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Research Article

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Exoskeleton Mechanism for Foot Drop Causes

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Abstract

Design and analysis of an active ankle orthosis, which will help the gait cycle of people who have difficulties performing the lower limb's dorsiflexion movement; this condition is called foot drop. Foot drop is a weakness or damage of the common peroneal nerve, including the sciatic nerve, or paralysis of the muscles in the anterior part of the lower leg. Active orthoses consist of moving parts with external power applied for motion. In the proposed exoskeleton, the selection of motors to provide torque to the ankle joint enables the lower limb to be raised. Also, a flex sensor controls the motion. Composite materials were used to increase the strength of the exoskeleton and reduce the weight. A Finite Element model was developed to investigate the forces' effect during the walking cycle on the proposed mechanism. The idea was to construct a small, consumer-appealing, and active orthosis, enabling comfortable daily usage and rehabilitation.

Keywords: Exoskeleton; Active ankle orthosis; Wearable; Gait cycle; Flex sensor; F. E. analysis; Design; Composite materials

Introduction

Stroke, disseminated multiple sclerosis, medulla spinal cord injury, and other diseases can affect dorsiflexion movement. A general term for this condition is foot drop. Foot drop is a gait abnormality that affects the foot's and the toes' lift. The possible causes of foot drop are either damage to the peroneal nerve, which consequently creates muscle weakness or paralysis of the muscles of the anterior part of the lower limb. People with gait disturbances have kinetic difficulties, and this is often reflected in their psychology. They compare themselves with others in their environment, a situation that can significantly harm their mental health. A potential solution for these problems is exoskeletons that may rehabilitate or assist in their gait. Consequently, they will also appear improvement in their behavior. It is noticed that the foot drop gait cycle differs from the normal one due to the difficulties encountered during dorsiflexion. The asymmetric gait leads in plantarflexion or in the galloping gait during the swing phase. This situation may be painful for the human skeleton. The role of active orthosis or exoskeleton in patients with foot drop is to lift the foot during the swing gait phase. The term 'exoskeleton' is used to describe a device that supports and enhances the performance of a non-disabled wearer. The term 'orthosis' is often used as a device that assists people with limb pathology. Depending on the disability of the body's part(s), there are several types of exoskeletons. There are knee exoskeletons, ankle exoskeletons, exoskeletons for lower, and upper limbs, a combination of exoskeletons, such as knee-ankle exoskeleton, and others. Some of them operate with pneumatic power, others with hydraulic, and others with mechanical power. Another interesting method to deal with foot drop disease is FES (Functional Electrical Stimulation). This method activates the paralyzed muscles through electrical stimulation. In this study, the exoskeleton defines an active ankle orthosis [1].

Considering those mentioned above and the need for foot drop patients to be independent, an active ankle orthosis controlled with flex sensors and operated with mechanical power was developed. The developed system was named it ExoGaitOr. The basic idea is to help people with a disorder on dorsiflexion at the swing phase. The challenge of this orthosis lies in portability, adaptability according to the patient's needs, as well as in the small size. Furthermore, it is essential to mention that ExoGaitOR consists of composite materials, which is interpreted in a low-weight exoskeleton with high strength. The composite materials provide in the ExoGaitOR the low-weight characteristic, in addition to its high strength. The sections below present the design of the ExoGaitOR and its endurance analysis.

Research Cases

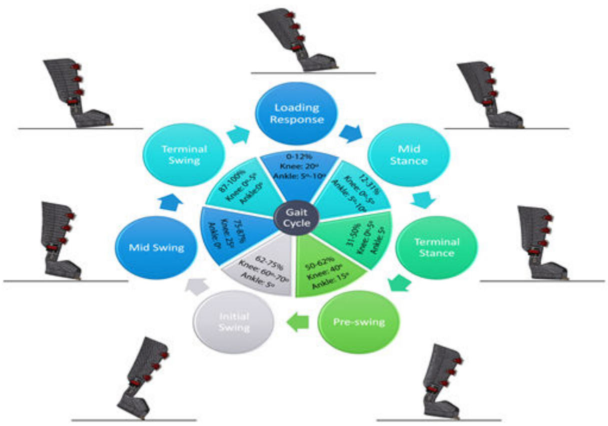

Figure 1: A complete walking cycle.

