Design and Fabrication of a Portable Lower Body Exoskeleton

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Abstract—In biology, an exoskeleton is the external skeleton that supports and protects an animal's body, in contrast to the internal skeleton of, for example, a human. Millions of people have mobility impairments that make walking slower and more fatiguing, while millions have occupations requiring strenuous locomotion. The paper describes a prototype of a portable lower-body exoskeleton that has been designed and fabricated, powered by a system of motors to assist humans in activities such as walking and running by providing energy and additional support for limb movements. It also offers enhanced stability to senior citizens and certain rehabilitation patients by reducing the strain on the knee and ankle joints and helping prevent falls and accidents. A distinguishing feature of this exoskeleton is its cost-effectiveness and adaptive design, enabling it to cater to an individual's unique movements through personalized programming that optimizes the actuator's performance for an efficient and tailored experience.

Index Terms—Biomechanics, Design, Fabrication, 3D Printing, Robotics

I. INTRODUCTION

In today's fast-paced world, increased mobility demands can strain our knees and ankles, posing significant challenges, especially for senior citizens and rehabilitation patients with weakened lower-body strength. To address these challenges, a prototype of a portable lower-body exoskeleton was developed. The lower-body exoskeleton is a wearable device designed to provide external support to the legs, featuring powered braces equipped with motors and sensors to aid mobility and reduce joint strain. Its lightweight design enhances comfort, allowing natural movement while offering the necessary support. Compared to existing solutions, this exoskeleton is cost-effective, versatile, and user-friendly, featuring motors and other mechanical components that minimize physical exertion. The adjustable settings and intuitive control interface cater to individual needs. The device includes mechanisms at both the knee and ankle joints, assisting with extension, flexion, and movement, calibrated through an Arduino board based on individual gait analysis.

The exoskeleton's lightweight design, achieved through additive manufacturing techniques, plays a crucial role in its applicability as a rehabilitation aid. By using optimized structures and lightweight materials, such as high-strength polymers like ABS and PLA, the exoskeleton maintains its durability and safety while minimizing unnecessary weight. This lightweight construction enables patients to wear the device for extended periods without feeling burdened or fatigued, enhancing their overall comfort and wear ability For senior citizens, this exoskeleton helps maintain or improve mobility, counteracting age-related muscle weakness and joint issues, thereby enhancing their quality of life. In rehabilitation, it aids patients in regaining strength and balance, speeding up the recovery process and reducing the risk of falls.

This paper outlines the methodology employed in the design and development of this lightweight, portable lower-body exoskeleton.

II. PROBLEM STATEMENT

For many people today their daily activities require some form of mobility and instant movement, the knees and ankles are subjected to increased strain, making them more susceptible to injuries. This strain is particularly challenging for rehabilitation patients who are advised to avoid unnecessary stress on their affected joints during the recovery process. Similarly, senior citizens face mobility issues, weakened bones, and conditions like arthritis and osteoporosis, which increase their risk of falls. Consequently, there is a growing need for an affordable, customizable device that can assist in day-to-day activities while providing limb support for senior citizens and rehab patients.

III. AIM

This project aims to develop a device designed to reduce metabolic effort during activities such as walking or running. Additionally, it aims to assist senior citizens and rehabilitation patients by providing enhanced stability, supporting limb movements, and preventing falls. This device seeks to improve mobility and safety for users, particularly in daily activities.

IV. LITERATURE REVIEW

The paper published by P. Slade, M. J. Kochenderfer, S. L. Delp, and S. H. Collins [1], demonstrates that exoskeleton optimization can be efficiently performed in real-world conditions, using data-driven methods and wearable sensors to personalize assistance, achieving a 9.4% increase in walking speed and a 23.8% reduction in metabolic energy consumption compared to normal footwear.

The study carried out by M. Grimmer, B. T. Quinlivan, S. Lee, P. Malcolm, D. M. Rossi, C. Siviy, and C. J. Walsh [2], found that the ankle moment-inspired technique reduced biological moment and power at the hip and ankle, with energy savings extending to the knee, hip, and center-of-mass, suggesting that humans adapt their gait to maximize energy efficiency based on exosuit assistance.

