidents (CVA) or spinal cord injuries (Tsukahara; Hasegawa; Sankai, 2009). Considering the increase in the life expectancy of Brazilians, the trend is that in Brazil this number will increase even more (Araújo, 2010).

The precariousness of the accessibility of physical handicaps existing in Brazilian cities causes unpleasant consequences for these individuals, such as interruption of professional life and dependence of third parties for daily activities (Santos, 2011). In addition, lack of muscle movement causes physical problems such as the appearance of lesions or bedsores. Such disorders still cause psychological damage, affecting the individual's self-esteem and decreasing their quality of life (Tsukahara; Hasegawa; Sankai, 2009).

Parallel to the increase in the number of people with disabilities, there is also an increase in the number of athletically active people who seek physical fitness to maintain good health and health. In this way, meniscus lesions have become very common among professional and amateur athletes and are one of the most common causes of knee surgeries, requiring post-intervention treatment (Cavanaugh; Killian, 2012).

One means of mitigating the negative effects or even restoring the mobility of an affected limb is through motor rehabilitation programs. Adequate physiotherapy promotes patient recovery by returning it to society. However, a shortage of therapists and physiotherapists makes the workload of the professionals active in the area very large (Homma; Fukuda; Nagata, 2002). Due to the high number of patients and the long treatment time, the use of robotic devices may offer advantages for motor rehabilitation (Ju *et al.*, 2005). Robotic rehabilitation is an area of growing research within biomedical engineering, dedicated to the application of robotic devices in modern rehabilitation (Botelho *et al.*, 2015). In this context, the use of robotic orthoses stands out.

The term orthosis refers to orthopedic mechanisms positioned externally to an affected limb and its purpose is to restore or potentiate lost or weak functions of that limb. Robotic orthoses, which use actuators controlled by electrical signals, are classified as active orthoses and have been widely used in motor rehabilitation of upper or lower limbs, by performing repetitive movements in an automated way (Ju *et al.*, 2008; Pons *et al.* Varoto, 2010).

Several research groups have carried out work related to the development of equipment and strategies to aid, treat and evaluate patients who need motor rehabilitation, obtaining promising results. In Brazil, one can cite in this research area the works developed by Araújo (2010), Varoto (2010) and Santos (2011).

It is of great importance the development of devices that can contribute in the researches of assistive technology and rehabilitation programs, offering to the individual with some difficulty motor rehabilitation alternatives through these equipments.

This work presents the development of the prototype of a monoarticulated lower limb orthosis, dedicated to the accomplishment of the movement of extension and flexion of the human knee. The result achieved is a compact, sturdy, low-weight and functional device.

## 2. EXPERIMENTAL PROCEDURE

The prototype of active orthosis developed in this work has the objective of reproducing the movements of extension and flexion of the human knee of a user in the seated position, and consists of a mechanical structure composed essentially of two metallic rods: one fixed, corresponding to the hip-knee extension; and another mobile, corresponding to the knee-ankle extension. These rods are attached at the knee joint by the axis of an actuator responsible for joint movement. The prototype is fixed on a bench for assembling and performing tests. Other mechanical components were added to the prototype according to the design needs. Figure 1 shows a simplification similar to the developed prototype.

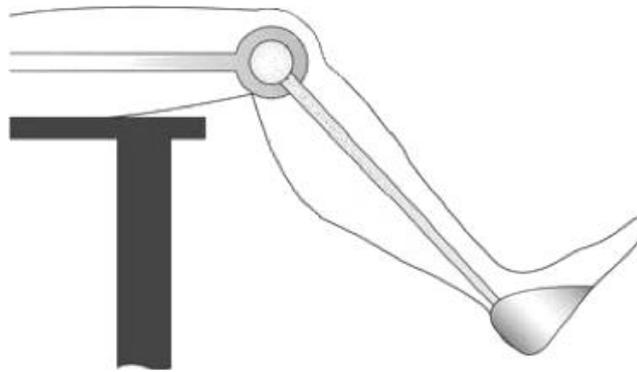


Figure 1. Robotic exoskeleton model for lower limb (Botelho *et al.*, 2015)

