Exosuit for Alternative Hip Actuation: A Proof of Concept

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Abstract. *This paper designs an exoskeleton-based prototype geared up like a suit, named "Exosuit". Such construct provides an alternative approach for exoskeleton actuation systems, based in a composed system of linear actuators and integrated transmission instead of rotative actuators. Such actuation system controls the hip joint motion, joint hard to control with superficial electrical stimulation. The structural and actuation system design requirements are calculated based in anthropometric and rehabilitation walking properties. Experimental test trials were conducted to retrieve kinematic data of unassisted gait at slow rehabilitation speeds and exosuit-assisted gait. The experimental results are processed with a signal-processing program, defining and comparing the average gait cycle of each gait type. The conclusions show that, despite an excessive range of motion due to mechanical limitations, the exosuit-assisted gait replicates the kinematic shape of normal hip joint motion and could be further improved.*

Keywords: *Exoskeleton, Exosuit, Rehabilitation*

1. INTRODUCTION

Spinal Cord Injury (SCI), which is often caused by trauma, is a devastating condition that affects, per year, 23 new cases per million inhabitants globally, as presented in Lee (2014). SCI is a public health problem, responsible for disabling a young and active portion of the population.

In a complete SCI, the individual is unable to voluntarily control the muscles whose enervation lies below the lesion and will not perceive sensations from those body parts. Furthermore, there may be additional consequences, such as the inability to breathe, and urinary incontinence. In view of the prospective of limited recovery among these individual, technological resources appear to be one of the promising alternatives for assisting movement and promoting rehabilitation. Among technologies that induce limb movement, there are active orthoses or exoskeletons and neuromuscular electrical stimulation. Both types of assistive devices are currently under intensive research, however, the integration between the two type of technologies is still in early stages of development.

Aiming to work in that interdisciplinary field that brings together biomechanics and engineering, a first idea to bring both technologies to a same project would be to use electrical stimulation in some leg muscles to create the core of the gait movement and the exoskeleton structure to provide support to the user. Such combination can be advantageous since it is complex and impractical to stimulate all the leg muscles to replicate a healthy gait, principally when dealing with surface electrodes. At the same time, the exoskeleton structure can be designed to house smaller actuators, since they are not the main power source for movement.

The hip joint movement is one which isolated stimulation is difficult to achieve using only surface electrodes due the fact that the $gluteus\ maximus$ muscle is below a thick layer of fat tissue. Therefore, a typical exoskeleton approach can be made for this joint, with the use of a mechanical actuator. Focusing only in the hip movement, there is no need for the development of a full exoskeleton. Therefore, a structure more-like a suit that can be geared up in the back and the legs of the user and, additionally, house all the actuation and controlling systems on board the support, is a valid approach.

Additionally, one of the objectives of this model of active orthosis, from now on called "hip exosuit", is to develop an alternative actuation system from the ones more commonly used to build exoskeletons or similar constructs. In this way, this model of assistive device is innovative not only in the objective of, in future works, creating a model that uses both electrical stimulation and usual exoskeleton technologies, but also presenting a uncommon actuation system.

In section 2 we address different system actuation approaches, our experimental apparatus and the analysis procedure. In section 3, our results are discussed and outlined in the conclusions.

2. MATERIALS AND METHODS

2.1 Design Overview

The standard type of actuation approach used in exoskeletons or similar systems, such as prosthesis, is based in rotative motors. Those motors are placed or connected directly in the joint that they are meant to move, transmitting the rotational movement of the motor into the rotational movement of the joint. Those motors require proportionally great torques and power to replicate the usual biped movement.

To differentiate this work's actuation system and provide a alternative approach to joint movement, the unit used in this work is a linear actuator combined with a transmission system. The model of linear actuator chosen is the ANT-38 model, from Sito Motors Co., that is an model which operates with constant linear speed and transmission force. The transmission system that transfers the power from the actuator to the equivalent hip joint of the exosuit was designed with sheaves and steel cables. The calculations that led to the choice of specific characteristics of the linear actuator and transmission system are developed furthermore.

