

Mechanical Design of an Active Hip and Knee Orthosis for Rehabilitation Applications

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Abstract

This paper presents the mechanical design of an active hip and knee orthosis for rehabilitation applications. The exoskeleton device consists of two motorized joints providing 2 DOF per leg and can support a non-standard critical user (1.90 m in height and 100 kg in weight) in rehabilitation gait conditions (gait speed ≈ 0.3 m/s). The work's methodology is firstly established with literature review to explore relevant orthotic projects already developed. Then, project requirements are defined, including critical user conditions, joint restrictions and rehabilitation gait torques and angular motion. The exoskeleton's structure is modelled following critical static and dynamic conditions and solved analytically for static failure and stiffness criteria. The actuation drive components are designed based in numerical modelling and also solved for static failure and stiffness criteria. The project's mechanical components are then designed following the results once they reached acceptable safety levels. The mechanical components can be subdivided into three main groups: lumbar support, limb structural links and actuation drives. Those groups are integrated to construct a prototype of the orthotic device. The assembled prototype presented the aimed robustness when tested for basic motion control associated with an equivalent rehabilitation gait pattern with artificial loads. The test trials showed low levels of induced deflection and the

actuation drive was able to replicate the torques required, therefore, making the orthosis to meet successfully the intended mechanical prerequisites.

Keywords

Mechanical design • Active orthosis • Hip-knee orthosis • Rehabilitation

1 Introduction

For many decades, orthoses have been playing an important role in the field of rehabilitation where many paraplegic, hemiplegic and spinal-cord injury patients have been benefiting from the orthotic devices. Since its first introduction in the US patent in 1935 [1], there have been many academic publications dealing with its development and control for various applications. In [2], an active bilateral orthosis intended for paraplegic assistance was developed. In [3], the goal was designing a simple, affordable and efficient semi-active hybrid orthotic system for support and facilitation of unilateral pathological human walking. Such solution supports neurologically injured patients' gait function towards safer and physiological patterns. In [4], a wearable active knee orthosis for walking assistance was developed, consisting of an active knee joint, a double-tendon-sheath transmission system aimed at reducing the weight of the orthosis and achieve preferable maneuverability. In [5], the main focus was minimization of the problems of speed, noise, and weight associated with orthoses, therefore, an externally powered model was developed using a bi-articular muscle mechanism with a bilateral-servo actuator.

The number of paraplegic patients is significant. For instance, in the United States alone, there are approximately 5.6 million paraplegic people [6]. In Brazil, according to *Instituto Brasileiro de Geografia e Estatística (IBGE)*, in 2015, about 6.7% of the Brazilian population showed some type of disability [7]. It can be inferred that a considerable part of this population consists of paraplegic patients. Due

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to this limitation, many people lose their quality of life and even professional opportunities, a condition which may lead to social exclusion. Aiming this problem, we propose a mechanical design and an early stage prototype of an active hip and knee orthosis.

In Brazil, lower limb exoskeleton models have already been developed by some projects such as [8] among others. However, we do believe that, still, there is room for new projects to emerge. Since this is the first work in the field of rehabilitation robotics from the research team from the Laboratory of Embebed Systems and Integrated Circuit Applications (LEIA) of the Universidade de Brasflia, Brazil, the early stages of a mechanical design project are developed.

First, the project's physical requirements are established using the Brazilian population's anthropometric proportions and physical conditions to determine a non-standard critical user parameters. Additional data retrieved from a standard gait pattern is also taken in account to define the torques and motion pattern that the actuation drive should provide for a rehabilitation gait pattern. With the boundary conditions defined, the system's static and dynamic models are solved using static failure and stiffness criteria. The defined mechanical conditions are used to design the mechanical components and their respective materials. A prototype of the assembled robotic exoskeleton was constructed and is presented in the results section. This work's conclusion section brings the final view in the results of the orthosis mechanical components and overall project.

2 Methods

2.1 Physical Requirements

Aiming at the design of a rehabilitation exoskeleton for use with spinal cord injury (SCI) individuals in a rehabilitation gait protocol, which operates at low speeds (≤ 0.3 m/s), there is no need for motion drives actuating in the frontal and transverse planes. Therefore, it is possible to neglect the gait-induced torques in the non-sagittal planes. That simplification is based on two considerations: First, the exoskeleton only provides motion in the sagittal plane. Second, the user does not apply any extra loads or torques to the structure, except the ones caused by the inertia and weight of the leg. Also, due the low gait speed, around 0.3 m/s, the inertial effects are expected to be minimal.

