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Design and Fabrication of Powered Exoskeleton for Patients of Incomplete Paraplegia

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Abstract

This study addresses the pressing issue of paraplegia, a debilitating condition characterized by the loss of voluntary lower limb movement due to spinal cord injuries. Drawing upon data from the Paraplegic Center Peshawar's, Pakistan Annual Report (2019-2020), revealing that 67.5% of reported spinal injuries pertain to paraplegic patients, this research emphasizes the urgency of developing effective interventions for this population. Conventional approaches, including physical therapy and passive assistive devices, have demonstrated efficacy in cases of incomplete paraplegia. However, to address the limitations of existing methods, this study proposes the integration of active assistive technology, with a specific focus on powered exoskeletons. These innovative devices employ a sophisticated array of sensors, microcontrollers, and actuators to facilitate the attainment of a normative gait pattern, thus enhancing the performance of daily life activities. Despite the demonstrable benefits of powered exoskeletons, their commercial availability remains limited, particularly in developing nations. This research project endeavors to bridge this gap by conceptualizing and fabricating a locally-sourced prototype, marking the initial stride toward realizing this vital technology. Through an exhaustive exploration of the existing literature, it was discerned that a dearth of South Asian-specific guidance exists for aspiring developers of this technology. Additionally, the scarcity of essential hardware components, such as rotary actuators and batteries, in the local market posed a formidable challenge. The endeavor undertaken herein demanded substantial temporal and financial resources, rendering the pursuit seemingly daunting and, in some respects, unrealistic. However, against the odds, the project achieved its primary objectives, underscoring its feasibility and potential for further refinement and expansion. This study serves as a beacon of progress, illustrating that despite inherent challenges, transformative advancements in assistive technology for paraplegic patients can be realized.

Keywords: *Actuators, Robotics, Microcontrollers, Rehabilitation, Exoskeletons.*

Introduction

The term "paraplegia," stemming from the combination of 'Para' signifying two and 'Plegia' denoting paralysis, specifically refers to the impairment of both limbs, notably the legs. This condition arises from damage to the thoracic, lumbar, or sacral segments of the spinal cord, often accompanied by muscle paralysis of the trunk in cases of thoracic spinal cord injuries. In contrast, injury to the cervical region leads to quadriplegia, or paralysis of both upper and lower limbs. The predominant aetiology of these injuries lies in traumatic incidents, yielding a spectrum of long-term repercussions. Common causal factors encompass automobile accidents, falls, gunshot wounds, sports-related trauma, and postoperative complications (Maher C. 2021).

Exoskeletons represent a distinct category of orthotic devices designed to complement and enhance the physical capabilities of the user, facilitating crucial functions and movements. This synergy necessitates precise tailoring of the exoskeleton to the user's anatomical proportions (Paraplegic Center Peshawar Archives. 2017-2019). Fig. 1 provides a visual representation of HAL 5 exoskeletons.

Figure 1 HAL 5 Exoskeleton

Modern iterations of exoskeletons predominantly rely on electromagnetic actuators, although certain models still incorporate hydraulic and pneumatic actuators. Initially developed for military applications, exoskeletons continue to play pivotal roles in various professional domains with demanding physical requirements (de la Tejera, J. et al. 2021).

This investigation concentrates on the application of powered exoskeletons within the clinical and rehabilitative sphere, particularly focusing on lower limb interventions. Over the course of its evolution spanning decades, this technology has undergone notable advancements in skeletal fabrication materials, actuation mechanisms, and power sources, resulting in a diverse array of exoskeleton classes and categories within the field.

Literature Review

The practical manifestation of exoskeletons dates back to half a century ago, with the pioneering work of Hardyman in the 1960s. Initially devised for military purposes, these early exoskeletons operated on hydraulic actuators, albeit with notable drawbacks of bulkiness, instability, and operator safety concerns (Kawamoto, H. et al. 2003). In the subsequent decade, this concept found application in the biomedical realm for paraplegic patients. However, technological limitations of that era posed significant hindrances to widespread implementation (Ryder, M. C., & Sup, F. 2013).