Aybuke Kececi, in his study [3], explores machine learning techniques for user authentication using the HugaDB dataset, which includes human gait data collected through wearable accelerometers and gyroscopes from 18 individuals performing activities such as walking, running, sitting, and standing.

The paper presented by Q. Wu, X. Wang, F. Du, and X. Zhang [4], presents a powered hip exoskeleton (PH-EXOS) with six degrees of freedom, controlled by a fuzzy adaptive controller, designed to assist locomotion for individuals with walking impairments, with preliminary treadmill tests showing its effectiveness in reducing walking effort.

S. H. Collins, M. B. Wiggin, and G. S. Sawicki [5], through their paper, demonstrate an unpowered ankle exoskeleton, using a lightweight elastic device and mechanical clutch, can reduce the metabolic cost of human walking by assisting the calf muscles and tendons during locomotion.

J.-H. Kim, M. Shim, and D. H. Ahn through their study [6], developed a modular knee exoskeleton for hemiplegic patients, using force-sensitive resistors, a torque sensor, and an encoder to detect user intention, with a control algorithm-based on a finite state machine, validated through experiments on standing, walking, and sitting.

V. DESIGN

This section presents the methodology employed during the design process for the exoskeleton. The subsections explain each stage in this process in a rigorous, more detailed manner, to understand why a particular study or step was taken.

V.I. Biomechanics of the knee and ankle joints

To conceptualize a design for the exoskeleton, a major pre-requisite was to understand the biomechanics of the knee and ankle joints.

a. Gait cycle

The gait cycle refers to the pattern of movement that occurs during walking or running. It encompasses the sequence of events that take place from one foot striking the ground to the same foot striking the ground again. The gait cycle is divided into two main phases: the stance phase and the swing phase.

The stance phase begins when one foot makes contact with the ground and ends when the same foot lifts off the ground. It is further divided into several sub-phases: the heel strike phase, foot flat phase, midstance phase, heel-off phase, and toe-off phase. The swing phase starts when the foot lifts off the ground and ends when it makes contact with the ground again. It consists of three sub-phases, the early swing phase where the leg swings forward after toe-off, the mid swing phase where the leg continues to swing forward, passing the supporting leg and the late swing phase where the leg prepares to make contact with the ground. The phases discussed in this section are illustrated in Figure 1 for better visualization.

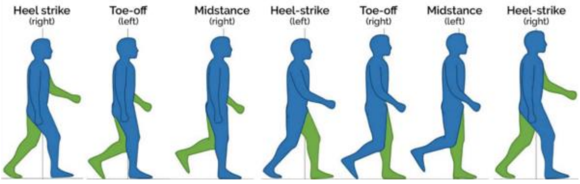

Fig.1 Gait cycle

b. Degrees of freedom of the knee

The Degrees of Freedom (DOF) of the knee refers to the different types of movements that can occur at the knee joint. The knee joint has six degrees of freedom which is illustrated in Figure 2. They can be classified into three translational and three rotational movements. For the design of the exoskeleton, only one degree of freedom was considered based on the application of the product. This was mainly the flexion-extension rotational degree of freedom which is the primary movement of the knee joint, allowing for bending (flexion) and straightening (extension) of the leg.

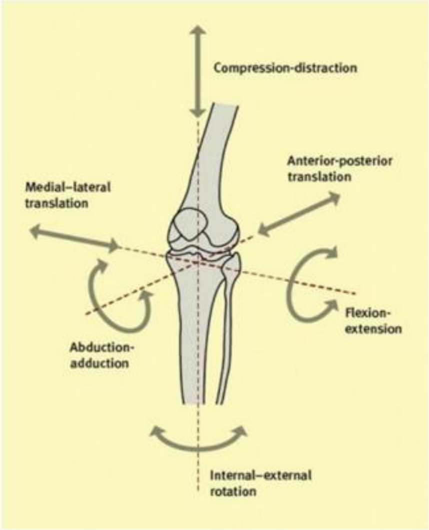

Fig.2 Degrees of Freedom of the Knee

V.II. Determining the amount of torque exerted by the ankle and knee joints

To estimate the torque requirements for an exoskeleton system, a comprehensive analysis was performed to evaluate the torque generated by the human body's ankle and knee joints. This evaluation enabled the determination of the necessary motor specifications for the exoskeleton to adequately assist the user.

a. Reducing System Complexity by Segmenting the Mechanism into Ankle and Knee Joint Analysis

Since the exoskeleton requires high-level calculations for both the knee joint and ankle joint, the problem was broken down into two separate parts – the knee joint and ankle joint.

