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

COBEM-2017-2174
A NEW MECHANICAL PROJECT FOR A LOWER LIMB EXOSKELETON

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Abstract. *This work presents the design of a robotic exoskeleton for lower limbs, called Ortholeg 2.0. This prototype has a main goal giving the capacity of walking, sitting, standing, climb up and down stairs to people with total or partial loss of lower limbs movements. The movements of the joints are produced by electrical motors equipped with mechanical reductions to produce smoother movements by reducing its speed and increasing torque. Projected to be lighter and more efficient than previous model, Ortholeg 2.0 was designed considering modern materials of premium quality to its construction, like carbon fiber, aluminum alloys and special polymers. This design processes resulted in a new tubular main frame structure, lighter than previous one, more ergonomic and with a better adjustment for user's height.*

Keywords: *exoskeleton, robotic, Ortholeg, biomechanics*

1. INTRODUCTION

According to Brazilian Geography Institute (IBGE), in 2010, more than 13 million Brazilian had some grade of disability to walk and climb stairs. That is a growing number due the high rates of accidents, acute trauma is the most dramatic cause of spinal cord injury, and other factors. Worldwide, and estimated 185 million people use a wheelchair daily. Just over 20 per cent of the global population is now aged over 65 years, and this proportion tends to exceed 35 per cent by 2050.

A loss of physical function can have multiple impacts on a person's life, such as the ability of achieving economic independence, also, individual may experience limitations in their ability to participate in social activities, shown by Brodwin, 2009. This motivate the development of lower limb exoskeleton to help those people to recover the capacity of walking, sitting, standing, climb up and down steps to people with total or partial loss of lower limbs movements.

Early studies about lower limbs orthosis for motion aid can date back to the 1960s in the United States and in the former Yugoslavia, respectively for military and medical purposes. Since then orthosis and exoskeletons has been developed continuously in different types of mechanical structures, actuators and interfaces. This continuous development is possible due the technological progress in many areas, including robotics, sensors, actuators, micro components and control system software (Bogue, 2015a). Various exoskeletons are available on the market and offers to people with spinal cord injury the opportunity to walk.

Robotics exoskeletons, that are essentially active orthosis with motor or actuators controlled by computers, have an immense potential for various application offering support during early treatment of spinal cord injuries and also on final stages of rehabilitation and in commonwealth life as an exercise modality to promote physical, mental and social well-being and to mobility as a wheelchair alternative.

Ortholeg is a pseudo anthropomorphic exoskeleton for lower limbs designed for user in weight from 50 to 70 kg and height from 1.55 to 1.75 m. The prototype is basically a mechanism consisting of a group of rigid connections joined by rotational joints. Each joint has one degree of freedom and is equivalent to human leg structure. The system is moved by four electrical motors. On each leg, one actuator is responsible for the hip joint movement and other actuator is responsible for the knee joint movement.

The first prototype, Ortholeg 1.0, has a similar structure configuration, a mechanism consisting of a group of rigid connections joined by rotational joints (Araújo, 2009), the key differences are in the parts geometry and building materials. Those design changes aim a lighter structure, a better adjustable fitting system and a more compact structure. Weight and volumetric reductions can be achieved due to selection of modern materials of premium quality.

2. BIBLIOGRAPHIC REVISION

There are many differences between an exoskeleton and most other forms of robots, the major one is that motion and actions of exoskeletons must follow exactly those intended by who wears it. To achieve this some technology is required, like precise actuator control, advanced position/force sensors and high-speed signal processing. Technological progress makes possible to wearable exoskeleton become real-life products. Some examples of lower-limb exoskeletons include Rex (Rex Bionics), ReWalk (ReWalk Robotics), Ekso (Ekso Bionics), HAL (Cyberdyne), ALEX (University of Delaware), X1 (NASA) and Indego (Vanderbilt University). The first two are shown in Fig. 1.

Figure 1. Rex and Rewalk exoskeletons (adapted from Bogue, 2015b)

Rex is a self-balancing, battery-powered lower-limb exoskeleton that can perform basic functions such as walking front, back and side, turning left and right, sitting down and standing up, all these actions controlled via joystick and powered by DC motors, and an on-board, lithium-ion battery pack allows around 2 hours of continuous operation. It is aimed for paraplegic users, even though potentially it can be used by people with tetraplegia, it is the only available exoskeleton that not requires crutches of a walking frame to provide stability.