The subsequent decade witnessed the expansion of assistive devices to encompass upper limb support, rendering them more universally applicable. By the close of the 20th century, exoskeletons characterized

by limited degrees of freedom and predominantly passive functionality became available in the market. A prominent impediment faced by products of this era was the absence of comprehensive programming support (Ryder, M. C., & Sup, F. 2013).

The advent of the 21st century ushered in an era of accelerated progress, facilitated by enhanced software technologies. The Berkeley lower-extremity exoskeleton (BLEEX) stands as an early exemplar of this technological shift (de la Tejera, J. et al. 2021). Constructed through Computer-Aided Design (CAD), this device underwent rigorous analysis and refinement, incorporating mechanical systems and an oxygen-measuring apparatus to gauge its efficacy. The BLEEX serves as a pioneering model with implications for future iterations.

Researchers at the University of Tsukuba in Japan introduced the inaugural HAL exoskeleton, leading to the formation of Cyberdyne Inc. in 2004 to further its development. The HAL exists in two iterations: the HAL-3, exclusively augmenting lower limb function, and the HAL-5, extending support to the upper body. Both versions target assisting the elderly and individuals with disabilities in regaining strength and mobility. The HAL system interfaces wirelessly with a Linux-based computer to facilitate adjustment of system parameters and assessment of user performance. While the HAL suit has demonstrated enhanced stride frequency and length in 25% of mobility-impaired patients, it may not be universally suitable for all rehabilitation cases. Its efficacy is contingent upon intact neuron signals, rendering it less effective for those with severe paralysis or erratic neuron firing. Subsequent exoskeleton models introduced to the market in the ensuing decade prioritized adaptability in design, tailoring each device to the specific requirements of the individual, as opposed to producing standardized exoskeletons.

The contemporary pinnacle of technological achievement emerged in 2014 with the release of Exoskeleton 6.0 by ReWalk. This model, along with subsequent iterations, engendered a paradigm shift in exoskeleton design, encompassing the Levitation 2 Knee Brace (Strange, A. 2014), Dephy Exo- boot (INDEGO Technologies. 2021), Indego (Levitate Technologies 2022), Airframe (ReWalk Technologies. 2022), Fortis K-SRD (Ryder, M. C. 2015)., EKSO bionics eLegs, ReStore Exo-Suit, and Guardian XO Alpha (Guardian Xo Alpha. 2022).

1) EKSO Bionics ELegs

The inception of research on the Ekso Bionics eLegs exoskeleton can be traced back to 2004 at the University of California, initially under the moniker of Berkeley Lower Extremity Exoskeleton (BLEEX). The hydraulic actuators within the eLegs, as illustrated in Fig. 2, were responsible for mobilizing the hip and knee joints along the sagittal plane. It's worth noting that BLEEX also featured actuation of the ankle joint. These actuators delivered a peak hip torque of 150 Nm. Noteworthy specifications include a weight of 45 lbs. and a battery life of six hours. The exoskeleton houses its computer and compressor in a backpack configuration. The integration of the actuated hydraulic system results in an overall operational efficiency of 14%, indicating potential for further refinement.

Figure 2 EKSO bionics eLegs (theverge.com)

Distinctively, eLegs does not rely on skin sensors for detecting myoelectric impulses. With the exception of a pressure sensor positioned beneath the foot, it does not engage in measurements at the interface between the human body and the exoskeleton. Instead, each joint is equipped with an array of sensors, including encoders and linear accelerometers, which ascertain the precise location, velocity, and acceleration of each segment. Through the application of inverse dynamics, eLegs computes the torques and loads based on its own movements. Furthermore, each footplate incorporates four pressure sensors at strategic locations (heel, mid-foot, ball of foot, and toes) to discern the distribution of the user's weight and gather crucial gait cycle data (Paraplegic Center Peshawar Archives. 2017-2019).