2.2 Brazilian Population Spectrum and Critical User

The data which provided the information about the average height and weight of the Brazilian population was obtained

from the Brazilian Institute of Geography and Statistics - IBGE based on a survey carried out in 2008. According to this survey, almost half of the Brazilian population (49%) aged 20 or over is overweight. This data is part of the study of anthropometry and nutritional status of children, adolescents and adults in Brazil released in 2009 and which was part of the 2008/2009 family budget survey [9]. The survey showed that, from 20 to 24 years of age, the medians of height and weight of the Brazilian men were 1.73m and 69.4kg while that of women were 1.61m and 57.8kg respectively.

However, in order to assess most of the users dimension spectrum, a non-standard critical user was defined. In such a user, due to body dimensions and weight, the internal stresses and deflections are higher due also forces, so if the orthosis can withstand the critical user, it can also sustain sub-critical users. Therefore, the critical user was set standing 1.90m tall and weighing 100 kg.

2.3 Anthropometric Proportions of Human Body

Anthropometry is the basis of exoskeleton and orthosis design since the device is aimed to incorporate with human body parts. In this work's case, the lower limb sections (hip and knee) that are considered. As presented in many exoskeletons projects development, such as in [10], the technique of anthropometry was also used for dimensioning the structural components such as the: (a) *waist length* of the anthropomorphic hip, and (b) *limb-line links lengths* which include the hip-knee and knee-ankle anthropomorphic links. While the links lengths are easily defined for a standard population due its direct relation with the user's height, the waist length is more variable because its additional relation with the user's weight and physiological proportions.

Based on the standard properties of human body provided from [11], the structural components dimensions of the exoskeleton were calculated, which include the dimensions of: (a) *waist length*, (b) *Hip-Knee link length*, (c) *Knee-Ankle link length*. For the calculation of these parameters, the critical user was used. The dimensions of the anthropomorphic links are shown in Table 1.

2.4 Mechanical Design Requisites

For the remaining gait-related characteristics, the actuation torques required for the motion drives of the hip and the knee joints at the sagittal plane in a rehabilitation gait condition are obtained from [12]. There, the critical torques for the hip and knee joints are normalized by the used body mass and can be further divided into the absolute minimum and maximum torques for each joint. For both hip and knee joints, the

Table 1 Mechanical Design Requisites

Component	Requisite established
User's max. height	1900 mm
User's max. weight	100 kg
Rehabilitation gait speed	0.3 m/s
Waist length	435 mm
Hip-knee link length	445 mm
Knee-Ankle link length	435 mm
Number of DOF hip joint	1 DOF
Number of DOF knee joint	1 DOF
Hip joint angular range	−20° (Flexion) 120° (Extension)
Knee joint angular range	0° (Flexion) 135° (Extension)
Hip joint torque range	0.07 Nm/kg (Flexion) −0.28 Nm/kg (Extension)
Knee joint torque range	0.14 Nm/kg (Flexion) −0.25 Nm/kg (Extension)
Absolute max. torque Hip	28 Nm
Absolute max. torque Knee	25 Nm

absolute maximum torque is found during extension. Table 1 shows the summary of the requirements for the mechanical design in this project.

2.5 Exoskeleton's Mechanical Project

With the exoskeleton's physical requirements defined, the next step was to design its mechanical components. Static and dynamic modeling of the exoskeleton's mechanical structure are developed considering separate individual sections. In this approach, each one of the individual sections represents an anatomical link of the lower body, ranging from the lumbar column to the ankle joint. The ankle itself is not modeled as a joint in this work, since the orthosis is aimed for hip and knee actuation. Therefore, the system has five different individual sections, but can also be divided in two main groups: (1) leg section and (2) lumbar and hip section, being both connected through the hip joint.

The main group systems are represented as free-body diagrams in Fig. 1, where, in order to present a reduced and clearer view of the whole model, the screw-joint variables were omitted. In the free-body diagrams, the letters P and R are force variables, M and T are moment/torque variables, l and w are dimensional variables and θ_h and θ_k are the joint rotation angles.