For the design of the mechanical structure of the prototype, were explored the principles of static and mechanic of materials to determine the forces acting on or inside the elements, because the size of these elements depends on the internal loads and the material they are made of (Hibbeler, 2010). According to these principles, the equilibrium of a body requires a balance of forces and moments, represented by  $F$  and  $M$ , respectively, and expressed by Equations 1 and 2 (Hibbeler, 2010).

$$\sum F = 0 \quad (1)$$

$$\sum M_o = 0 \quad (2)$$

For safety reasons, in a structural or mechanical design it is important that maximum shear and flexural stresses be restricted to allowable values for the material. The use of a safety factor  $FS$ , given by Equation 3, is the method of specification of the maximum permissible stress for the material of a structural element (Hibbeler, 2010; Beer and Johnston Junior, 1995).

$$FS = \frac{\text{Last stress}}{\text{Admissible stress}} \quad (3)$$

According to Hibbeler (2010), to avoid the potential for failure, the  $FS$  chosen should be greater than 1. Callister Junior and Rethswich (2012) state that  $FS$  values normally range between 1.4 and 4.0. A  $FS = 2$  was defined for the determination of the permissible bending and shear stresses of the material chosen for the manufacture of the rods. Rearranging Equation 3, the allowable project stresses are described by Equation 4.

$$\text{Admissible stress} = \frac{\text{Last stress}}{FS} \quad (4)$$

The material chosen for the manufacture of the prototype was aluminum due to its characteristics as low specific weight in relation to other metallic materials, such as steel, and mechanical strength. Their respective ultimate flexural and shear stresses are shown in Table 1.

Table 1. Last stresses of aluminium (Beer e Jhonston Junior, 1995).

Last flexion stress (MPa)	290 MPa
Last shear stress (MPa)	185 MPa

Simplifying the geometry of the movable rod as a homogeneous rectangular bar, its length  $L$  was defined as 20 mm. An equivalent load  $P$ , acting transversely to the shank, was considered at a distance  $L$  from the point of rotation (knee joint), as shown in Figure 2.

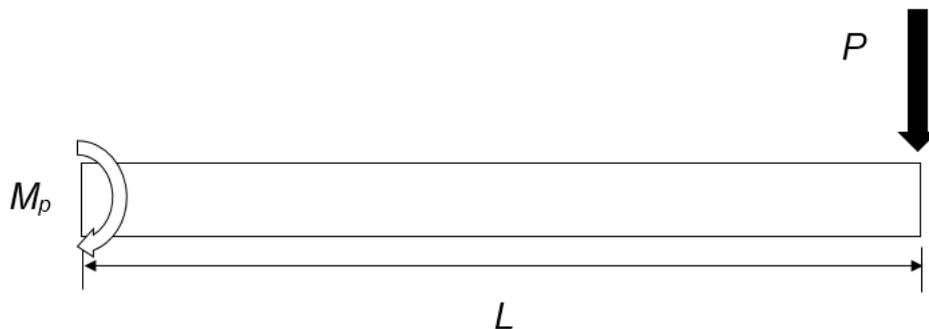


Figure 2. Simplification of the action of the equivalent load  $P$  on the movable rod.

The equivalent load  $P$  must be capable of causing a torque  $M_p$ , equivalent to the torque  $T_j$  required at the knee joint, for the extension movement to occur at the point of rotation of the shaft (knee joint). During the execution of the extension movement,  $T_j$  varies according to the angular position  $\theta$  of the knee-ankle segment relative to the vertical  $y$ -axis. Figure 3 shows the free body diagram of the segment considered for the calculation of  $T_j$ .

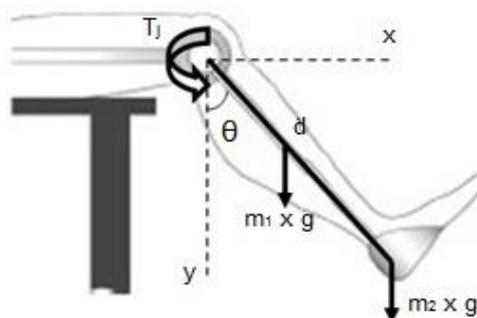


Figure 3. Free body diagram

Where  $g$  is the acceleration of gravity, adopted  $10 \text{ m/s}^2$ ,  $m_1$  and  $m_2$  are the calf mass (2.91 kg) and the leg mass (0.73 kg) of a leg, respectively, whose values are approximate for a person of 60 kg and 1.60 m high. For this same individual considered, the knee-ankle segment  $d$  has the size of 0.38m (Araújo; Alsina, 2010). Applying the equilibrium condition (Equation 2) to the free-body diagram considered, we obtain Equation 5, which determines  $T_j$  as a function of the angle  $\theta$ .