For the knee joint,
The torque required by the joint to move against the given body mass would be given by the formula,

$$\tau_{Knee} = F_{\perp} \times r \times sin\ \theta_K \tag{1}$$

Since the device is an assistive device, the aim is to reduce the effort needed by the individual by 20%, hence the required torque by the motor at the knee is,

$$\tau_{Motor\ at\ Knee} = F_{\perp} \times r \times \sin\theta_K \times 0.2 \tag{2}$$

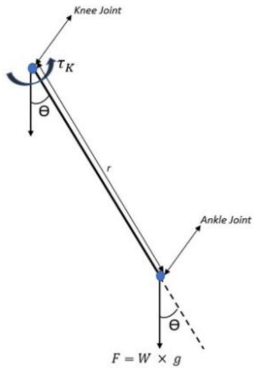

Fig.3 Representational free body diagram of forces and torque acting on the knee joint

Consequently, for the ankle joint,

$$\tau_{Ankle} = F_{\perp} \times r \times sin\,\theta_A \tag{3}$$

$$\tau_{Motor\ at\ Ankle} = F_{\perp} \times r \times \sin\theta_A \times 0.2 \tag{4}$$

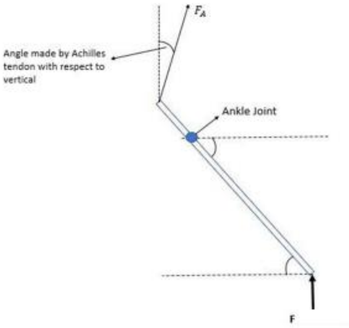

Fig.4 Representational free body diagram of forces and torque acting on the ankle joint

Where,
$\tau =$ Torque
$F_{\perp} =$ The normal reaction force exerted by the body during the standing condition
Given, $F_{\perp} =$ mass of the individual × gravity
$r =$ The distance between the knee joint and the ankle joint
$\theta_K =$ Angle of inclination of the knee with respect to the vertical during walking
$\theta_A =$ Angle of inclination of the ankle with respect to the vertical during walking

V.III. Design of the portable lower body exoskeleton

After considering the forces acting on the knee and ankle, the torque generated by these joints during normal human walking was calculated. Based on the analysis, it was concluded that the exoskeleton model should supply approximately 20% of the power produced by the human joints.

The limb structure was analyzed, and a compact main leg component was designed with a partially hollow section to accommodate the shin. This adjustable cavity allows the exoskeleton to adapt to users of varying heights. A structural covering was then designed to prevent knee buckling, a common issue in older adults. For the ankle joint, a foot plate of considerable thickness was developed to provide adequate rotational support.

Following the design of the exoskeleton's main frame, a support structure depicted in Figure 7 was developed to house the motors and electronics. This structure, featuring two mounting holes for the motors, offers high mechanical strength and stability.

The movable components of the main frame are powered by motors connected through gears, ensuring smooth and continuous power transmission. To boost the torque output of the motor, a spur gear assembly was used. The gears were designed based on the torque requirements of the model and the output torque of the motors. Gear casings were created for both the knee and ankle joints to ensure proper gear meshing and prevent slippage which is shown in Figure 6. Additionally, these casings provide protection against external factors, enhancing the durability of the gear assembly.

Figure 5 presents the isometric and front views of the 3D design developed for the exoskeleton.