2) ReWalk 6.0

The ReWalk system exhibits a weight of around 23.3 kg (51 lb.). The accompanying backpack, responsible for housing batteries compatible with Windows-based computers and devices, adds an additional weight of roughly 2.3 kg (5.1 lb.). The robot leg attachment contributes to the load with an approximate weight of 21 kg (46 lb.) (Strange, A. (n.d.). 2014). Users are afforded the choice of three operational modes: walking, sitting, and standing. The signals corresponding to these modes are transmitted to a computer through a conduit such as a smart watch (ReWalk Technologies. 2022).

3) Levitation Knee Brace

The Levitation 2 knee extension assistance brace represents a groundbreaking advancement in the realm of "bionic" knee extension technology. It stands as the inaugural high- performance knee extension brace of its kind worldwide. Notably, it is engineered to bear your body weight while simultaneously facilitating knee joint extension, thereby alleviating pressure across all three compartments of the knee— a phenomenon referred to as "tri-compartment offloading." The pioneering "bionic" hinge of Levitation actively engages your leg muscles, enabling you to exert more effort, extend your activities for prolonged durations, and achieve feats beyond prior expectations. As you flex your leg, surplus energy is conserved and subsequently utilized to aid in leg extension.

Independent research has demonstrated that Levitation's robust knee extension assistance not only enhances natural mobility but also reduces knee joint contact forces to an extent equivalent to a weight reduction of over 40 pounds. Irrespective of conditions like osteoarthritis or post-knee injury recovery, bionic knee braces like Levitation hold the potential to alleviate discomfort and enhance mobility (Mooney, L. M. et al. 2014). Refer to Figure 3 for a visual representation of the Levitation knee brace.

Figure 3 Levitation knee brace (info.springloadedtech.com)

4) Dephy Exo-boot

As illustrated in Figure 4, the bilateral exoskeleton comprises three fundamental components: a set of fiberglass struts affixed to each boot, unidirectional actuators situated along the anterior segments of the shanks, and a battery and control unit encircling the waist. In detail, both boots incorporate a medial and lateral fiberglass strut securely attached to the front section, flanking the metatarsophalangeal joint. These struts are linked to the boot's heel through a lightweight, non-stretchable cord (Levitate Technologies, Inc. 2022).

Figure 4 Dephy Exo-boot (neurobionics.robotics.umich.edu)

5) INDEGO Exoskeleton

The Indigo Therapy Exoskeleton stands as a powered lower- limb assistive orthosis, characterized by five integral components. It boasts extensive adjustability, enabling swift customization for a patient within a matter of minutes. This exoskeleton envelops and provides support to the legs and lower back, granting individuals with restricted lower mobility the capacity to assume a standing position and engage in ambulation during therapy sessions. Distinguished by its user- friendly controls and adaptable design, the Indego Therapy Exoskeleton empowers patients recovering from stroke, spinal cord injuries, and various gait impairments to experience the natural act of standing and walking. Notably, despite its mere 27-pound weight, the Indego Exoskeleton possesses the remarkable capability to support patients weighing up to 250 pounds (INDEGO Technologies. 2021). For visual reference, please consult Figure 5, depicting the exoskeleton in detail.

Figure 5: INDEGO Exoskeleton (Indego.com)

6) Guardian XO Alpha

As depicted in Figure 6, the Guardian XO Alpha is a powered exoskeleton that encompasses the entire body. Through a remarkable feature, it fully offloads the exoskeleton's weight during operation,

significantly reducing the operator's metabolic expenditure and physical exertion. This innovative design effectively addresses the "lift gap" ranging from 35 to 200 pounds (15 to 90 kilograms), making it suitable for a diverse array of industrial applications. The Guardian XO Alpha employs an efficient "get-out-of-the-way" control mechanism that minimizes response time by utilizing integrated sensors to detect operator movements in a matter of milliseconds. This grants the operator the freedom to move unencumbered and spontaneously in unstructured environments where heavier machinery may be impractical. Remarkably, the donning and doffing of the robotic suit can be accomplished independently in under 30 seconds, with added provisions for swift emergency egress. In the event of a power disruption, redundant hardware and software safeguards ensure "passive braking" to safeguard the operator. The system's high responsiveness enables the operator to execute fall- prevention maneuvers, including stumble recovery, with remarkable ease (Guardian Xo Alpha. 2022).