Background theory

The basis of this study is some of the physiotherapy principles, such as the gait cycle and the ankle joint's force or moments or degrees of ankle flexion during the gait cycle. According to them, the gait cycle of people suffering from foot drop is different from the usual. Consequently, this work aims to 'mimic' the normal gait. Firstly, it should be noted that the human's gait cycle (Figure 1) constitutes distinguishable periods or movements or phases. The gait cycle consists of two main phases: the stance phase and the swing phase. The stance phase is 60% of the gait cycle and includes the loading response, the mid-stance, and the terminal stance. This phase lasts from the beginning of the gait until before the foot swings. In other words, the described move is the plantarflexion move. The swing

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phase starts after the stance and is the additional 40 % of the gait cycle. This phase includes the pre-swing, the initial swing, the mid-swing, and the terminal swing phase. As we can understand, this phase starts when the foot is on dorsiflexion. Figure 1 displays a complete and normal gait cycle. The swing phase of people with foot drop differs from the regular one (Figure 2). Therefore, they adopt galloping walking [2].

The following diagrams are derived from the bibliography. They are ostensive and show the difference between the normal gait and foot drop gait. Possible deviations may exist. It is worth mentioning that the gait cycle is different from human to human and depends on any injuries that may have occurred to someone.

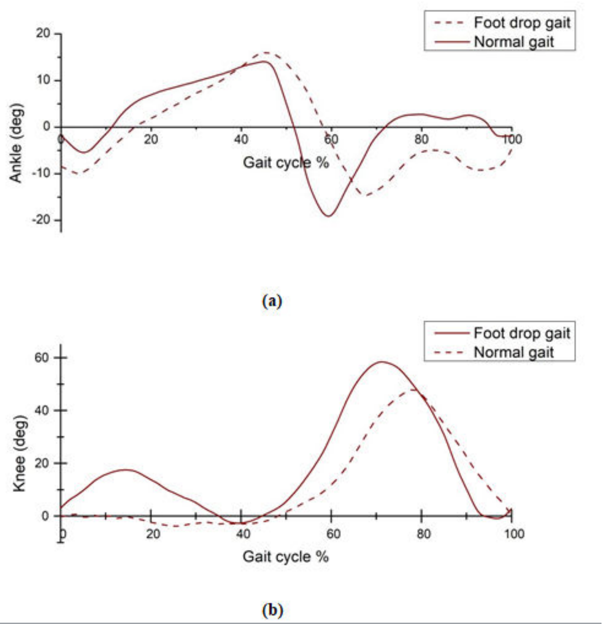

Figure 2: Ankle a) and knee; (b) comparison of and foot drop degrees.

For the design of ExoGaitOR, the theoretical forces, moments, and degrees of the ankle during gait were utilized. Considering the previously mentioned values and the charts below, we can calculate the moment (Figure 3b) and the vertical ground force reaction (Figure 3a). The anterior and posterior force is insignificant. Furthermore, the maximum degrees of every phase of the gait cycle of the ankle and the knee are critical points of the study as they are the building blocks of the ExoGaitOR's control system.

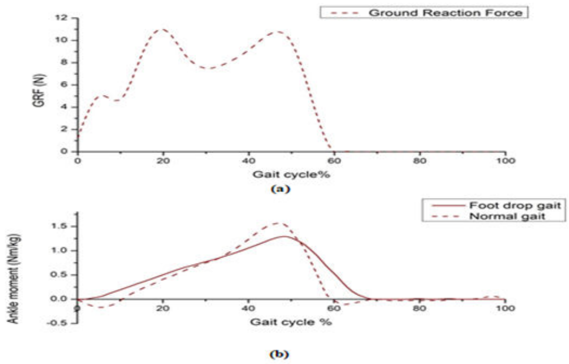

Figure 3: Graph representation of the vertical ground reaction forces (a) and the comparison of ankle moment.

Design of the exoskeleton

The orthosis' composite parts were designed using the commercial design software Solidworks. The orthosis consists of two components; the upper and the lower one. The upper orthosis part (Figure 4, b) is placed around the tibia to provide support. Also, it is used as a base for the mechanism and the control system (gear set and servomotors). The patient's foot is surrounded by the lower orthosis part (Figure 4, a) of the exoskeleton, which impels the foot to lift after applying the force. These two parts are connected at the ankle joint. Their geometry follows the foot's morphology so that it will be possible to wear it inside the shoe. It is worth mentioning that the upper orthosis part of the exoskeleton's stable support is achieved by using a hook and a loop fastener on the tibia and a rubber band on the lower orthosis part of the exoskeleton. Moreover, the motors' bases are located on the sides of the upper orthosis part. The straight bevel gears have been added, different diameters and numbers of teeth, to transmit the torque from the servo motor to the lower orthosis part (Figure 4, c and d). As a result, the torque (of the servo motor output) increases. The effective transmission of torque is accomplished with the connecting parts (Figure 4, e and f). Furthermore, the ball bearings are used to stabilize the rotating shafts and reduce friction [3].