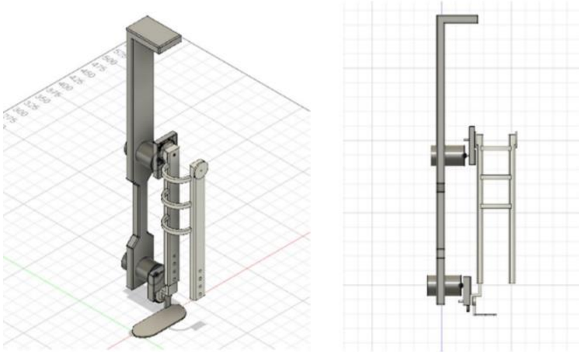

Fig.5 3D Design

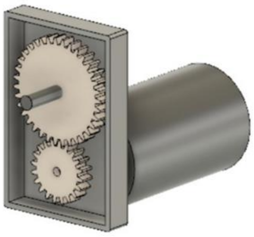

Fig.6 Gear Casing

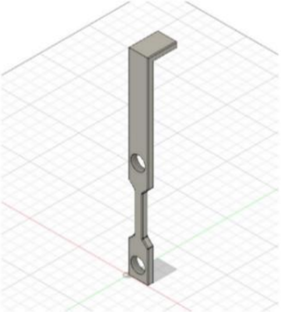

Fig.7 Support Structure

V.IV. Driving mechanism

To give the device the necessary range of motion, the driven gear was placed onto the motor, and the driving gear was mounted onto the moveable exoskeleton sections. The motor's rotations per minute were controlled by using code that was fed from an Arduino Uno board connected to an L298N motor driver. The gait cycles of multiple individuals were evaluated using an adapted open-source technology, focusing specifically on the angles of inclination of the knee and ankle, as well as the timing of these inclinations. Based on these observations, the code was written appropriately and supplied to the Arduino board. The Arduino, in conjunction with the L298N motor driver, then regulates the rpm of the motors to provide the requisite angle of inclination to the moveable components of the exoskeleton for the various gait cycles. The motor was mounted on a supporting structure parallel to the exoskeleton's leg, with one end at the ankle and the other at the waist. This was done to prevent the motor from slipping out during its operation

V.V. Gait Analysis

Gait analysis is a systematic evaluation of an individual's walking pattern or gait. It encompasses the measurement, observation, and assessment of various parameters associated with how a person walks. Gait analysis offers valuable insights into a person's biomechanics, muscle activation patterns, and overall movement patterns during walking. It plays a crucial role in the realm of prosthetics and orthotics, where experts utilize gait analysis to determine the most appropriate design and alignment for prosthetic limbs or orthotic devices. This ensures optimal functionality, comfort, and alignment, leading to enhanced mobility and an improved quality of life for individuals with limb variations or gait irregularities. The gait cycles of various individuals were investigated and analyzed using an open-source gait analysis software during the implementation of this project. Based on the gait analysis results, the data is input into a microcontroller, which then sends signals to the actuators to replicate the user's walking pattern, making the exoskeleton highly personalized. Figure 8 illustrates the gait of a specific individual as captured by the open-source software, while Figure 9 shows the knee's angle of inclination versus time for the same individual, which is input into the microcontroller.

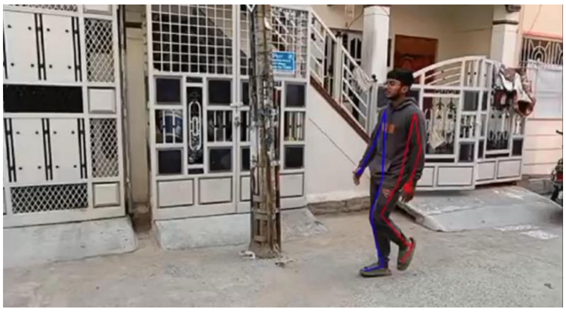

Fig.8 Gait of a certain individual as captured by the open-source software

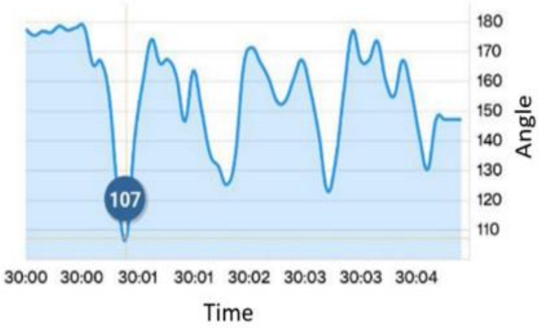

Fig.9 Angle of inclination of the knee vs Time of the same individual to be fed into the microcontroller

