FPL Lower Body Exoskeleton

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***Abstract* — The main focus of this project aims to develop a lower-body exoskeleton that will aid linemen in climbing utility poles and reduce physical strain. Climbing utility poles is a difficult job placing a lot of stress on the human body in not-so-ideal conditions. This exoskeleton equipped with motors and sensors will help the linemen ascend and descend reducing the overall pressure this job requires. The methodology combines mechanical with electrical and performs various forms of testing of the components to find the maximum outputs. The results of this project can be significant, as it could potentially provide a promising solution for enhancing the safety and productivity of linemen in the utility industry. It can also lead to further developments in wearable exoskeleton technology for other physically demanding tasks.**

***Index Terms* — Mechatronic Engineering, Electronic Control, Mechatronic Product Design and Innovation, HALL Sensor, Motion Control, Interactive**

I. Introduction

Florida Power and Light, FPL, has found a need for a lower limb exoskeleton to assist their power line workers in ascending and descending the poles they work on. FPL chose a mechanical engineering and electrical engineering team to collaborate and build a powered exoskeleton for the lower half of one's body, from the waist down. The mechanical team had the responsibility of designing a functional frame that can withstand the forces of the user as well as numerous external forces. Kaden Poulter, Thomas Kipping, Moosa Atiya, Christopher Oliveira, and Ford Perry, make up the electrical engineering team. All of the members of both teams are extremely grateful and appreciate the incredible opportunity to work with a leader in the utility space.

The electrical team has taken the frame developed by the mechanical team and is in the process of interfacing a power and logic system to assist the worker in climbing the pole. This project will encompass a semi-autonomous system that provides assistance only when requested by the worker. The core goal of this exoskeleton is to help the user in a work environment without bringing on any added risks. Therefore, the system must have inherent safety features to mitigate risks. Furthermore, the device must be powerful enough to assist any user within a specific range of characteristics.

The system will be broken up into multiple parts that work together to accomplish the shared goal. The power module, being the most important, will supply the entire device with all of the electricity necessary. The logic components are needed for the operation of the device and mitigation of risk, to power on the motors only when needed. Finally, the power output, or motors, will be exerting all the work when force is needed to assist the user in a step up.

II. System Components

The device is best represented by being split up into several different components. These components will both be purchased and designed and developed by either the mechanical or electrical team. However, they will all be integrated together, creating a finished and functional exoskeleton.

A. *Motors*

The driver of all the force that will be assisting the user in climbing will be the C6374 170KV Brushless DC (BLDC) motors. Located on each knee our device will incorporate the use of two of these motors. Originally designed for use in an electric skateboard, the C6374 has a high voltage rating which enables a high torque output. Furthermore, when operating within our 30A limit these motors only draw roughly 1.8 Amps Per hour when working with the load.

B. *Battery*

Considering the stretch goal of having one full hour of operation time and the current draw of the motors. Two of the Dewalt 20V 2Ah batteries will be more than sufficient to power the system. At only 1.8Ah each while under continuous operation, the motors should only draw a collective 3.6Ah out of 4 at the maximum. This will leave an additional 0.4Ah to allow the peripherals to operate at full power. This would mean the entire system can operate continuously for at least an hour on the first set of batteries. Furthermore, the ergonomic design of the Dewalt battery and its interface to the system enables an easy way to quickly swap the batteries in the event that the charge is depleted.

C. *Motor control Board - ESC*

To manage the C6374 BLDC motors a compatible motor control board must be used. The purpose of this board is to accurately and efficiently deliver the power and signal to the motor. The FSESC 4.12 50A interfaces seamlessly with the chosen motors as well as the Arduino Mega 2560 Rev3. While it does seem redundant to have both the FSESC and Arduino in the logic system, both are necessary. Without a clear direct path of communication between the Arduino and the motors, a proprietary motor control board is needed. These boards are typically used in electric skateboards to relay the signal from the remote to the motor which in turn controls the speed of the motor. The board does this by increasing and decreasing the power sent to the motor, as needed. In this case, the FSESC will ensure the motors are acting in accordance with the user's needs.