$$T_j = \left( m_2 + \frac{m_1}{2} \right) dg \sin \theta \quad (5)$$

Given that  $T_j = M_p$ , the equivalent charge  $P$  was then calculated through Equation 6.

$$P = \frac{M_p}{l} \quad (6)$$

Once the load  $P$  was defined, the diagrams of shear force and bending moment were worked out along the length of the movable rod in order to determine the maximum shear and bending loads.

Given the maximum shear load  $V_{max}$  and the design allowable shear stress  $\tau_{adm}$ , the required minimum cross-sectional area  $A_{min}$  is calculated according to Equation 7 (Hibbeler, 2010).

$$A_{min} = \frac{V}{\tau_{adm}} \quad (7)$$

Maximum shear and flexural stresses are calculated from Equations 8 and 9 (Hibbeler, 2010).

$$\tau_{max} = 1,5 \frac{V_{max}}{A} \quad (8)$$

$$\sigma_{max} = \frac{M_{max} c}{I} \quad (9)$$

### 3. RESULTS AND DISCUSSION

The permissible bending and shearing stresses considered in this work and calculated from Equation 4 are shown in Table 2.

Table 2. Permissible stresses of the project .

Permissible flexural stress	145.00 MPa
Permissible shear stress	92.50 MPa

Figure 4 shows the variation of  $T_j$  as a function of  $\theta$ .

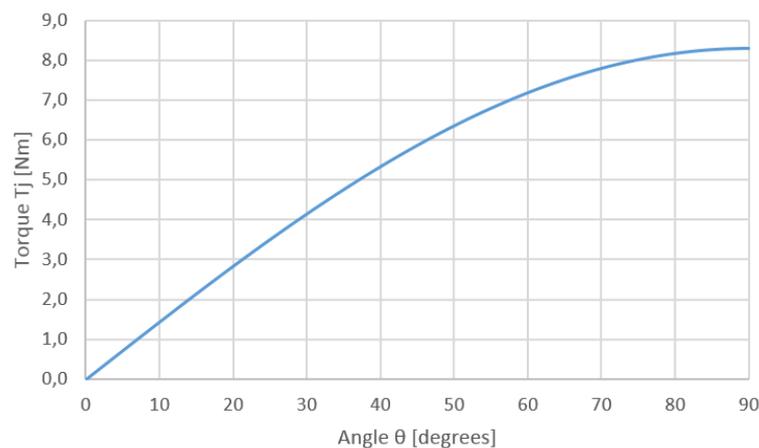


Figure 4. Variation of  $T_j$  as a function of  $\theta$

It is observed from the graph that the maximum  $T_j$  is reached when  $(\theta = 90^\circ)$ , position corresponding to the maximum extension of the knee, and has a value of  $8.3 \text{ Nm}$ . The equivalent charge  $P$  was calculated through Equation 6, resulting in  $P = 41.5 \text{ N}$ .

Once the load  $P$  was defined, the diagrams of the shearing force and bending moment were worked out along the length of the movable rod, shown in Figures 5 and 6, respectively.