The first steps to design the hip exosuit and actuation system were to define an anthropometric range capable of suit a good parcel of human subjects. Therefore, the model developed was not only designed to be adjustable for different heights and body measures, but was also designed for a critical case of power and torque requirements, that is a taller and heavier subject than an average human specimen. The anthropometric relations applicable for the test subject are taken from Herman (2007), and are shown in Tab. (1).

Table 1: Anthropometric dimensions and characteristics.

	Anthropometric Relation (Herman, 2007)	Critical Case Dimension
Weight (kg)	W_{body}	100
Height (m)	H_{body}	1.80
Normalized Hip Torque ($N \cdot m/kg$)	T^N_{hip}	0.8
Upper Leg Weight (kg)	$0.161 \cdot W_{body}$	16.1
Upper Leg Length (m)	$0.245 \cdot H_{body}$	0.44
Hip Torque ($N \cdot m$)	$T^N_{hip} \cdot W_{leg}$	12.9

After the anthropometric parameters were already set, the next step was to define the transmission system, crucial item to choose the power and torque requirements of the linear actuator. After analyzing the Brazilian norm for sheaves present in Provenza (1996), it was chosen a $F2$ sheave model with twice the minimum diameter, that would be something of the order of $110\ mm$. Since the actuators are displaced in the back support of the exosuit, were needed two sheaves to guide the transmission cable to the hip joint.

Once with the dimensions of the sheave, the actuation force and the stroke length that the linear actuator should provide could be calculated, as shown in the first two equations of Tab. (2). The angle ψ represents the maximum angle reached by the hip in an normal gait, and was taken from Herman (2007), where it can be set as $\psi \approx 45^o$.

The other considerations needed to design the actuation system were gait-related ones. Since the exosuit's application is an rehabilitation scenario, the gait properties, such as actuation speed, are also dependent in such characteristics. From the results of Bohannon (1997), a conservative rehabilitation gait can be estimated as $0.3\ m/s$. The stride length was measured as $0.75\ m$ with the same subject that participated in the experimental gait tests presented in subsection 2.2. Once with both factors and the stroke length, it was possible estimate the actuation speed, presented in the last equation of Tab. (2).

Table 2: Actuation system calculated requirements

	Governing Relation	Calculated Requirement
Stroke Length (mm)	$\psi \cdot r_{sheave}$	43.2
Actuation Force (N)	$\frac{T_{hip}}{r_{sheave}}$	235
Actuation Speed (mm/s)	$L_{stroke} \cdot (\frac{l_{gait}}{v_{gait}})^{-1}$	17.3
Actuation Torque ($N \cdot mm$)	$T_{act} \equiv T_{hip}$	12.9

With the actuation system calculated requirements, the real model could be designed. From the actuators available in the market, the one with the best cost-benefit was an ANT-38 from Sito Motors Co. with roughly twice the force and torque required by the system, but with also half the speed of actuation. From that actuation characteristics, a reduction system was designed into the transmission sheaves to compensate the actuation speed in sacrifice of the actuation torque. In the transmission system, the first sheave is connected directly to the actuator, and the second sheave is a reduction-type one, with two diameters. The smaller diameter of the second sheave is the one connected by steel cables to the first sheave, creating the reduction that meet the actuation requirements.

Once the actuation system was solved, the exosuit structure was designed. As mentioned in the introduction section, the approach chosen was an adjustable suit-like structure that could be easily geared up. The core of the exosuit is a rigid back support like a backpack that can be adjusted by a series of straps to best fit into the subject's body. The back support not only houses the main actuation system and its controller, but also provides more stability to the user by maintaining its spine column erect.

The back support is connected to the more exoskeleton-like external structure that supports the transmission system and contours the body of the user. In displacement terms of the elements of the transmission system, the main sheave is placed in the end of the lateral beam to guide the steel cable to the beam that guides the lateral structure to the exosuit's hip joint. A small connector between the two sheaves maintains pressure in the cables during actuation. The connection between the equivalent structural upper leg and the user's upper leg is also by straps.

The whole exosuit structure provides only one degree of freedom: the rotation of the hip joint in the sagittal plane. The project also opted to add only one leg in this first prototype so the other leg could provide additional support and stability in a case of malfunction of the prototype.