Figure 6: Guardian XO alpha (Sarcos.com)

The cost of the aforementioned exoskeletons falls within the range of $40,000 to $80,000, rendering them financially out of reach for the majority of individuals with paraplegia. While these exoskeletons are designed to anticipate user actions, occasional glitches may occur, leading to struggles with the device. This can prompt a cognitive shift and potentially impact muscle recruitment, potentially exerting greater stresses on the lower back and increasing the risk of pain or injury.

Certain individuals with specific impairments should exercise caution when considering the use of the ReStore Soft Exo-Suit. This includes those with limited ankle mobility, which may impede safe walking, as well as individuals with cognitive or mental health conditions that could hinder adherence to instructions. Additionally, the weight of these exoskeletons, except for the Guardian XO Alpha and Dephy Exo-Suit, can pose handling challenges.

It's worth noting that local fabrication and assembly of these devices could offer a significant cost reduction, as labor and facility expenses in certain regions, particularly in the subcontinent, tend to be substantially lower than in the western world. Despite their benefits, most of these devices are not highly portable and may pose difficulties in terms of wearability due to the time required for donning.

Design, Modeling and Fabrication

A. Design Phase

In recent years, significant strides have been made in the development of robotic systems aimed at augmenting human motion through actuation capabilities. These assistive devices, leveraging mechatronic and robotic technology, represent a burgeoning field of research and innovation. Notably, certain systems are required to produce substantial torques, such as 54 Nm, to effectively support human movements. For example, over 30 Nm is necessary to fully support the knee joint during typical walking. This necessitates a

demand for high precision and accuracy in the production of such formidable torques to provide natural assistance. Moreover, it is imperative that assistive robots maintain a compact and slender profile to minimize discomfort stemming from the physical presence of the robot hardware. This consideration imposes specific challenges in the selection of actuators. Electric motors equipped with gear reducers have been a prevalent choice for powering assistive robots, meeting the demands of end-users. However, it is crucial to acknowledge that these assistive devices are not without their limitations and drawbacks.

In response to the shortcomings of prior assistive human devices, innovative actuators have been introduced, with series elastic actuators being a notable example. These actuators integrate electric motors and springs as essential components. The spring, strategically positioned between the actuator and the human joint, serves a dual purpose as an energy buffer and a torque detector. This configuration enables precise control over the generated torque. Despite their advantages, it's important to recognize that series elastic actuators also have their own set of constraints and limitations (Kong, K. et al. 2012).

In this project, a specially designed linear actuator (Arduinopak. 2022) was implemented for the exoskeleton. This actuator is equipped with a tailored control system. The motor drive, integrated with the Arduino board (OR97. 2022), interfaces with the linear actuator. To gauge pressure force, a force-sensing resistor (FSR) (Electrobes. 2022) is employed. Upon activation, the FSR relays a signal to the Arduino board, prompting the actuator to respond accordingly. This intricate system ensures precise and dynamic control over the exoskeleton's movements.

The design phase comprised the following two parts:

1. Mechanical Design.
2. Control Design.

1. Mechanical Design

The core mechanical framework of the exoskeleton revolves around a linear actuator, tasked with effecting linear rotation in the lower limb section. The structure is predominantly fashioned from polyethylene, with specific components of the Ankle Foot Orthosis (AFO) being connected through aluminum strips. The integration of the linear actuator onto the mold is achieved through the application of an oxyacetylene welding process, ensuring secure and stable attachment. This meticulous construction process ensures the exoskeleton's functionality and durability.

2. Control Design

The exoskeleton's control system is meticulously assembled, integrating a suite of essential electrical components. These key elements include:

- Force Sensing Resistor (FSR)
- Arduino Board Uno R3
- Motor drive

These components form a cohesive and fashionably interfaced electrical system, enabling precise control and operation of the exoskeleton.

The circuit diagram for the entire control system is illustrated in fig 7.