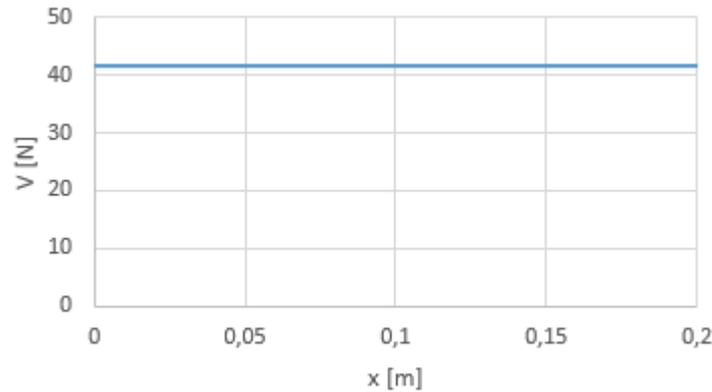


Figure 5. Shear force diagram

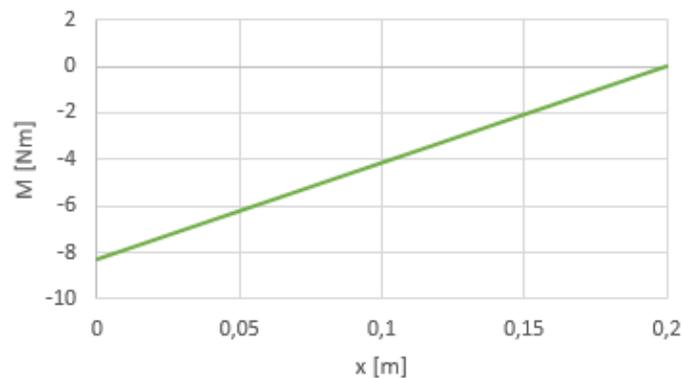


Figure 6. Bending moment diagram

According to the diagrams,  $V_{max} = 41.5 \text{ N}$  and  $M_{max} = -8.3 \text{ N}$ .

Given the maximum shear load  $V_{max}$  and the allowable shear stress of the design  $\tau_{adm}$ , the required cross-sectional area  $A_{min}$  is calculated according to Equation 5, resulting in  $A_{max} = 4.488 \times 10^{-2} \text{ m}^2$ . Such a cross-sectional area is too small for application in the design, which would hamper both the rod manufacturing process and future modifications in the mechanical structure, such as the insertion of new components or extensions. It was decided to define the dimensions of the rectangular section of the rods based on the exoskeleton Exo-H2 of Technaid S.L.®, due to this device to present dimensions more appropriate for the purpose of the project. The fixed rod and the movable rod developed in this design, as well as their dimensions in millimeters, are shown in Figures 7 and 8, respectively.