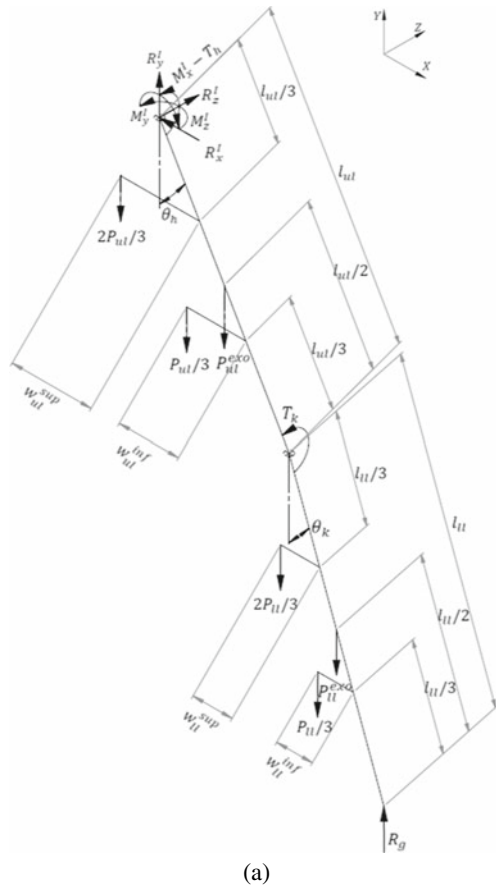
The association between the mechanical model and the physical requirements, where the anatomical dimensions and

gait torques correspond to the system's boundary conditions, enables solving it for the ultimate safety factors of the overall project. Such process is done using an analytical approach associated with an iterative algorithm coded in MATLAB environment. The first outputs of such process are the reaction forces/moments in all individual mechanical components. Once defined those intermediate variables, material and structure's geometric profile are taken into account to generate the second set of outputs, which are the stresses and deflections in the different sections of the system. With those variables defined, static failure and stiffness criteria are applied to ensure the safety of all the system's mechanical components.

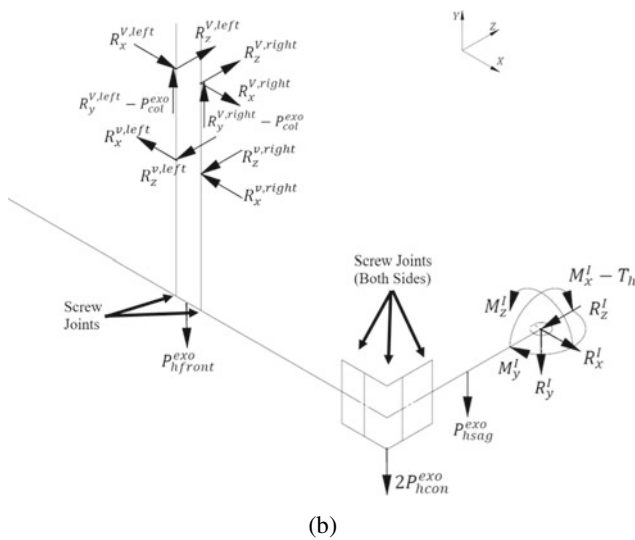
3 Results and Discussion

From the methods, concepts and assumptions presented in section II, the orthosis mechanical components were designed. They can be divided in two major classes: (1) Actuation direct drive (ADD) components and (2) Structural components. The first class includes all the components that are responsible for the actuation or transmission of the joint torques provided by the actuator. The second class contains the anthropomorphic-based components that surround and provide support to the user's body.

It is important to state two remarks relative to this first prototype. First, one of the aims was to validate the actuator drive construct and its capabilities to replicate the motion and



(a)



(b)

Fig. 1 Free-body diagrams of **a** Leg section and **b** Lumbar and Hip section

torques of an rehabilitation gait. Secondly, to evaluate the mechanical design of the whole structure to support the gait-related loads. Therefore, user-related specs, such as links with variable lengths or adjustable connections with the purpose to adapt to different users were not developed in this current work.

3.1 Design of the Actuation Direct Drive

From literature [13], many options regarding the actuation drive used in different exoskeleton models were analysed. From those, the actuation units that present a good power generated/used ratio and absolute torques provided are electrical motors with harmonic or planetary gearhead drives. Therefore, for this project, a MAXON set that combines a EC90 motor drive and a GP52 planetary gearhead is chosen as driving unit.

Aiming at direct actuation in the exoskeleton’s anthropomorphic joints, there was the need to design a coupler to hold the actuation unit in its respective joint position and allow the torque transmission to the next anthropomorphic link. Therefore, the full actuation set consists of (1) Actuation unit, result of the combination of the MAXON motor-gearbox set and (2) coupling components, which includes a roller bearing, a bearing block, and a shaft coupler.

The full actuation drive is shown in Fig. 2a. The *Outer Arm* and *Inner Arm* components, which were designed to connect the actuation unit to the link bars are show in Fig. 2b. The *Inner Arm* component connects the motor shaft and the distal link bar, acting as the effective rotation unit. The *Outer Arm* connects the gearhead coupler to the proximal link bar and was also designed as a mechanical limiter that restricts the rotation angle of the actuation mechanically. The analysis of shear force, torsion, compression of the actuation unit were all performed numerically and the data obtained were used to design these parts. The use of *Outer Arm* as a mechanical limiter helps to avoid any possible damage to the user, thus, making the project safer.