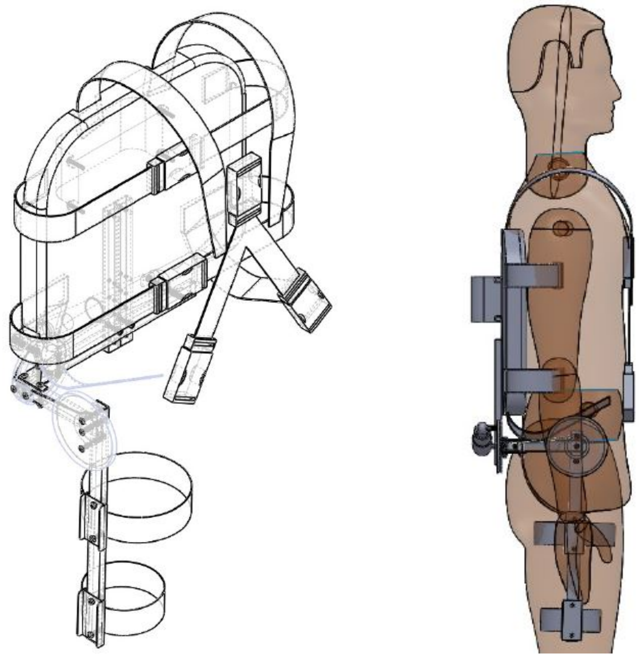
From the informations presented both Tab. (1), Tab. (2) and the structure's description presented in the previous paragraphs, the exosuit structure, actuator and transmission system were designed. Their characteristics and properties are shown in Tab. (3).

Table 3: Final design dimensions, characteristics and properties of the hip exosuit prototype.

Exosuit Structure		Actuator		Transmission System	
Total Weight (kg)	8.5	Stroke (mm)	50	Reduction Factor	2.45
Frontal Length (mm)	260	Force (N)	500	Force (N)	210
Lateral Length (mm)	420	Torque ($N \cdot m$)	27.5	Torque ($N \cdot m$)	11.3
Height (mm)	790 - 890	Linear Speed (mm/s)	9.0	Linear Speed (mm/s)	22.1
Angular Range (^{o})	-58.7 - 34.5			Angular Speed ($^o/s$)	23.0
Actual Gait Speed (m/s)	0.14			Theoretical Gait Speed (m/s)	0.38

Regarding to the materials used to build the exosuit, the support is made of an back support of an ergonomic seat. The external structure is made of aluminum beams, feature that helps to reduce the weight of the whole construct. The sheaves are made of Nylon and the $1\ mm$ diameter transmission cables are made of stainless steel.

The CAD models of the assembled exosuit in standalone and anthropomorphic versions are shown in Fig. (1).



(a) (b)

Figure 1: CAD schematics of the hip exosuit prototype in (a) Standalone version; (b) With anthropomorphic model.

2.2 Experimental Test

With the assembled exosuit built and ready to operate, an experimental test was conducted to analyze its gait kinematics and compare with the ones of unassisted gaits at rehabilitation speeds. In order to maintain a constant speed during the test trials, the test trials were performed in a JOG FORMA treadmill model from Technogym®, that can work at very slow speeds. To retrieve the experimental kinematic data, it was used an 3-Space inertial sensor model from Yost Labs.

Since the kinematic data at slow rehabilitation speeds are scarce, three gait tests were conducted in the same subject, being two of them of unassisted normal gaits at slow speeds, and one with the exosuit. The speeds chosen to work with were: the conservative rehabilitation speed of $0.30\ m/s$, the slowest possible speed of the treadmill of $0.10\ m/s$, and the exosuit normal gait speed of $0.15\ m/s$. In all three trials, the inertial sensor was placed approximately at the half distance of the length of the upper leg. All tests were conducted for 60 seconds after the subject had already reached walking steady-state, in order to eliminate transitory-state data.

2.3 Experimental Data Analysis

The data retrieved from the inertial sensors was exported in $.bag$ files, and treated in MATLAB® platform. The kinematic analysis of the angular data followed the biomechanical convention, that sets flexion angles as positive and extension angles as negative. In this way, the movement is set as positive when the leg is moving forward, and negative when moving backwards.