D. *Sensors*

The sensor system is designed to track the motion of the user and is an integral part of the safety system of the exoskeleton. The sensors are MPU-6050 accelerometer gyroscope modules. These are able to measure acceleration, roll, pitch, and yaw. There are two sensors placed on each joint, one on top and one on the bottom. This is done to measure the acceleration at each end of the joint. This measurement can be used to calculate the angle (θ) of the user's knee with the equation shown in Equation 3.

$$\alpha = arccos\left(\frac{a_{X1}{}^{*}a_{X2} + a_{Y1}{}^{*}a_{Y2} + a_{Z1}{}^{*}a_{Z2}}{\sqrt{a_{X1}^{2}+a_{Y1}^{2}+a_{Z1}^{2}} * \sqrt{a_{X2}^{2}+a_{Y2}^{2}+a_{Y2}^{2}}}\right). \quad (1)$$

$$\beta = \frac{\alpha * 180}{\pi}. \quad (2)$$

$$\theta = \beta - 180. \quad (3)$$

The sensors use the total acceleration in order to be used in the safety system. This section of the safety system is the fall detection system. The sensors are used to constantly calculate the total acceleration of the system. During normal use, there is always acceleration which is calculated by each sensor separately using Equation 4. If a user were to fall, the total acceleration would reach zero due to free fall. Using this information, the sensors are able to communicate when the user falls to the Arduino.

$$Tot_{accel} = \sqrt{a_X^{2} + a_Y^{2} + a_Z^{2}}. \quad (4)$$

E. *Exoskeleton Frame*

Designed by the mechanical engineering team, the frame is the backbone of the entire device. It has been developed to support workers in an ergonomic and safe manner. Furthermore, the design encompasses adjustability to customize the dimensions for any expected size of a worker. In addition to these options, the mechanical team also maximized the safety of the device through the frame. The requirements are that the device must be able to withstand a 50,000 Newton impact and falls of up to 36.6 Meters. The mechanical team met these requirements and surpassed them, providing stress tests that prove negligible deformation in these conditions. Another feature of the frame is the mechanical stop. This mechanism prohibits the powered components of the device from overextending and injuring the user.

F. *Microcontroller - Arduino*

The Arduino Mega 2560 Rev3 is the brain of the device. The team chose this microcontroller due to its affordable price, a high number of charge cycles, a high number of pins, and 15 PWM outputs. Additionally, the 256 kilobytes of flash memory, 16 MHz clock speed, and 8 kilobytes of SRAM set this board apart from the competitors. The high processing power and large interface for connecting peripherals enable strict control over the entire system. This microcontroller is the heart of where all the logic for the device is stored making it incredibly important. All of the user's requests for the device will first be run through the Arduino and then out to the motors. The Arduino will also be looking for feedback from the motors to ensure a seamless transition between each step.

III. Power Systems

The power system will be the most important part of the entire device. Without a power source and method of delivery, the peripherals and motors will be inoperable. The power system is composed of three distinct components: The power source, the power distribution, and the hardware inputs.

A. *Power Source*

The power source that is going to be utilized for the lower body exoskeleton suit is going to be two Dewalt 20-volt batteries that have a capacity of 2 amp-hours and require 1400 watts for the input. The reason for selecting this battery as the power source is because of the simplistic accessibility the lineman workers will have to remove and replace the batteries.

The batteries will interface the system with two separate battery adaptors. These adaptors are designed specifically to fit a Dewalt 20V battery, allowing for easy battery swaps. Moving down the line from the adaptor, the batteries/adaptors will be in parallel connected by the 14 AWG wires that the adaptors come with.

B. Wiring

From the battery adaptors on, the wiring will deliver the power to the peripherals and the motors. The wiring being used is 14 AWG copper wire. The reason is, 14 AWG copper can withstand up to 15 amperes of current at any given time. Seeing how our batteries are rated at 2Ah and the motors will only draw 1.66 amps at a maximum, this wire will be more than enough to withstand the current that is running through them. Furthermore, 14 AWG copper is sturdy enough to withstand any expected bending, movement, abrasion, and abuse throughout the operation. The table below describes the various gauges of wire depending on the length of the wire and the total Amps.