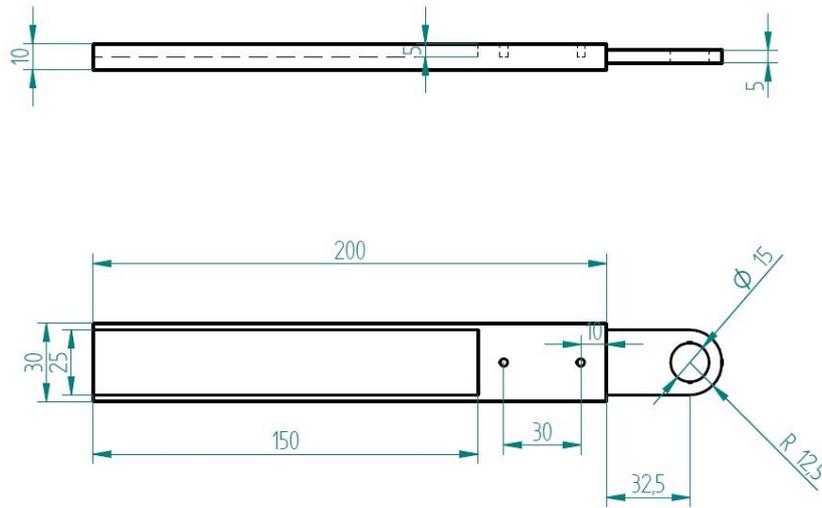


Figure 7. Fixed rod

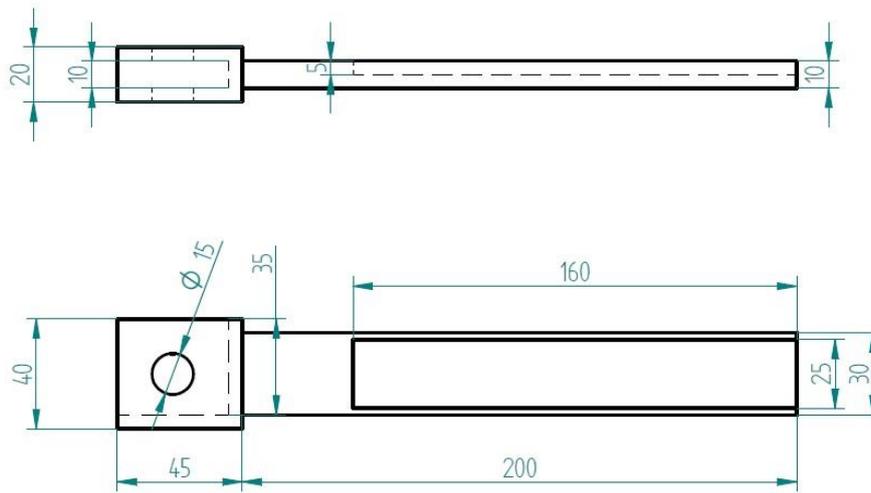


Figure 8. Movable rod

Maximum shear and flexural stresses are calculated from Equations 6 and 7 and are shown in Table 3.

Table 3. Maximum flexural and shear stresses .

Maximum flexural stress	5.533 MPa
Maximum shear stress	0.208 MPa

It is verified that the stresses acting on the system are lower than the permissible stresses (Table 2).

The actuator selected for the movement of the prototype joint is a DC motor, model BOSCH® CHP 9 390 082 031 (Figure 8).



Figure 8. DC Motor BOSCH® CHP 9 390 082 031

This model features a gearbox with a worm gear and irreversible crown, which is an important element for maintaining the limb in a position when the engine power has stopped.

Figure 9 shows the device mounted to the test bench of the Laboratory of Automation and Control of the Federal Institute of Espírito Santo, São Mateus campus.

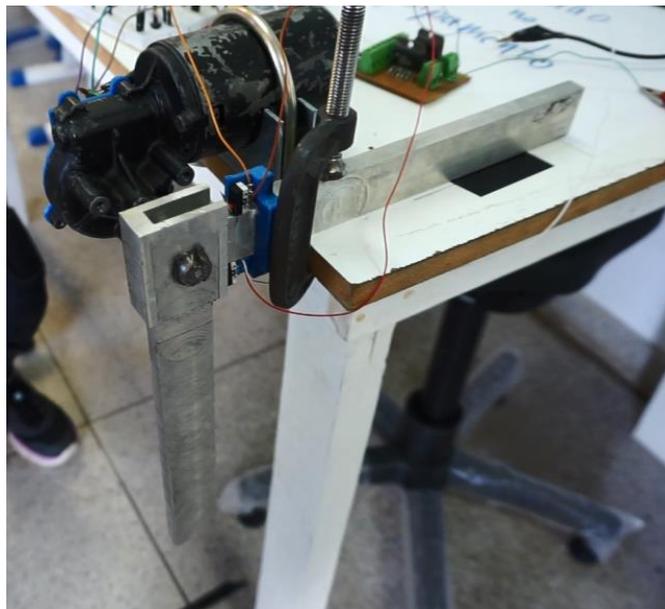


Figure 9. Prototype developed

The mechanical structure of the prototype, whose selection of material and choice of dimensions were developed according to the concepts of the mechanics of materials, met the expectations of the project. The rods, made of aluminum, have compact size, low weight and mechanical resistance appropriate to the design. The dimensions chosen for the rods allow the addition of extensions and adaptation of ergonomic components for real tests in human users in later works.

A feasible proposal for future work is the adaptation of the prototype to a chair, along with extensions that allow the connection between the bracing and the user to perform knee extension and flexion movement. Figure 10 present an outline of such a proposal.