Based in the experimental output data, a signal processing program was coded to read and process the kinematic data. The final average cycle of each trial was achieved by the following set of steps: firstly, the cycles of each trial are defined based in the peaks found. Secondly, polynomial approximation functions create unique regression functions for each cycle. A error-based filter is applied on the regression functions to eliminate the ones that do not provide good approximations. Furthermore, the remaining approximation functions are averaged, and a new polynomial-based approximation is defined from the averaged function.

3. RESULTS

With the structural design project of the exosuit finished, a real model prototype was built, as shown in Fig. (2), already geared up by the subject that is also used in this work's experimental tests.

(a) (b)

Figure 2: Pictures of built hip exosuit prototype in (a) Front view; (b) Side view

A project factor difficult to replicate was the calculated actuation speed to achieve the rehabilitation gait speed of $0.30\ m/s$. Even that the theoretical transmission speed was more than sufficient to reach the desired speed, the experimental results showed that the actual speed reached during the gait tests was less than a half of the desired one.

The first factor that cause such difference in speed is the delay that the onboard controller takes to change its direction of actuation. Such problem is related to the nature of the product and could not be fixed due the controlling system being isolated and closed to external modifications. Hence, in order to optimize the work done by the actuator, it acts continuously until it reaches almost its limit, and only then it changes its direction of actuation, but the direction-change delay is still there. Another factor that can be taken in account to slow the actuation speed is the friction that was not accounted between pieces and structure, and between the cable and the tensioning connector. The final factor that contributes greatly for the speed reduction is the gradual loosening of the transmission cable, since the sheaves themselves and their pinning elements, that holds the cables to the sheaves, are made of nylon and start to loosen with time of work.

Although it was perceived a difference between the theoretical and real gait speeds in exosuit test trial, there was no perceptible change in the transmitted torque and force to the hip joint, since the hip angle could reach the structural mechanical limits of the exosuit, as shown in the results ahead in the paper.

Some of the properties of the gait trials are shown in Tab. (4). As can be seen, even being at a slower speed than the other trials, the stride length of the exosuit gait is greater than them. That fact can be explained by taking in account that the prototype was designed to use the full extension capacity of the actuation system, creating bigger steps that also take longer to complete the gait cycle, but that in the end reaches a speed that is almost half of the conservative rehabilitation gait speed.

Table 4: Test trials gait properties

	Normal Rehabilitation Gait	Slower Rehabilitation Gait	Exosuit Gait
Speed (m/s)	0.30	0.10	0.14
Stride Length (m)	0.53	0.25	0.75
Stride Period (s)	1.76	2.54	5.35

Figure (3) shows the retrieved experimental data from the exosuit gait. As can be seen, the approximation functions create decent results, and the gait cycles, despite presenting some sort of new average set point after half trial, still conserves its form.