ReWalk is a lighter exoskeleton, when compared to Rex, and it is more suitable for people who can balance and stand themselves with aid of crutches when walking, standing and rising from a chair. It is powered by electric motors that supply movement at the hips, knees and ankles, its battery-pack and computer are contained in a backpack. It is controlled via a remote control worn on the wrist. ReWalk has been tested in the USA, Europe and Israel and is supported by the most published data of all exoskeleton systems in the rehabilitation market and is used by more people worldwide than all other exoskeletons combined.

Ekso Bionics is a company that produce exoskeletons both for military and for medical applications. The first medical lower-body exoskeletons it produced was the eLEGs that was superseded by the Ekso 1.1 and Ekso GT, an exoskeleton that is also aimed for paraplegia who can balances users upper body and shift weights while walking, as presented by Strickland, 2012.

HAL exoskeleton is produced by Cyberdine a spin-out company from the University of Tsukuba. Several product generations and variants have been developed and many potential applications are foreseen, for predominantly medical purposes. By October 2012, over 300 HAL suits were in use by 130 medical facilities and nursing homes across Japan (Bogue, 2015c). In February 2013 It became the first powered exoskeleton to receive a global safety certificate. In August of the same year, the unit received an European community (EC) certificate, allowing its use for medical purposes in Europe. HAL exoskeleton is controlled by a system that receives signal from sensors on user's skin and convert them into electronic signals which initiate the intended motion.

Other existing exoskeleton is ALEX, developed in University of Delaware. This exoskeleton is a gait rehabilitation device which apply most suitable amount of force on the leg to help it to move along desired path. The limitation of ALEX is that it can only be used on a treadmill, and not as a locomotion aid system, only as a rehabilitation device, Banala, *et. al.*, 20019. Nasa's X1 exoskeleton is other gait training device, it can both assists or resists movement, it is made by the actuators positioned at hips and knees. It was developed as an assistive exercise device technology. Rea, *et. al.*, 2013.

3. METHODOLOGY

The new mechanical project aims weight reduction, increase of resistance, a new height adjustment system, more compact structure and lower joint friction coefficient. Those five points were considered during design process. And then designed in a CAD/CAE software.

The first step was selecting materials for construction, published in a previous paper, by making a study of varied materials available on market. Main frame of device and joints are mainly from aluminum 6061 and 7075. Some parts of fixtures (connection parts to users) are made from high density PE and Copolymer. Support and connection in lumbar region were made from more rigid Kydex. Joints and moving parts of mechanism were equipped by components from plastics Iglidur® J with very low coefficient of friction. Components from Prepreg carbon were implemented for better energy transfer between user's body and device. Gogle, *et al.*, 2015.

A strategy to reduce weight is design parts with a low mass density. The first prototype's main frame was built by aluminum plates with holes. That achieve a light weight structure but it's rigidity is directly affected since aluminum has a lower rigidity coefficient in comparison to other structural materials like steel and those plates are slim shaped, resulting in a small cross-sectional area, that means a lower resistance to mechanical loadings. A way to solve this problem was design a tubular structure that offers a bigger cross-sectional area without adding too much material in comparison with aluminum plates used in first prototype.

Tubular structure allows the implementation of a better height adjustment system that allows slightly adjustments while the older system only allows adjustments of at least 20 mm by changing position of the plates that are fixed to each other by screws, shown in Fig. 2. Old's system range is 100 mm and is present only in thigh structural plate. The new system is present in tight and shin tubes, it utilizes a sliding method: a tube is connected to a joint and a tube with a small diameter is mounted inside it and fixed with screws, the other end of this smaller tube slides inside a tube with bigger diameter, that is connected to other joint, and fixation is made by a clamp that fasten the sliding system. That system is shown in Fig. 3. The tubular main frame was also planned to accommodate inside the tubes wires from actuators and sensory subsystem connected to control electronics in backpack.