VI. FABRICATION

Additive Manufacturing (3D printing) was utilized to fabricate the parts of the exoskeleton model due to its design flexibility, cost-effectiveness, and reduced production time compared to traditional methods. The materials selected were ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic acid), after evaluating various options and considering budget constraints. ABS and PLA were preferred for their ease of use and efficiency in the 3D printing process, as well as their suitable mechanical properties for the application.

Once the parts were 3D printed, they were assembled with precision to ensure a secure fit. The shin component was first inserted into the hollow main leg section and tightened with an M6 plastic knob head screw. The two main leg sections were then aligned and bonded using an epoxy resin-based adhesive to secure the knee brace covering. The ankle section and foot plate were attached to the shin component using an M4 screw, with the driven gear inserted onto the same screw to couple the motor with the foot plate via the driver gear. A locknut was employed to tighten the assembly, ensuring free rotation and preventing screw loosening, while washers were used to facilitate smooth movement. This completed the fabrication of the main frame.

The supporting column was equipped with two DC motors, capable of operating at variable voltages between 12V and 24V, to drive the model. Two driving gears were installed onto the motors, and gear casings were added to maintain proper alignment and prevent gear slippage, ensuring continuous operation.

Finally, the fabricated model was integrated with electronic components, including an Arduino UNO and a motor controller, powered by a Li-ion battery. Electrical connections were made using jumper cables, completing the assembly process. Figure 10 depicts the fabricated prototype in its initial form, prior to the integration of electronic components.

Fig.10 Isometric view (Left) and Front view (Right) of the fabricated prototype

VII. WORKING OF THE EXOSKELETON

The operation of the exoskeleton is divided into two phases:

Knee Phase: Based on data obtained from gait analysis, the input parameters, including RPM and time delay, are programmed into the Arduino using a C++ script. When the power supply is connected and the circuit is activated, the Arduino controls the motor at the knee joint, delivering the required torque for a specified duration. This phase lifts the knee to a predetermined angle, completing the first phase of the operation.

Ankle Phase: Following the knee phase, the Arduino, via the motor controller, activates the motor at the ankle joint. This motor applies torque to the foot plate through the gear mechanism, enabling upward or downward movement based on the gait cycle data.

These two phases operate in a continuous loop, coordinating with the user's gait cycle to facilitate assisted walking and enhance mobility for the wearer. The logic implemented in the code for the microcontroller is illustrated in the flowchart shown in Figure 11.

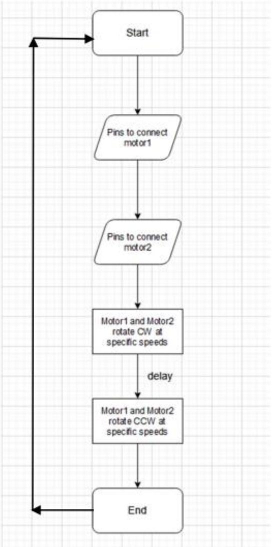

Fig.11 Flowchart for the logic of the code used by the microcontroller to actuate the motors

VIII. RESULTS

The results can be divided into two main phases.

VIII.I. Prototype Design and Finalization of Electronics for Powering the Model

After an in-depth analysis of the human lower limb structure, a comprehensive yet straightforward exoskeleton model was designed using Fusion 360 3D software. Key features of the design include a protective covering and an extendable shin section. The protective covering is critical for limiting knee movement to the desired range and preventing knee buckling, particularly beneficial for elderly users. The extendable shin component allows for height adjustment, enabling the model to adapt to users of varying heights.