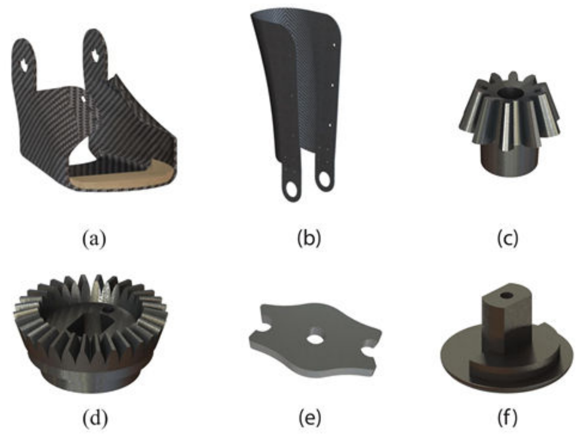

Figure 4: ExoGaitOR fundamental design part.

For the Arduino Nano microcontroller's safe installation, a plastic housing, which consists of two parts, has been designed (Figure 5, c). Properly shaped openings are utilized to connect the cables to the ports of the board (Figure 5, b). Additionally, a small base with a hole is engineered and placed at the right side of the Arduino box. The patient can wear the base mentioned above, either on his pants or on his belt, using a hook (Figure 5, a).

Figure 5: The enclosure of the Arduino Nano microcontroller.

Control system

The present exoskeleton aims to provide power to the ankle joint. In that way, the patient can overcome the lack of the adequate load needed during the gait cycle (especially in the swing phase). The exoskeleton's main operating parts are the flex sensor, the Arduino microcontroller, the servomotors, and the straight bevel gears. The flex sensor is placed at the back of the knee joint due to its smaller curvature and morphology compared to its front surface. The flex sensor measures the degrees of the angle formed between the tibia and the thigh. The Arduino microcontroller receives these data. Then the microcontroller analyzes the input data according to the gait cycle data of the patient, which are obtained through kinematic analysis - diagram of knee angles as a percentage of walking time (Figure 2, b and Table 1). Finally, it gives the output commands, based on a diagram of ankle angles as a percentage of walking time (Figure 2, a), with the two servomotors (Figure 6, no 1). The torque transmission from the motors' vertical axes to the horizontal axis of the joint of the lower orthosis part of the exoskeleton is performed with the bevel gears sets (Figure 6, no 2 and 3). The servo motor's output axis has a pinion (Figure 6, no 2), which rotates at the same speed as the servo. The pinion cooperates with the gear (Figure 6, no 3), and as it rotates, it drags it, forcing it to perform a rotating motion. The gear drives the torque to the exoskeleton joint through the connection shaft (Figure 6, no 4), tending to either raise or move down the lower orthosis part (Figure 6, no 6). The rise of the lower orthosis part corresponds to the dorsiflexion, while the moving down of the lower orthosis part's action represents the plantarflexion.

	Normal gait				Foot drop gait			
	Swing phase		Stance phase	Stance phase	Swing phase			
	Ankle	Knee	Ankle	Knee	Ankle	Knee	Ankle	Knee
min	-19.81	0.07	-2.37	0.19	-10.42	0.81	-15.19	1.74
max	1.83	55.96	12.67	20.39	14.71	14.33	0.52	40.18

Table 1: Minimum and maximum angles of knee and ankle.

The positive and negative torque shows opposite directions. This indicates a change in the rotation's direction of the servo motor axis. The above description refers to the typical operation of the integrated equipment (motors, bevel gears, connecting shafts). Two batteries power the electronic system. The power supplies are placed on the patient's waist. More specifically, they are installed in specially shaped cases on the user's belt. The transfer of power to the microcontroller and servomotors is conducted using cables.

Figure 6: Assembly of the ExoGaitOR. 1: servo motor, 2: pinion gear, 3: gear, 4: connection part, 5: upper orthosis part, 6: lower orthosis part.

Material properties

As it was mentioned above, ExoGaitOR orthosis is a wearable exoskeleton in the shoe. Therefore, it should be constructed using a lightweight material with a minimum volume and high strength. A potential solution is the utilization of composite materials. The materials that were used are presented in Table 2 and 3. The ExoGaitOR's gear mechanisms are made of structural steel.