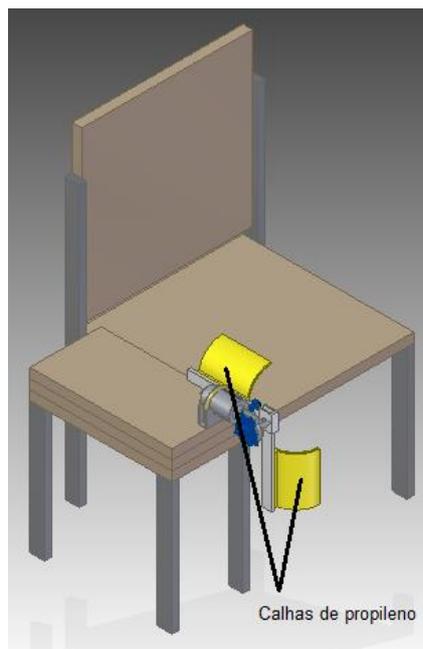


Figure 10. Adaptation of the prototype to a chair

It was concluded that the initial objectives were satisfactorily achieved. The prototype active orthopedic developed orthosis of the developed lower limb presents the possibility of evolution of the researches in Assistive Technology in the Federal Institute of the Espírito Santo campus São Mateus.

#### 4. ACKNOWLEDGEMENTS

We'd like to thank the Federal Institute of Science Technology and Education for this great opportunity of research and for laboratory and equipment support, and Volare Vehicles for the donation of DC motors for the project.

#### 5. REFERENCES

- Araújo, M. V. and Alsina, P. J., 2010. "Determinação do torque mínimo de acionamento de um atuador elétrico usado nas articulações de uma órtese de membro inferior". In: *Proceedings of the VI National Congress of Mechanical Engineering*. Paraiba, Brazil.
- Araújo, M. V., 2010. "Desenvolvimento de Uma Órtese Ativa Para os Membros Inferiores Com Sistema Eletrônico Embarcado". UFRN, Rio Grande no Norte, Brazil.
- Beer, F. P.; Jhonston Junior, E.R., 1995. "Resistência dos Materiais". 3. ed.: Pearson Makron Books, São Paulo, Brazil.
- Botelho, T., Soprani, D., Carvalho, C., Mut, V., Frizzera, A. and Ferreira, A., 2015. "Control of a Lower Limb Robotic Exoskeleton using Impedance Control". In: *Proceedings of the 1st International Workshop on Assistive Technology (2015)*, Vitória, Brazil. 23-26.
- Callister Junior, W. D. and Rethwisch, D. G., 2012. "Ciência e Engenharia de Materiais: Uma Introdução". 8. ed. Ltc, Rio de Janeiro.
- Cavanaugh J. T. and Killian, S. T., 2012. "Rehabilitation following meniscal repair" *Current Reviews In Musculoskeletal Medicine*, [s.l.], v. 5, n. 1, p.46-58, mar. 2012. Springer Nature. <http://dx.doi.org/10.1007/s12178-011-9110-y>.
- Hibbeler, R. C., 2010. "Resistência dos Materiais". 7. ed.: Pearson Prentice Hall, São Paulo, Brazil.
- Homma, K.; Fukuda, O.; Nagata, Y. 2002. "Study of a wire-driven leg rehabilitation system". In: *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*. IEEE, 2002. v. 2, p. 1451–1456.
- Instituto Brasileiro de Geografia e Estatística: Cartilha do Censo 2010 - Pessoas com Deficiência. Brasília, Brazil (2012).
- Ju, M. *et al.*, 2005. "A rehabilitation robot with force-position hybrid fuzzy controller: hybrid fuzzy control of rehabilitation robot." *IEEE Transactions On Neural Systems And Rehabilitation Engineering*, Taiwan, v. 13, n. 3, p.349-359, set. 2005.
- Pons, J.L. *et al.*, 2008. "Wearable Robots: Biomechatronic Exoskeletons".
- Santos, D.P. dos, 2011. "Projeto Mecânico de Exoesqueleto Robótico para Membros Inferiores" USP, São Paulo, Brazil.

- Tsukahara, A., Hasegawa, Y. and Sankai Y. Y., 2009. “Standing-Up Motion Support for Paraplegic Patient with Robot Suit HAL”. In: *INTERNATIONAL CONFERENCE ON REHABILITATION ROBOTICS, 11., 2009, Kyoto*.
- Varoto, R., 2010. “Desenvolvimento e Avaliação de um Protótipo de Sistema Híbrido para Membro Superior de Tetraplegicos”. USP, São Carlos, Brazil.

## **6. RESPONSIBILITY NOTICE**

The authors are the only responsible for the printed material included in this paper.