The design utilized materials tailored to the functional needs of the exoskeleton. The main frame was fabricated using Acrylonitrile Butadiene Styrene (ABS) due to its high mechanical strength and chemical stability, reducing the risk of skin irritation or allergic reactions. The supporting extension was constructed with Polylactic Acid (PLA), selected for its lightweight properties and sufficient structural strength. This material choice aimed to keep the overall weight of the model low, excluding the electronic components.

The electronic components were selected to deliver adequate torque to both the knee and ankle joints, following a specific sequence determined by gait analysis data. These components were mounted on the supporting structure, optimizing available space and maintaining a compact design. Jumper cables were employed to ensure secure electrical connections throughout the system. The power transmission between the motor and the main frame was facilitated using a gear mechanism, which provided consistent and sufficient torque at the knee and ankle joints.

The resulting model is highly portable and lightweight, enhancing user convenience and facilitating ease of use.

The model was subjected to load simulations using the same multibody dynamics software to evaluate its performance under specific conditions. Analysis of the results indicated a significant reduction in stress experienced by the knee and ankle joints when the exoskeleton was utilized, demonstrating its potential effectiveness in alleviating joint strain during movement.

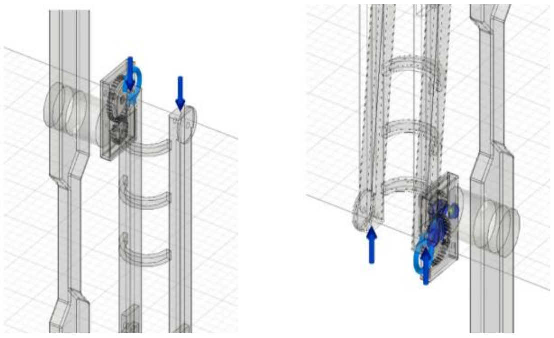

Fig.12 Load and Boundary conditions on the knee of the exoskeleton

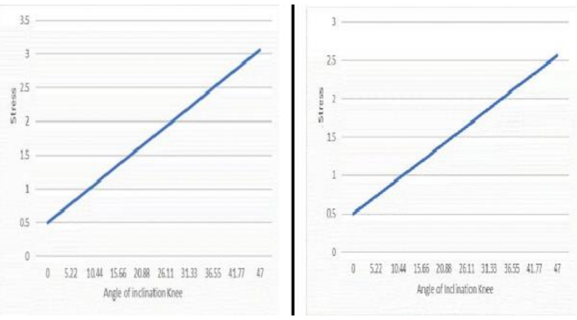

Fig.13 Stress vs Angle of inclination of the knee, without the working of the exoskeleton (Left) and with the working of the exoskeleton (Right)

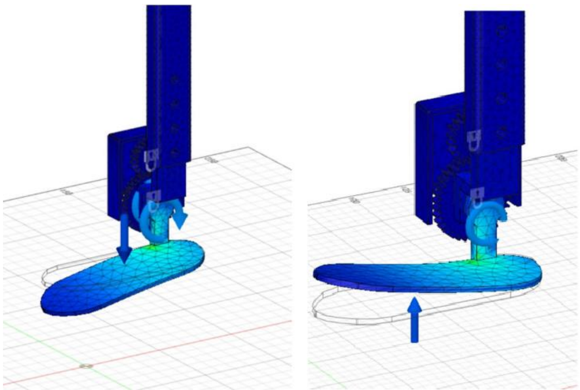

Fig.14 Load and Boundary conditions on the ankle joint of the exoskeleton

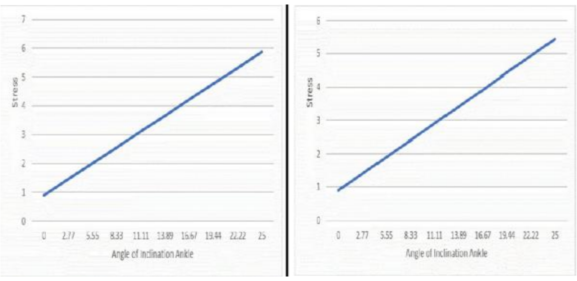

Fig.15 Stress vs Angle of inclination of the ankle, without the working of the exoskeleton (Left) and with the working of the exoskeleton (Right)

Figures 12 and 14 illustrate the load and boundary conditions applied at the knee and ankle joints, respectively, during the simulation. These conditions were selected to closely replicate the actual loads experienced by the knee and ankle joints in real-life scenarios.