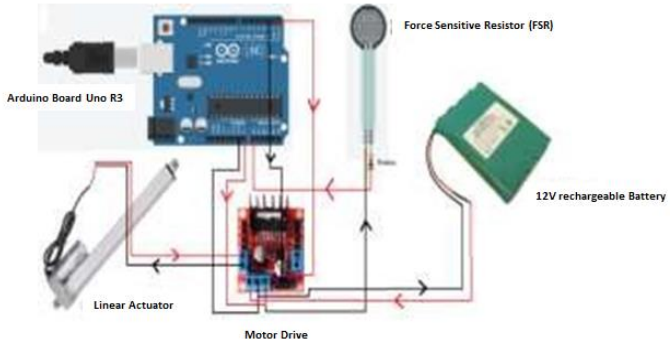

Figure 7 Circuit Diagram of Control System

B. Fabrication

The fabrication of the powered exoskeleton was achieved in two major phases.

1) Manufacturing of AFO (ankle-foot orthoses)

The produced Ankle Foot Orthosis (AFO) has undergone a slight modification from the original design provided by the International Committee for Red Cross (ICRC). While the documented specimen from ICRC is exclusively constructed from propylene, the version utilized in this project incorporates aluminum components to augment its durability and resilience. This enhancement ensures a sturdier and more robust AFO for effective use in the exoskeleton.

2) Installation of essential hardware

The pivotal aspect of the fabrication process lies in transforming it from a conventional mold into a powered exoskeleton. This transformation is achieved through the following sequential steps:

- Introducing a linear actuator that facilitates non-linear angular motion. It is meticulously welded at the rear section of the mold, strategically positioned to generate the necessary push and pull forces essential for aiding the subject in their walking strides.
- Attaching the Force Sensing Resistor (FSR) to the sole of the mold, ensuring its optimal performance in reacting to external stimuli.
- Establishing connections between the sensor, actuator, and Arduino, where coding is executed to facilitate sensing and subsequent control of the actuator.
- Connecting the actuator to an external power source (12 V) to render it fully functional.
- Positioning both the battery and Arduino at an elevated point on the exoskeleton to ensure balanced weight distribution, contributing to overall stability and comfort during use.

C. Final Prototype

The prototype was designed and modeled utilizing Solid Works. This encompassed the careful assembly of all components to impart the exoskeleton with its definitive form and structure. Subsequently, the automatic control system of the prototype underwent rigorous testing, employing a 12V rechargeable battery as the external power source. This phase validated the functionality and performance of the exoskeleton's control mechanisms.

Figure 8: Side view (Right) of the final prototype

Analysis of the Developed Prototype

A. Performance Analysis of the Developed Prototype

The evolution of exoskeleton technology represents a dynamic frontier in this decade, marked by a progressive pursuit of achieving lifelike and precise motion that seamlessly integrates with the user's own body. Human locomotion predominantly occurs in the sagittal and frontal planes and exoskeleton applications are primarily directed towards enhancing stability and mobility in the limbs. By employing external actuators, such as exoskeletons, joint movements in specific limbs like the legs and arms can be significantly augmented. Moreover, exoskeleton applications hold immense potential in the realm of rehabilitation, especially during the recovery process. This project places a particular emphasis on prioritizing support for the knee and ankle joints. To attain a design that is both adaptive and pliable, it is imperative to carefully consider the joint mechanism, acknowledging the slight displacement inherent in actual knee joints that impact the shank. To faithfully emulate human gait, it is essential for the exoskeleton to possess the requisite strength and speed of motion, thereby enabling patients with incomplete paraplegia to regain their ability to walk. In practical terms, the mechanical components encompass crucial elements such as linear actuators, an orthosis mold, and aluminum strips. Complementing these are the electrical components, which include the Arduino board, a force-sensing resistor (FSR), and a motor drive. This integrated system harmoniously combines both mechanical and electrical elements to bring forth an exoskeleton design that holds significant promise in enhancing mobility and quality of life for individuals with mobility impairments.