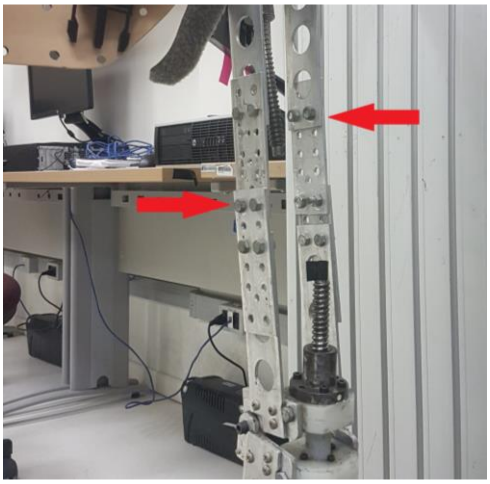

Figure 2. First prototype height adjustment system, the adjustment is made by changing position of the indicated screws

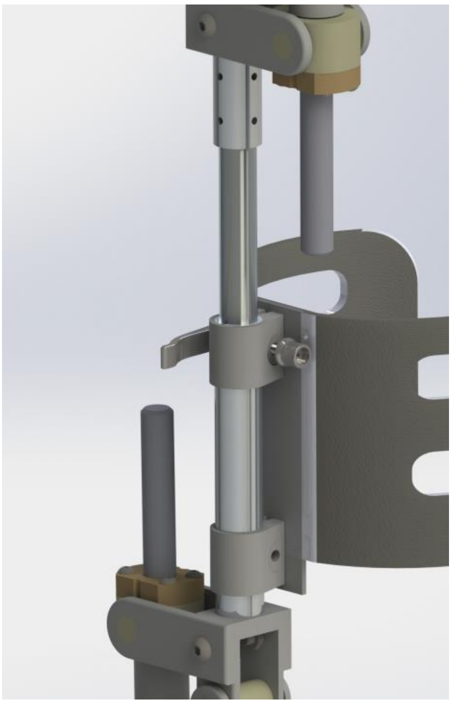

Figure 3. The new design of height adjustment system in thigh tube

The designed exoskeleton has six rotational joints, four of them are driven by 24volts/150W DC motors and two of them are passive joints and each motor gave an optical encoder with a resolution of 500 pixels per spin. The motorized ones are hips and knee joints, the passive ones are ankle joints. Each motor has a planetary gear box and is coupled to a screw, there is a nut made of Iglidur® J which drives the joint movement. As the motor is coupled to the screw, its rotation produces linear displacement of the nut in motor axial direction. This configuration, shown in Fig. 4, is more suitable to this project instead of attaching the motor directly on the axis of rotation of the joint because the high torque required to perform its movement, low angular velocity, angular positioning precision and reduced physical space.

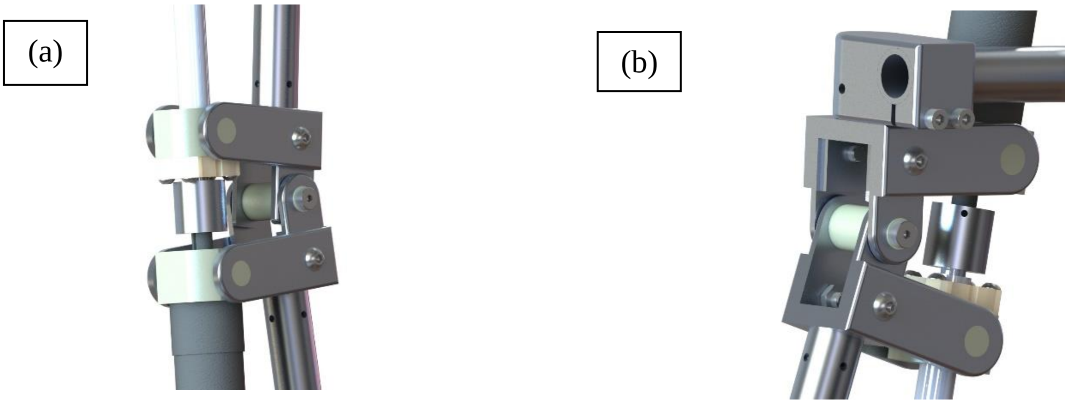

Figure 4: representation of (a) knee joint and (b) hip joint

In order to attach motors to joints, plates were designed to do so. Those plates guarantee a bigger torque, in comparison with the older prototype, due the distance they provide between motors fixtures and joint axis of rotation, acting like a lever. The lever distance in the new project is 62 mm while in older prototype is 50 mm. The ratio between torque produced by the new lever and the older lever can be demonstrated in Eq. (1). That came from Newton's Second Law of Motion. Where *T* means Torque and *d* is the lever length, the index *n* is for the new project and the index *o* is for the old prototype.

$$\frac{T_n}{T_o} = \frac{d_n}{d_o}$$

A new ankle joint and sole system was designed because was noticed that fixed ankle and rigid sole have negative impact on user's gait cycle, on waring comfort and consequently on power consumption itself. Analysis of the best design for the Ortholeg was conducted concerning following criteria, manufacturing and overall price, user-friendly design, variability and adjustability, reliability, weight and size, wearing comfort and safety issues. The final choice is shown in Fig. 5. It contains compression springs and they parameters were calculated using segment method, if a foot's weight is considered as 1.38 kg, compression springs with force around 35 N in full compression can be used.

