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Exo Arm-An EMG Based Orthotic Prototype

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Radu Ceausu earned BS and MS degrees in Mechanical Engineering from University Politehnica of Bucharest, Phd in Mechanical Engineering from Wayne State University, Detroit, MI. Academic research consisting in developing and validating original engine transient software models (including friction, controls, dynamics). Extensive teaching experience in mechanical engineering coursework: 3 years at Politehnica University Bucharest,8 years with Wayne State University, Detroit, MI; 11 years with Wentworth Institute of Technology, Boston, MA. Worked for more than 7 years of research and development of internal combustion engines at AVL PEI, Plymouth MI; AVL Gmbh, Graz Austria; John Deere PEI, Waterloo IA. Worked in analysis and development of advanced engine concepts encompassing all major engine systems (intake, combustion, cooling, exhaust, exhaust aftertreatment), applying models of different levels of complexity (0d, 1d, 3d, coupled 1d-3d). Analysis of aftertreatment systems, validation of analysis procedure, to support integration of aftertreatment systems on different vehicle platforms.

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Gloria Ma is a Professor in the Mechanical Engineering program at Wentworth Institute of Technology. She has been teaching robotics with Lego Mindstorm to ME freshmen for several years. She is actively involved in community services of offering robotics workshops to middle- and high-school girls. Her research interests include dynamics and system modeling, geometry modeling, project based engineering design, and robotics in manufacturing, artificial intelligent in manufacturing, and engineering education.

Yusuf Eid, Wentworth Institute of Technology

Yusuf Eid received his BS in Mechanical Engineering from Wentworth Institute of Technology. Throughout his time at Wentworth, he studied various subjects focusing on stress and strain analysis as well as simulation-based design. Yusuf also participated in various internships throughout his time at Wentworth, including project management and manufacturing roles. Through his time at Wentworth and guidance from his professors and peers, Yusuf was able to utilize his experience to contribute to the design and creation of the Exo-Arm.

HAN THANH HUA, Wentworth Institute of Technology

Han Hua: Mechanical Engineering major, Wentworth Institute of Technology Han Hua studies mechanical engineering with experience in CNC machines. As a technician in medical manufacturing, and possessing

business management skills, he is a well-rounded individual with a diverse skill set. As a mechanical engineering student, Han has a strong foundation in the principles and theories of the field. Han's experience as a technician in the medical manufacturing industry has given him practical experience in applying this knowledge to real-world problems. He understands the importance of precision and reliability in medical device production and has developed the skills necessary to produce high-quality components. He can identify areas where improvements can be made in the manufacturing process and implement changes to increase efficiency and reduce costs. Han's knowledge can apply to the medical manufacturing industry, where cost-effectiveness and efficiency are critical to success. Because of this, he was able to help immensely with the cost and budget aspect of the Exo-An:

Nathanael Hillyer, Wentworth Institute of Technology

Nathanael Hillyer graduated from Wentworth Institute of Technology in 2023 with a BS in Mechanical Engineering. Throughout his education, he took part in multiple research projects exploring theoretical quantum physics and graphene exfoliation techniques. He is currently employed as a mechanical engineer, focusing on the design and implementation of high precision atomic timing devices.

Exo Arm-An EMG Based Orthotic Prototype

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Abstract: Millions suffer each year from muscle deficiency resulting from various medical conditions such as muscular dystrophy, nerve damage, stroke, neurapraxia, spinal cord injury and more. The Exo-Arm capstone project seeks to demonstrate the potential of Electromyography (EMG) based orthotic devices for strength enhancement and rehabilitation. For this capstone project an EMG based exoskeleton arm was designed and fabricated. This device is designed to be attached to a user's arm and respond directly to the signal from the user's muscles. Once a user flexes their biceps, the skin electrodes detect the change in voltage and the EMG signal is sent to an Arduino nano. The Arduino microcontroller takes this raw signal and runs it through a smoothing algorithm and returns a clean signal. Once the clean signal passes a given threshold, a signal is sent to the motor controller which activates the electric motor.