In the process of conducting a performance analysis for the developed prototype, accurate measurements of the subjects (patients) play a crucial role in determining the necessary loads, body length segments, and other critical factors that the final product must cater to. It's noteworthy to mention that the subjects selected for this study were restricted to individuals falling within the age bracket of 15-30. Additionally, each subject had to meet the specific criteria outlined in the table below:

Table 1. Subject's Inclusion and Exclusion Criteria

Inclusion	Exclusion
This exoskeleton was aimed towards the functionality of lower extremity (leg, ankle, foot).	Complete injury of the lower limb. Pain in lower leg and/or knee joint when verbalized.
The subject should be able to stand on their knees. The subject is unable to stand and walk on his own due to injuries i.e., Spinal Cord Injury, or Polio.	Delicate bone such as within the case of osteogenesis imperfecta (Osteogenesis imperfecta (OI) is an inherited (genetic) bone disorder that is present at birth. It is also known as brittle bone disease)

The rationale behind these exclusions is to preempt any unforeseen injuries or complications that may arise during the trial on a live subject. The comprehensive analysis of the human lower-limb exoskeleton commenced from the farthest segment (foot) and systematically progressed proximally. The subsequent sections detail the load calculations and measurements conducted.

Table 2: Body Segment Length

Body Segment	Length (cm) Real measurements	Length (cm) Reference
Foot	25	26
Shank	47	37
Shank to Foot	53	44
Thigh	37	43

The subjects' measurements were recorded in March 2022, with a height of 5.5 feet (170 cm) and a weight of 60 kg. It's pertinent to highlight that the subjects had a spinal cord injury that impacted their lower limbs. The specific weights of individual body segments can be found in Table 3. These measurements and considerations form a crucial foundation for the subsequent stages of the study.

Table 3: Body Segment Weight

Body Segment	Weight (N)
Thigh	61.74
Shank	25.46
Foot	8.4
Upper body	492.4

B. Linear Actuator Torque

In order to measure torque, a linear actuator equipped with a power screw featuring a single thread with a mean diameter (dm) and a pitch (p), subjected to a force (F), was employed. To ascertain the torque needed for both elevating and lowering the load, the subsequent expressions and formulae were utilized. This approach provided an accurate means of quantifying the required torque in the experimental setup.

Raising Torque

$$\mathbf{TR} = \frac{\boldsymbol{Fdm}}{\mathbf{2}}\left(\frac{\boldsymbol{l+\pi f dm}}{\boldsymbol{\pi dm - fl}}\right) \qquad (1).$$

Lowering Torque

$$\mathbf{TR} = \frac{\boldsymbol{Fdm}}{\mathbf{2}}\left(\frac{\boldsymbol{l+\pi f dm}}{\boldsymbol{\pi dm - fl}}\right) \qquad (2).$$

F = Amount of force to be actuated.
dm = The outer diameter of a lead screw.
l = lead, equals to the number of start times pitch length.
f = friction coefficient between lead screw and material.
F = W = 588 N. dm = d – 0.5P =0.017735 m. f = 0.25. l = np = 8 mm. From 1 and 2:
TR = 0.964 Nm. TL = 0.536 Nm.

Therefore, the required torque to raise (TR) and lower (TL) the load for knee linear actuator respectively are 0.964 Nm and 0.536 Nm. The maximum angle that the actuator displaces with respect to the exoskeleton is obtained as follows:

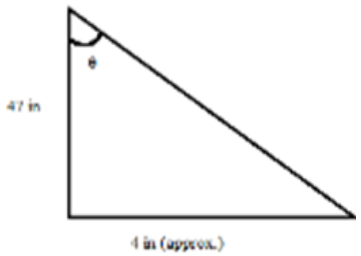

Figure 9 Maximum Angle θ calculations

$$\tan\theta = \frac{P}{B} = 4.86^{o}$$

C. Linear Actuator Torque

The completed exoskeleton, depicted in Figure 10, was fabricated using polypropylene as the primary raw material. Aluminum strips were strategically employed to securely fasten the upper and lower components of the exoskeleton. Following the meticulous assembly of these parts and rigorous testing on the subject for performance evaluation, the Force Sensing Resistor (FSR) came into play. This sensitive component, upon detecting the applied force by the subject, promptly transmits a signal to the microcontroller—the Arduino Board. Subsequently, the Arduino Board activates the linear actuator, initiating linear motion which in turn moves the lower limb of the subject at a specified angle. It is imperative for the subject to utilize crutches during exoskeleton operation to maintain balance. The linear actuator is strategically positioned between the shank and the thigh. In addition to the exoskeleton as a whole, the linear actuator attached to the knee contributes a weight of 0.6 kg to the system. This final product embodies the culmination of meticulous design and engineering efforts, poised to enhance mobility and functionality for individuals with mobility impairments.