Length (Feet):	**5 Amp 12V Wire (60W):**	**10 Amp 12V Wire (120W):**	**15 Amp 12V Wire (180W):**
15 Ft	16 AWG	12 AWG	10 AWG
20 Ft	14 AWG	12 AWG	10 AWG
25 Ft	14 AWG	10 AWG	8 AWG

Table 1.1

C. Power to the Peripherals

The peripherals in this system require no more than 5 Volts. Seeing that the power source is 20V a step-down converter must be incorporated. The L7805 20V to 5V converter power supply module is the device being used. Here the wiring will be spliced off from the mainline and connected to the L7805 to then run down to the Arduino Mega Rev 3 and the accelerometer sensors. This step-down converter will ensure the safe operation of the Arduino and sensors without overloading their system with voltage.

C. Power to the Motors

From the splice on the mainline down the rest of the power is sent to the motors and their respective control board. Each board can operate with the full 20V power supply. This being said, the batteries in parallel will be directly connected to the FSESC 4.12 via 14 AWG wiring. Using the proprietary 10 AWG wiring and connection points between the C6374 Flipsky BLDC Motors the power system will be complete.

IV. Florida Power and Light Safety Requirements

Florida Power and Light have provided certain criteria for the execution of building a lower-body exoskeleton. This set of specifications/requirements is very important for us to follow as this will make sure the employees using this equipment will be safe and be able to use it to their advantage.

There are over ten different specifications provided that we followed as stated but will be demonstrating only three of those in our presentation. For the lower-body exoskeleton to be deemed "successful," it must pass and meet the requirements of the following three specifications given in Table 2.1, Table 2.2, and Table 3.2.

Requirement	**Specification**
The system shall have a locking mechanism that can lock and unlock	≥ 54 Nm ≥ FOS of 2

Table 2.1

Requirement	Specification
The system shall be able to ascend and descend a utility pole disregarding any obstacles on the pole.	5.5-inch wide obstacles 360-degree movements

Table 2.2

Requirement	Specification
The system shall provide a hybrid active and passive solution to generate torque at the knees and hips to reduce the user's workload and strain.	> 10 Nm active

Table 2.3

The first specification that must be followed when building an exoskeleton for FP&L is the locking mechanism. This is important because it ensures that the exoskeleton will be able to safely support the weight of the equipment and the user. If the locking mechanism fails, the equipment could fail and potentially injure the employee or others nearby. Following this specification ensures the safety of both FP&L employees and the public.

The second specification that must be followed is the ability of the exoskeleton to ascend and descend a utility pole, disregarding any obstacles on the pole. This is crucial because FP&L employees often work in challenging and unpredictable environments, such as during storm restoration efforts. Being able to safely and efficiently navigate utility poles is essential to completing their work.

The third specification that must be followed is the hybrid active and passive solution to generate torque at the knees and hips. This is important because carrying heavy equipment for extended periods can cause significant strain and fatigue on the body, potentially leading to injuries. By providing a hybrid active and passive solution, the exoskeleton can assist the user in carrying the weight and reduce the risk of strain and fatigue.

V. Software

The software of the system is powered by and runs through the Arduino. It controls the sensors, and motor control boards which control the motors, and allows the system to communicate as a whole. The software also allows the fall detection system to function and halts all functions when it is triggered.

A. *Fall Detection*

As previously mentioned, the software works with the sensors to form the Fall Detection system. The software sets the range and sensitivity of the accelerometer gyroscopes in order to be less sensitive towards smaller movements like taking steps. This is done to reduce the chance of a misfire of the Fall Detection system. The software constantly loops to read the acceleration using the mentioned equation, Eq. 4. There is a conditional set in the loop to read when the acceleration drops to near zero, meaning there was a fall. This conditional will print to the serial console and stop all functions. The system is put into a loop that will not allow any reading on the sensors or movement on the motors until the Arduino is fully reset. This is done in order to avoid an accidental reset in case of an accident.

B. *Motor Control*

The software interfaces with the motor control boards (FSESC) in order to control motor movement. The first portion of software that controls the motors is the VESC software. VESC is an open-source software that has a feature to configure the motors with important parameters, including resistance, inductance, and lambda tuning. The software also allows the motors to be limited in the current and duty cycle that can be run. The current must be limited to meet the control board requirements and for safety purposes to protect the user. The duty cycle is limited to control the speed the motor will run when in use and to maximize the torque output of the motor.