Properties	Values		
Stress limits			
Tensile (MPa)	x	y	z
	513	513	50
Shear (MPa)	xy	yz	xz
	120	55	55
Compressive direction (MPa)	x	y	z
	-437	-437	-1.5
Strain Limits			
Tensile	x	y	z
	0.0092	0.0092	0.0078
Shear	xy	yz	xz
	0.02	0.015	0.015
Compressive direction	x	y	z
	-0.0084	-0.0084	-0.011

Elasticity			
Young modulus (MPa)	x	y	z
	59160	59160	7500
Poisson ratio	xy	yz	xz
	0.04	0.3	0.3
Shear modulus	xy	yz	xz
	3300	2700	2700

Table 2: Epoxy carbon woven (230 GPa) wet properties.

Properties	Values
Density	7850 (kg/m3)
Young Modulus	2·106 (MPa)
Poisson ration	0.3
Shear Modulus	79615 (MPa)
Bulk Modulus	166670 (Mpa)
Tensile yield strength	250 (MPa)
Tensile ultimate stress	460 (MPa)

Table 3: Structural steel mechanical properties.

Finite element analysis (FEA)

The Static analysis of the lower part of the orthosis was performed using commercial F.E software Ansys (Acp Pre and Post, Static Structural). Two cases for the static analysis of the orthosis have been studied, depending on the gait cycle's phase. The first one is at the stance phase, and the second one at the swing phase (Figure 1). In every FEA, it is essential to identify the boundary conditions (Forces, Moments) and the element's size (Mesh). The boundary conditions were discussed in chapter I and are summarized in Table 4. To generate the proper mesh and element size, a mesh independence study has been have done for the main component, the lower orthosis part (Figure 7).

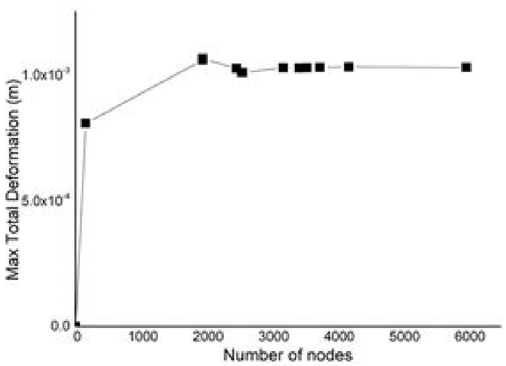

Figure 7: Mesh Independence study for the orthosis.

According to Table 4 and Figure 2, the values on the swing phase are much smaller than the ones on the stance phase. For this purpose, the stance phase appears to be more intriguing. The results of the static analysis are based on this phase of gait.

	Moment (N·m)	Force (N)
Stance phase	124	1024
Swing phase	-9	0

Table 4: Maximum loads during gait.

For each FEA, it is essential to use a specific type of element, depending on the analysis. Shell181 was selected for the orthosis, as ExoGaitOR's lower part was modeled in total with four plies and composite shells. During the analysis, the results with four plies on the model were not the expected at some points. For this reason was decided that a fifth ply in specific areas of the model is more suitable. Figure 8 shows these areas in blue. It is essential to point out that these areas have the maximum loads [4].

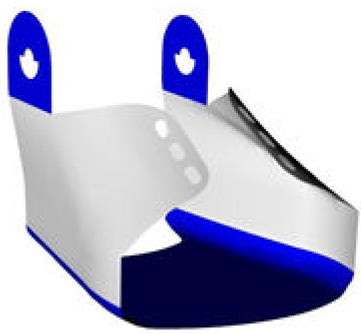

Figure 8: Areas with one more ply.

Results

The study's results are presented in Figures 9 and 10, depending on the patient as it had explained before. The values of moment and GRF are determined based on the patients' weight. In each case, the model should be adapted to meet the requirements of the patient. The primary variables of this study are the Total deformation and the Equivalent stress based on Von Mises criteria. In the specific analysis, two cases are studied: one using in total four plies and one using five plies. It has been noticed that the difference in the equivalent stresses between the two cases was not necessary. On the other hand, the deformation's values were almost double in the four plies case compared to the five plies case [5].

As a consequence, the model with the five plies has been chosen. Based on the analysis performed with FE, we can conclude that the maximum total deformation is on the front bottom of the sole in the lower part of the orthosis. More specifically, the calculated value is 1.7 mm, which is acceptable. In addition, the minimum total deformation found at the area where the motor is placed, as the entire model is theoretically supported there.