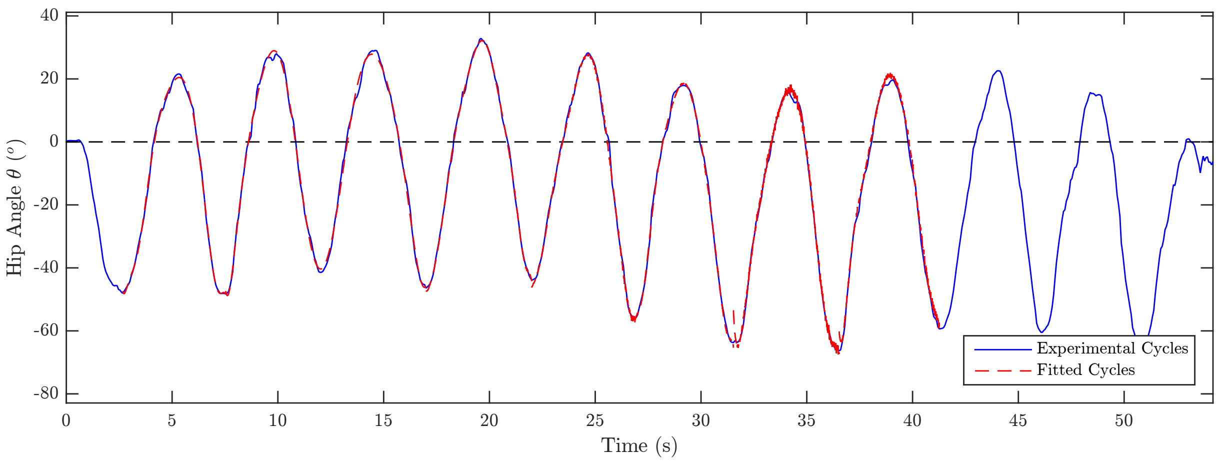


Figure 3: Experiment-retrieved hip angular data

As mentioned in the "Experimental Data Analysis" subsection, the raw data of the test trials, such as the one presented in Fig. (3), were processed and then determined the average gait cycles for each gait type. Figure (4) presents these average results for the three tests.

The results depicted in Fig. (4) show that the kinematics of the hip angle change subtly between the unassisted gait trials, however, the exosuit assisted trial differs greatly from the others. Such as mentioned prior in this section, the reason behind that difference is the actuation system design, that achieves a higher angular range for a longer stride in order to compensate the delay that the controller takes to change its direction of actuation.

With respect to the kinematic data analysis, despite the visible difference between the scale of assisted and unassisted gait cycles, the shape of the average hip angle remains similar for the three trials. Therefore, it can be seen that the exosuit is able to generate a movement that, even if not close in magnitude to a normal movement, matches the pattern of a normal gait. Furthermore, it can be hypothesized that if the the actuator time delay to change its direction is reduced, the range of actuation could also be reduced to match a normal range of movement, possibly bringing the magnitude of angular range closely to a normal gait. Such modification could potentially generate a more natural gait.

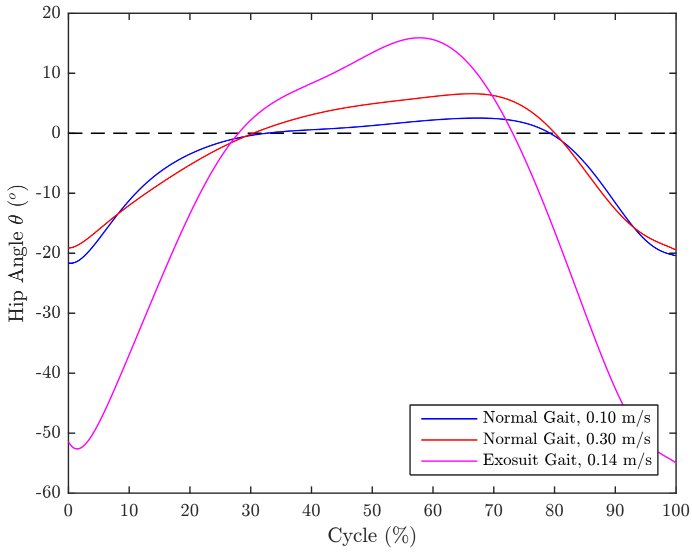


Figure 4: Hip angular average cycle for experimental tests

4. CONCLUSIONS

From the initial premise of creating an alternative actuation system for the hip joint movement, this study was able to design a combination of a linear actuator and a simple transmission system with satisfactory action to generate walking motion. The strong points of this project are: 1) the simplicity of gearing up the structure on the user and 2) The user's control during walk. It was observed that the system could still be improved to generate a more natural-like gait pattern.

The experimental tests conducted to generate the kinematic data of unassisted gait in rehabilitation speeds and assisted gait at the fixed exosuit speed were able to return resourceful data for basic signal processing. The output of the processed data generated the average gait cycle of the test trials.

The analysis of the kinematics of the gait trials provided a better view in how, for the exosuit-assisted gait, the range of motion is being overworked in order to compensate the actuation limitations. However, even with the excessive range of motion, the pattern of the exosuit gait is still acceptable, and can be further improved.

The experimental trials also proved the success of the structural design. The exosuit was able to sustain intensive work with a subject whose physical characteristics almost meet the critical case the structure was built to support.

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6. KNOWLEDGMENTS

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7. INFORMATION RESPONSABILITY

The veracity of information presented in this work are of sole responsibility of the authors of the paper.