The torque relation to the current and duty cycle under resistance is shown in Table 3.1. The second part of the software that controls the motor is Arduino programming. This software interfaces with the calculation of the angle of the knee from the sensors to form a string of conditionals. The conditionals dictate when the user is trying to move. This will in turn move the motors. The motors will move inside a loop while the user is taking a step. A conditional within the loop will stop the motor when the user stops moving.

Amps	Volts	Duty Cycle	Torque
7	20	4%	4 Nm
30	20	7%	8 Nm
35	20	10%	8 Nm

Table 3.1

VI. Benchtop Testing

To gain a better understanding of how the components we have chosen will operate under the specific circumstances of this project, we created a benchtop test knee joint. This setup allowed us to test the motor torque at different weights, the amount of current required to move different amounts of weight, and the amp hours required to power the knee joint for the desired amount of time.

A. *Benchtop Setup*

The test bench setup consists of two sections of laser-cut MDF wood with versahubs on the bottom portion and bearings on the top portion. The versa hubs allowed for the tension to be dispersed over the area of the knee joint instead of all the stress being placed on the shaft. The shaft was a ½ in thunderhex shaft to transfer rotational force to the other versahub and leave the bearings to rotate freely. The pulley was a 3D printed part that contained holes at the same places that the versa hub had them with M4 bolts going through from the MDF wood through the versa hub and into the pulley.

The pulley ratio we found was a 4:1 gear ratio which allowed us to lift a heavier weight. Each side of the joint is connected to a 2ft piece of aluminum extrude using M5x8mm T-Slot nuts. By utilizing those T-Slot nuts, we were able to fasten the knee joint to one end of the extrude and place the motor housing on the other end. The motor housing was also made of laser-cut MDF wood and since the T-Slot bolts can slide up and down the aluminum extrude, we could tension the belt around both pulleys.

B. *Weighted Testing*

The first test we performed on the benchtop setup consisted of initially no weight and applying small a mounts of pressure ourselves and finding the proper values to constrict both the duty cycle and current to apply the most torque without overloading/overheating the motor control board. We found that limiting the duty cycle to around 4% and limiting the peak current to 30 A allowed us to provide ample torque while staying well below the motor control board's max current draw.

With those parameters in place, we ran a series of tests to understand the amp draw over a period of time. We extended and contracted the knee joint multiple times over the span of 5 minutes. We then performed the same test with both a 2.5lb weight and a 5 lb plate attached to the ankle area of the joint. We recorded the current in, the current running through the motor, and the duty cycle as shown in Fig 1. Using the data we recorded we were able to ensure that we could run the motor for an hour without exceeding the 2 Ah limit of the battery.

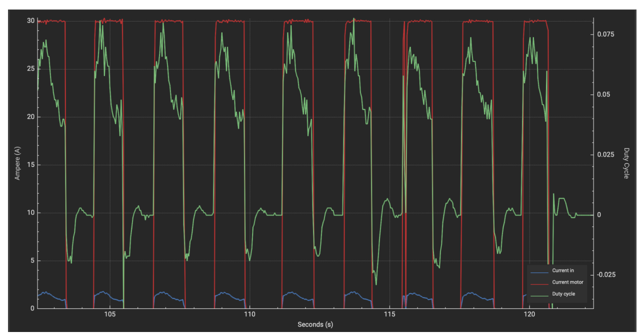

Fig. 1: 2.5 lb Weighted Test Results

VII. Full Assembly

Using the work from the Mechanical Engineering Team some amendments have had to be made. These changes stemmed from the challenges of incorporating the electronic components into the previous team's design. To combat this issue the Electrical Engineering Team took it upon themselves to design new knee joints and motor housing. These amendments allow for a seamless interface of the motor and pulley to the exoskeleton frame. As the project progressed a few other components have seen some changes. The battery pack and power system as well as some aspects of the logic system have had one or more revisions made.

Due to the amendments to the design, all of the components are sure to work in synergy. Given the requirements set by both the UCF Senior Design 2 class and FPL, the electrical team ensured that every change made would still meet the requirements. These alterations between both design phases even allowed the team to reach some of their stretch goals.