The materials for the actuation unit mechanical components were chosen considering factors such as strength/density ratio and ductility. Therefore, aluminum alloys were preferred for most components. The *Inner Arm* and *Outer Arm* were built with the 7075-T6 Aeronautical alloy, prizing its superior strength, while the 6061-T4 alloy

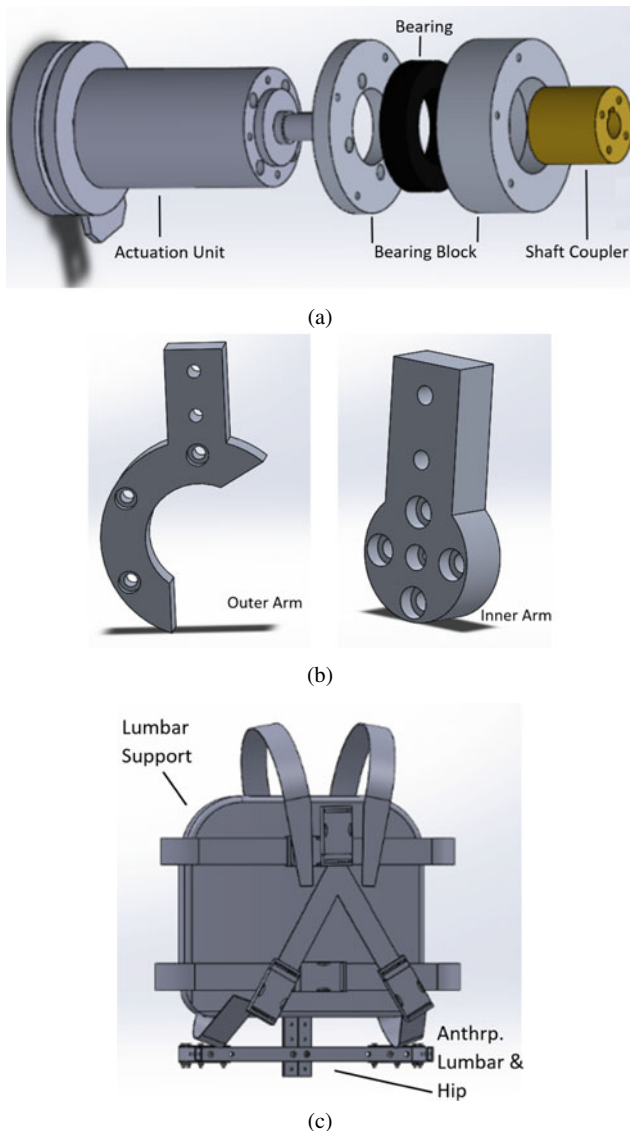


Fig. 2 Mechanical components, **a** actuation drive, **b** connectors for anthropometric links and **c** Lumbar support

is used in the bearing block. The shaft coupler, in the other hand, is built in brass and act as the safety piece aimed to deform in case of overload. The bearing used to hold the shaft coupler is a SKF 6008-2Z model.

3.2 Design of Structural Components

The structural components class includes the anthropomorphic rigid links (lumbar, hip, upper leg and lower leg) and the lumbar support that is fixed to the user. The final design of the

orthotic device's structure can be divided in four component categories: *Knee-Ankle Link*, *Hip-Knee Link*, *Hip and Lumbar Links* and *Lumbar Support*. The *Knee-Ankle* and *Hip-Knee* links are simple longitudinal structures that resemble their anatomical counterparts. In the other hand, the *Hip and Lumbar* structure does not present an exact anatomical match, since the hip part of the structure is designed to surround the user's body in a rectangular manner, and the lumbar column is positioned at the hip's back, and not in its center. The *Lumbar Support* does also have a unusual design when compared with other orthosis models, such as some shown in [1]. This model's support resembles a backpack (or a carapace) and is based in the work [14].

Following the literature review regarding exoskeleton's anthropomorphic structure, a similar trend of use of tubular/columnar links as structural components was found. Therefore, the geometric profile chosen for the structural links is a rectangular tube in aluminum 6063-T5 alloy. The rectangular tube's dimensions, such as wall width, were defined based in the system's analytical solution to ensure standard safety factors. These links will be padded to prevent damage to the user in the future.

The lumbar support was designed to be fastened around the user's back using adjustable straps. The lumbar support is built on a rigid frame associated with medium density foam that fit the user's back. The adjustable straps are made from A-grade polyester automotive belts.