Figure 5. The ankle joint system

4. RESULTS

Based on all improvement points in the first prototype, weight reduction, increase of resistance, improved height adjustment system, more compact structure and lower joint friction coefficient, a new design was made. The result was a completely new structure, it is tubular and more compact. Based on software simulations the new prototype weights approximately 5 kg less than older version. Figure 6 shows the old and new models side-by-side.

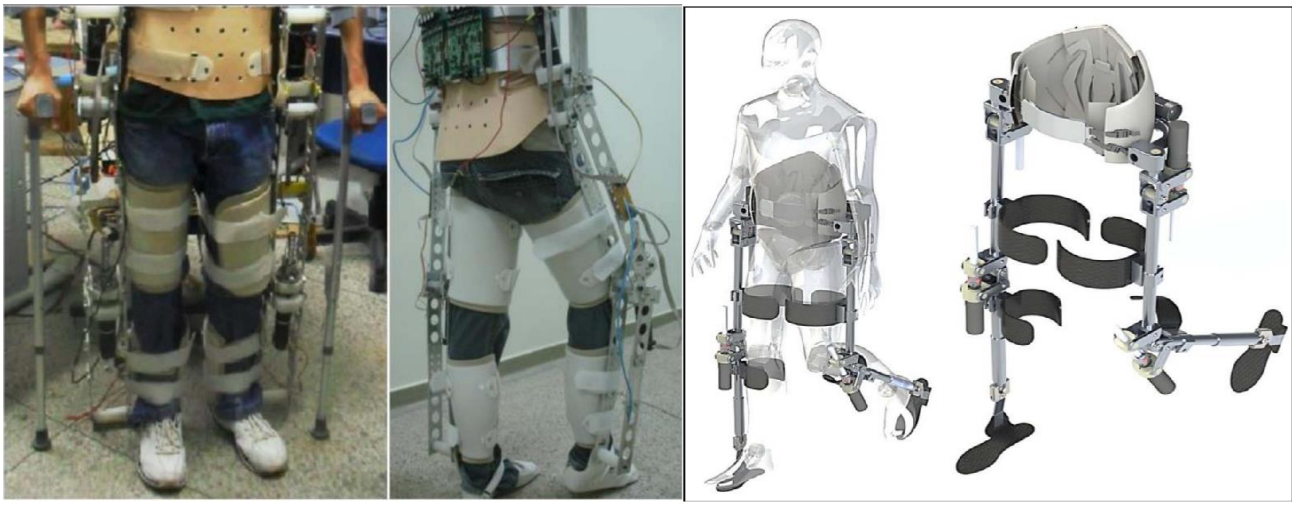

Figure 6. Ortholeg's first prototype on the left and new model on the right

The new project also presents a more ergonomic structure with better user's fixture system and an improved height adjustment system. The new height adjustment system presents a bigger range and an infinite number of positions inside this range, once the new solution is a sliding system.

All tubes that compose the main frame are from a standard market diameter. The new prototype still uses same actuators motors as in previous model, but with different lead screw and nut. Motor connectors and nuts in lead screws must be machined in Iglidur® J material. Prismatic joint parts should be made of aluminum 7075. Dimensional tolerances were considered in mechanical project, what should, along with low friction Iglidur® motor connectors, guarantee a lower friction coefficient.

Parts of the new prototype were already manufactured, like ankle joint, the carbon fiber shoe insert and users fixates, also made of carbon fiber. All tubes were already bought and joint parts are being machined.

5. CONCLUSION

The development of systems to aid patients with total or partial mobility in lower limbs, giving them the capacity of walking, sitting, standing, climbing up and down stairs, has been very fomented in past few years and shows being an area in ascension. The entire project of an exoskeleton requires a multidisciplinary effort. This paper showed the mechanical design, made in consonance with other areas like sensor data acquisition and electronics. The new mechanical project could achieve its goals of weight reduction and being a more compact structure. This new design was made aligned with which parts could be bought in market, reducing production costs of non-seriate parts.

6. ACKNOWLEDGEMENTS

This work is supported by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior).

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8. RESPONSIBILITY NOTICE

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