Figures 13 and 15 depict the Stress vs. Angle of Inclination plots for the knee and ankle joints, respectively. In both figures, the plot on the left illustrates the normal stress experienced by the joints without assistance, while the plot on the right demonstrates the reduced stress achieved with the support of the proposed exoskeleton. These comparisons highlight the exoskeleton's effectiveness in mitigating joint stress during movement.

The post-analysis results revealed a 20% reduction in stress at both the ankle and knee joints, corresponding to their respective positions and degrees of inclination. This finding demonstrates the effectiveness of the exoskeleton in alleviating mechanical strain and reducing the effort required at these critical joints during movement.

VIII.II. Fabrication of the prototype

The fabricated model was subjected to a series of tests with varying inputs to evaluate its performance under different conditions. Each test was carried out to simulate real-world scenarios, ensuring that the model responded accurately to the expected range of inputs. The results from these tests confirmed that the model met the desired performance criteria. Overall, the tests were successful, demonstrating that the model functions as intended and performs reliably under the given conditions. Figure 17 depicts the fully built and operating prototype equipped with all necessary electronic components, showcasing the integration of key components and the final working model after fabrication. This includes the mechanical structure as well as the embedded electronics, which are essential for the prototype's operation and performance.

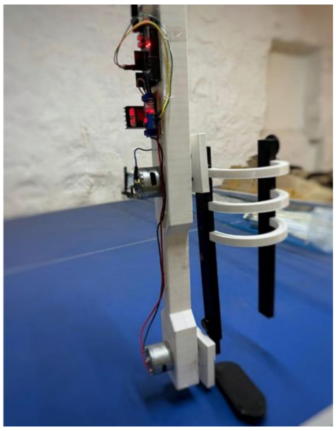

Fig.16 Completed working model of the fabricated prototype fitted with the necessary electronic components

IX. CONCLUSION

Based on the results obtained from both the simulations and the fabricated prototype, several conclusions were drawn, as outlined below.

The device’s design effectively reduces the energy expenditure of the ankle and knee joints. Simulation results indicated a significant reduction in the stress experienced at both the ankle and knee joints, demonstrating the device’s ability to decrease the physical effort required from the user.

Upon fabrication, it was found that the use of additive manufacturing techniques significantly reduced the weight of the exoskeleton compared to similar devices currently available on the market. The gait cycle of various individuals was analysed, and the corresponding data was input into an Arduino microcontroller, which controlled the actuation of the device’s movable parts, specifically the motors at the knee and ankle. This approach allows for the configuration of various modes, providing a personalized and effective experience for each user.

X. FUTURE SCOPE

The future of the portable lower-body exoskeletons holds significant promise, particularly in the areas of data integration and performance optimization. The integration of machine learning algorithms can enhance the exoskeleton’s assistance by analysing the walking cycle and adjusting support in real-time. These algorithms can learn from individual user patterns, personalizing the assistance based on walking style, speed, and terrain, while also anticipating user movements to improve responsiveness and efficiency.

Additionally, the use of high-tensile materials such as carbon fibre and advanced polymers could reduce the exoskeleton's weight while maintaining its structural integrity, thus improving comfort and efficiency. This would decrease the energy required to operate the device and enhance user-friendliness. Efforts to optimize power usage, through advanced energy-efficient components and intelligent power management, could extend battery life, reduce weight, and minimize recharging frequency, further enhancing user convenience and making the device more practical for daily use.

ACKNOWLEDGEMENT

This project would not have been possible without the invaluable guidance and support of our esteemed internal guide and professor, Dr. Ramesha H, Associate Professor, Department of Mechanical Engineering, DSCE. His profound technical expertise and consistent encouragement greatly contributed to the successful completion of this project. We would also like to express our sincere gratitude to the teaching and non-teaching staff whose indirect support was crucial throughout the project. Finally, to our friends for their constant encouragement, which played a key role in the successful completion of this work.

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