Since the *Knee-Ankle* and *Hip-Knee* Links have indeed simple designs, they are not displayed in detailed manner in this work. However the *Hip and Lumbar* linkage set and the *Lumbar Support* have more complex assemblies, being shown, respectively, in the lower and upper parts of Fig. 2c.

3.3 Prototype Construction and Analysis

With the mechanical project developed, the system components were built and the complete prototype was assembled at the laboratory of automation and control (*Grupo de Automação e Controle—GRACO*) of the University of Brasília (<http://graco.unb.br/>). Focusing in the mechanical validation of the project design, only one side of the prototype was built and tested, as presented in Fig. 3.

This first prototype, consisting of the combination of two of the three main groups (1) lumbar and hip set and (2) right leg set, once assembled weights approximately 13.1 kg. The third group set, which is the unassembled left leg would weight additional 5.6 kg, leading to a total weight of 18.7 kg for the complete orthosis model. However, unlike other lower body



Fig. 3 The active orthosis prototype with one mounted leg

exoskeleton models (usually HKAFO class), this one currently does not have an anthropomorphic ankle. Such limitation brings the impossibility of performing an completely assisted gait, as well making direct comparisons with other models specifications, such as weight or costs.

After the complete assembly of the prototype, the testing protocol was divided into three parts. Firstly, the actuation drives in both hip and knee joints were controlled separately to reach the respective joint's maximum acceleration. Such test aimed to asset the experimental setup built for the exoskeleton as well test a simple motion control strategy. The second experimental test was to load the orthosis with the equivalent weight of the leg to replicate the maximum torques reached in rehabilitation gait conditions (see Table 1). Again, this test was performed in each active joint separately and was able check: (1) the effective power of the actuation unit after the losses of the coupling components, and (2) the deflection level of the anthropomorphic links with a critical level of external loads. The final experimental trial was to create a motion control in which both joints would move simultaneously to replicate a rehabilitation gait pattern. Such test indicated if the exoskeleton's structure could stand the combined multi-articular movement loads and induced moments without significant deflections.

The experimental trials presented satisfactory results. The control strategy, despite being simple, was able to replicate a rehabilitation gait pattern under the desired range of the coupling components. In the second and third testing phases the orthosis structure showed mechanical robustness and low levels of load-induced deflection, while it could move the critical user's equivalent load without reaching the actuator's peak torque.

Despite this prototype's results, questions that might arise are if the model will still have the same results when assembled with both legs or in a eventual gait trial. For the first situation, we do believe that the deflections would only be higher in the *Hip and Lumbar* linkage, since a induced moment would appear due the dynamical variation of the antagonist leg. However, to counter an excessive deflection, the lumbar column structure is doubly reinforced, as shown in Fig. 2c. For the second situation, however, deflections in all links can be expected to be even higher due conditions associated with user interface or control. For example, a user could, intentionally or not, increase its muscular stiffness beyond the limits for which this exoskeleton was designed, reaching critical deflection or stresses. To counter that problem, the orthosis mechanical structure should be reinforced in future works.

4 Conclusions

This work has the main objective of designing the mechanical structure of a active lower limb orthosis for the hip and knee joints. Due to its focus on robustness, the Exoskeleton project was made aiming at its capacity to support the conditions associated to a non-standard critical user. At the same time, the project presents fair safety factors and is capable of providing mechanical security to the structure. The Exoskeleton prototype met the prerequisites successfully, and proved capable of acting in the area of rehabilitation.

However, as of future works, the authors are considering implementing a suitable control strategy using instrumentation or Brain-Machine Interface (BMI) with the help of Electromyography (EMG) or Electroencephalography (EEG) signals for operational control. The mechanical structure can also be redesigned in such a that, the links and the waist structures can be adjustable, thereby increasing the range of users size and making the structure compatible to more users with different sizes. Additionally, the structure can also be reinforced to ensure additional safety for the user.

With respect to the number of DOF, the mechanical structure developed in this work's prototype considers that, since it would not completely restrain the user's lumbar and hip, the user could develop some low-level adaption for core and hip movement to assist the gait. Therefore, for the time being and aiming at the hip and knee movements, 2 DOF per leg are sufficient for movement testing in the prototype. However, in future works the number of DOFs should be increased, even if some of them are designed as passive, to be able to replicate de DOFs of a more natural gait.

Acknowledgements The Authors thank CAPES and Laboratory of Embedded Systems and Integrated Circuits Applications (LEIA) for proving the necessary tools and finance that made this project successful.

Conflict of Interest The authors declare that they have no conflict of interest and are the sole responsables for the information presented in this work.

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