A. *Motor Housing and Thigh mounting*

After understanding that the core concepts of the exoskeleton's electronics would work we then moved to mounting the motor onto the MAE team's knee joint design as well as adding other key features for the exoskeleton to be properly mounted on a person's leg. The motor housing is placed on the bottom of the knee joint with slotted mounting holes to allow for the motor to move laterally for attaching and tightening the pulley's belt.

The next key aspect of the new design is the thigh mounting. The goal is to provide an adjustable surface to encase the user's leg to allow for the motor's torque to be able to assist in extending and contracting the user's leg. The four slotted holes allow for the design to lengthen depending on the size of the user's leg. We also created a bracket that will attach to the thunderhex shaft to prevent the knee from overextending if there is a malfunction in the system.

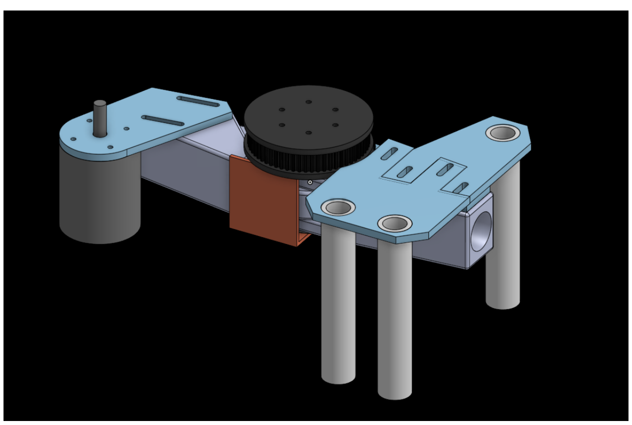

Fig. 2: Motor Housing and Thigh Mounting

VIII. Conclusion

Florida Power and Light (FPL) has partnered with a mechanical and electrical engineering team to develop a powered exoskeleton to assist their power line workers in ascending and descending poles. The exoskeleton will be a semi-autonomous system that provides assistance only when requested by the worker and will have inherent safety features to mitigate risks. The system is broken up into multiple parts, including motors, batteries, motor control boards, sensors, and the exoskeleton frame. The C6374 170KV Brushless DC (BLDC) motors will provide the force needed to assist the user in climbing. Two Dewalt 20V 2Ah batteries will power the system, with the FSESC 4.12 50A motor control board interfacing with the motors and the Arduino Mega 2560 Rev3. Sensors, specifically the MPU-6050 accelerometer gyroscope modules, will track the user's motion and calculate the angle of the user's knee, and also work as a part of the fall detection system. The exoskeleton frame is designed to support workers in an ergonomic and safe manner, withstanding a 50,000 Newton impact and falls of up to 36.6 meters.

Acknowledgment

We the authors would first like to thank Florida Power and Light (FPL) for their financial support and assistance in developing our exoskeleton project. FPL's commitment to safety and innovation has been instrumental in designing an exoskeleton that enhances the safety and productivity of linemen.

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Lastly, we would like to acknowledge all faculty that agreed to review our project and UCF for the education provided.

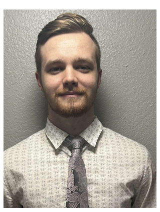
Biography

Ford Perry is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Electrical Engineering in May of 2023.

Moosa Atiya is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Electrical Engineering in May of 2023.

Thomas Kipping is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Computer Engineering in May of 2023. He will be working for L3Harris after graduation as a Software Engineer.

Christopher Oliveira is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Electrical Engineering in May of 2023.



Kaden Poulter is currently a senior at the University of Central Florida and will receive his Bachelor of Science in Electrical Engineering in May of 2023.

References

[1] L. I. Minchala, F. Astudillo-Salinas, K. Palacio-Baus, and A. Vazquez-Rodas, "Mechatronic Design of a Lower Limb Exoskeleton," in Mechatronic Systems in Engineering: Design, Control and Applications of, S. Yildirim, Ed. IntechOpen, May 3, 2017, pp. 1-19. DOI: 10.5772/67460.