For the Equivalent stress (Von Mises) the maximum stress is noticed on the top of the orthosis, where the motors are supported, and on the sole. The motors and the transmission system exert a totally of 124 Nm torque as they try to outcompete the GRF on the sole and lift the foot. For this reason, the maximum value of stress is expected in particular areas. It should be pointed out that the maximum stress value of the orthosis, found from analysis, is approximately 39 percent of the material maximum stress value (Table 2).

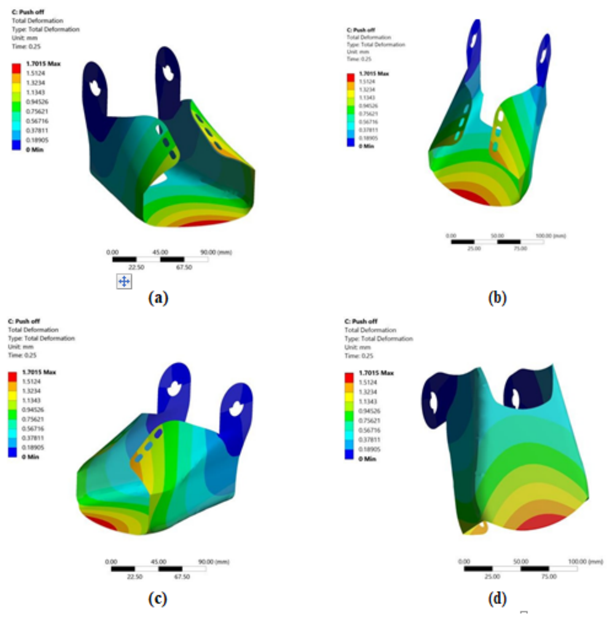

Figure 9: Total deformation of ExoGaitOR on stance phase.

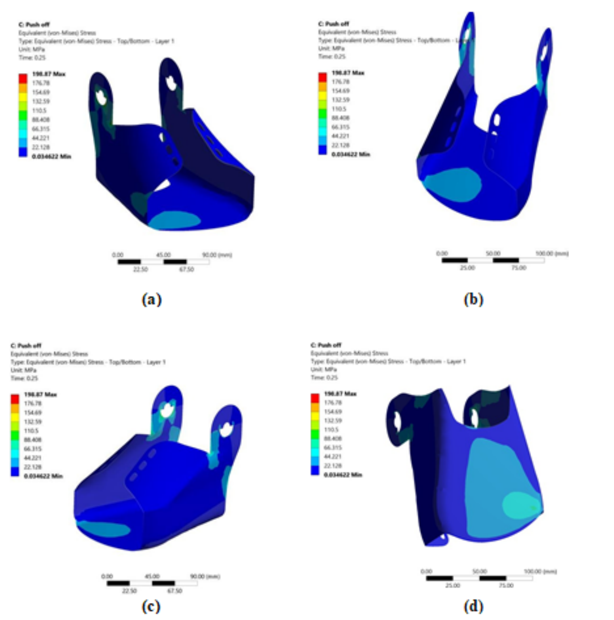

Figure 10: Equivalent stress of ExoGaitOR on stance phase.

Conclusion and Discussion

Patients with foot drop have difficulties in the gait cycle, especially in the swing phase. For this purpose, the study's main concern was designing and constructing a walking aid tool for drop foot patients as light and attractive as possible due to its small size. The primary exoskeleton's advantage is the simultaneous support and rehabilitation functions. This active orthosis is wearable inside the shoe. It comprises three systems; the transmission systems with two gears for increasing the given torque, an orthosis with two parts, the upper and lower part, and the control system. The study consists of various transmission mechanisms. The batteries and the microcontroller are placed in a specially designed case. The patient can place this case on his/her belt or around his/her thigh. The system control consists of a flex sensor with Arduino, batteries, and two motors. For the motor's selection, the considered load is only the foot's weight, as the mechanism supports only the lift of the foot during the swing phase. Finally, a composite material, such as Epoxy Carbon Woven (230 GPa) Wet, for the orthosis due to its lightweight and strength was chosen.

Ethical Approval

For this type of study formal consent is not required.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

The authors have consented to the submission of the case report to the journal.

Author contribution

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript and the material within has not been and will not be submitted for publication elsewhere.

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Competing Interests

There are no relevant financial or non-financial competing interests to report.

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