Figure 10: Lower Limb Exoskeleton

D. Range of Motion

To evaluate the range of motion, the linear actuator was energized using an external power source—a rechargeable 12V battery—post-final product assembly. This procedure aimed to achieve both maximum and minimum linear actuator displacements. Based on calculations, the required maximum angle was determined to be 4.86 degrees.

Figure 11 graphically depicts the extremes of this displacement, illustrating the full actuator movement range. The left figure represents the initial position with no movement, while the right figure demonstrates the shank rotated by an angle theta. This visual representation provides a clear understanding of the exoskeleton's dynamic capabilities.

Figure 11: Actuator Movement Range (The left figure depicts no movement while the right figure depict that the shank is rotated by an angle theta.

E. Load Test

To ascertain the amount of load exerted on the actuator, a dedicated load test was conducted, leveraging an external power source furnished by a 12V rechargeable battery. During this examination, the maximum value, or trigger resistance, reached was 200k. In instances where the Force Sensing Resistor (FSR) reading surpasses this threshold, the linear actuator does not initiate motion. This is a safeguard to prevent excessive force on the subject's foot. It's crucial to apply the necessary load to ensure that the FSR reading remains below this specified limit. Conversely, when the FSR reading falls below 200k, the actuator proceeds to execute linear motion, thereby achieving the intended movement. A concise summary of these findings is presented in Table 4, encapsulating the essential parameters of this load test.

Table 4. Actuator Trigger Load Test

Trigger Resistance	Lowering Torque (Nm)	Raising Torque (Nm)	Starting Angle (°)	End Angle (°)	Delay (sec)
<200kΩ	0.536	0.964	0°	4.86°	5s
>200kΩ	0	0	0°	0°	0s

F. Actuation Speed Test

In our exoskeleton design, we employed a linear actuator to yield the desired output. To evaluate its performance, a linear speed test was conducted using our designated power source, the 12V battery, in conjunction with a motor drive. The calculated speed of the actuator was determined to be 10 millimeters per second (10 mm/s). This metric serves as a crucial parameter in gauging the functionality and effectiveness of the exoskeleton's motion dynamics.

Conclusion

The primary objectives of the project were successfully achieved. Initially, the subject was identified as having incomplete paraplegia stemming from a spinal cord injury. Subsequently, the lower limb dimensions of the subjects were taken into careful consideration for the design and manufacturing of the device.

One notable achievement was the transformation of the exoskeleton from a purely passive assistive device to an active one. This entailed harnessing an external power input to actuate the lower limb of the subject. However, it's important to note that the initial objective of attaining a specific actuation mechanism was not fully realized. This was primarily attributed to constraints in financial resources. Consequently, a linear actuator was employed to provide the requisite torque for raising or lowering the lower limb.

In terms of performance evaluation, the exoskeleton was rigorously tested on subjects. The device underwent comprehensive assessments, and it successfully facilitated the actuation of the subject's lower limb. However, it was observed that the subject faced limitations in achieving a normal walking pace, largely due to the comparatively slower output of the linear actuator. This implies that the product is better suited for clinical rehabilitation or activities with a slower pace.

To further enhance functionality, consideration could be given to employing advanced actuators like the Maxon Exoskeleton joint actuator. This cutting-edge component integrates a brushless DC motor with an optimized rotor for reduced inertia, as well as encoders for precise feedback signals. Such an upgrade could potentially lead to substantial improvements in the exoskeleton's performance and expand its applicability in a wider range of scenarios.

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