[2] A. K. Varghese, "Design of a Lower Limb Exoskeleton," IJIRST – International Journal for Innovative Research in Science & Technology, vol. 2, no. 11, pp. 326, April 2016. ISSN: 2349-6010.

[3] A. K. Alshatti, "Design and Control of Lower Limb Assistive Exoskeleton for Hemiplegia Mobility," Ph.D. dissertation, Dept. Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, United Kingdom, Aug. 2019.

[4] Y. Li, X. Guan, X. Han, Z. Tang, K. Meng, Z. Shi, B. Penzlin, Y. Yang, J. Ren, Z. Yang, Z. Li, S. Leonhardt and L. Ji, "Design and Preliminary Validation of a Lower Limb Exoskeleton With Compact and Modular Actuation," in IEEE Access, vol. 8, pp. 68123-68131, 2020, doi: 10.1109/ACCESS.2020.2985910.

[5] J. Kang, Z. Li, S. Li, J. Wang, J. Chen, and Q. Li, "A powered lower limb exoskeleton for human gait rehabilitation," IEEE/ASME Transactions on Mechatronics, vol. 22, no. 5, pp. 2156-2166, Oct. 2017. DOI: 10.1109/TMECH.2017.2754379.

[6] L. Xiong, Y. Zhang, L. Wang, Y. Li, and Y. Li, "Development of a lower extremity exoskeleton for sit-to-stand assistance," IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 1639-1644, Dec. 2016. DOI: 10.1109/ROBIO.2016.7866732.

[7] C. Zhang, X. Liu, L. Chen, C. Cai, and Y. Chen, "Design and control of a lightweight lower limb exoskeleton for walking assistance," IEEE/ASME Transactions on Mechatronics, vol. 25, no. 2, pp. 651-662, Apr. 2020. DOI: 10.1109/TMECH.2020.2971587.

[8] Radder, B., & Schwab, A. L. (2019). A lower-limb exoskeleton for climbing stairs. In 2019 IEEE International Conference on Robotics and Automation (ICRA) (pp. 8369-8375). IEEE. doi: 10.1109/ICRA.2019.8794274

[9] Khan, M. U., Kim, J., & Jo, S. (2021). A Climbing-Assist Exoskeleton Using Compliant Mechanism for Lower Limb Mobility. IEEE/ASME Transactions on Mechatronics, 26(1), 126-135. doi: 10.1109/TMECH.2020.3034509

[10] Tagliamonte, N. L., & Lippiello, V. (2021). Development of a climbing exoskeleton for lower-limb assistance. IEEE Robotics and Automation Letters, 6(2), 2605-2612. doi: 10.1109/LRA.2021.3062522

[11] S. H. Kim, W. J. Choi, and D. H. Kim, "Design and Control of Lower Limb Exoskeleton for Climbing Steep Slopes and Stairs," in Proc. IEEE Int. Conf. on Advanced Robotics and Intelligent Systems (ARIS), 2019, pp. 21-26. doi: 10.1109/ARIS.2019.8858608

[12] A. R. Baida, M. Zaied, and N. Benhadj Braiek, "Design of a Climbing Lower Limb Exoskeleton for Paraplegic Patients," IEEE Access, vol. 7, pp. 80073-80084, 2019. doi: 10.1109/ACCESS.2019.2920852

[13] J. Li, Y. Gao, H. Huang, and W. Chen, "Design and Control of a Climbing Lower Limb Exoskeleton for Farmers," IEEE Access, vol. 7, pp. 156139-156147, 2019. doi: 10.1109/ACCESS.2019.2946089

[14] Y. Lu, X. Chen, L. Zhang, and X. Wang, "A Novel Linear Rotary Actuator and Its Application in Exoskeletons," IEEE/ASME Transactions on Mechatronics, vol. 23, no. 2, pp. 952-960, April 2018. doi: 10.1109/TMECH.2018.2814521.

[15] H. Yu, H. Huang, Y. Song, and J. Du, "Electromyography-Based Active Control for Lower-Limb Exoskeleton With Enhanced Human–Robot Interaction," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 27, no. 5, pp. 1054-1064, May 2019. doi: 10.1109/TNSRE.2019.2903108.