Introduction

The goal of this capstone project was to design and build a wearable exoskeleton, which we dubbed the “Exo-Arm”. The Exo-Arm will boost the user's bicep strength and will be equipped with electromyography (EMG) sensors attached to the user’s bicep, an Arduino controller, and electric motor to create the torque required according to the user’s need, as the EMG sensors deem fit. Furthermore, it will be portable and run on an attachable battery pack, allowing for greater convenience. Especially important is to create a relatively low-cost and practical exoskeleton so that even low-income patients can benefit from it. Overall, the Exo-Arm has the potential to improve the lives of people of many. There may already be similar products on the market, but Exo-Arm is meant to be more affordable and accessible, while including the unique aspect of being EMG sensor controlled rather than by manual control devices such as joysticks.

Capstone Project Objectives

The main objective of this Capstone project was to design and fabricate an assistive device that augments the function of the bicep, allowing the user to generate a greater force in bicep flexion using electromyographic sensors. This will no doubt be a useful device for people who suffer from physical disabilities or injuries.

The second objective was that while working on the capstone project, the team of four mechanical engineering students will improve their undergraduate learning experience. Pedagogical materials such as familiarizing mechanical students with Arduino microcontroller programming, where the students gained hands-on experience in selecting mechanical components and sensors, and simulation of a robotic arm with SolidWorks. The school of engineering provided complete support in terms of equipment and software required.

The third objective of the project was to present the prototype at the student university’s capstone projects show and a town show in Robotics, where other universities and companies present their projects. The feedback from their participation will help structure a better capstone design program for senior students and will impact the engineering education field.

Literature Review and Background Research

Arthritis and similar conditions affect millions of people all over the world. In fact, 20% of the entire world population deals with arthritis in some capacity [1]. Many of these people, despite their disabilities, are still required to work physically demanding jobs. The hardship such people face cannot be imagined.

Exoskeletons are a form of wearable robotics that enhance human physical abilities. They are designed to augment strength, provide stability and support, and aid in tasks that would be challenging without them. These arms provide numerous benefits across industries such as manufacturing, healthcare, and the military. Recent studies have evaluated the impact of exoskeleton arms in various fields. For instance, a study published in the Journal of Neuro Engineering and Rehabilitation assessed the impact of exoskeleton arms on stroke patients' upper limb function. Results revealed that exoskeleton arms significantly improved patients' ability to perform daily activities while reducing dependence on caregivers [2]. In manufacturing, another study in the International Journal of Industrial Ergonomics found that exoskeleton arms decreased musculoskeletal disorders in workers who frequently lift heavy objects and It reduced the risk of injury [3]. To design the Exo-Arm, principles of mechanical engineering from Dynamics, Mechanics of Materials, and Machine Design were applied. An electric motor, EMG sensors, and relevant software were utilized to enable the arm to exert greater force on the user's forearm than they could generate on their own. This would make lifting tasks easier while minimizing the risk of injury or strain. Due to the complexity of the topic, research was critical, and multiple references were consulted. One such scholarly report was "Assistive Arm-Exoskeleton Control Based on Human Muscular Manipulability" [4]. When it came to analysis, SolidWorks simulation was an important tool that allowed us to gain theoretical results in design. Numerous studies support the viability of our product, though existing prototypes are basic and limited. Unlike current exoskeletons for sale, our design utilizes electromyography (EMG) for control, enhancing user ease and precision. EMG's potential has been affirmed by the Journal of Neuro Engineering and Rehabilitation, whose study indicates its accuracy, low computational demand, and applicability to assisting those with arm disabilities [5]. This demonstrates its value for devices like the Exo-Arm, aiding tasks otherwise impossible for such individuals. Central to our design is the electric motor, which is used across industries including the medical device industry. The University of Technology and Life Sciences notes the increasing reliance on electrical engineering in healthcare, emphasizing the demand for compact, high power electric motors and actuators [6]. Incorporating these components into medical applications holds significant promise. This amalgamation of EMG and electric motor technology marks a unique approach, creating a future where exoskeletons empower individuals and reshape medical device paradigms. Another major aspect of our design was the unique software-hardware relationship we had to figure out. To do this, we needed to understand the function of an Arduino and how we could create a connection between it, the EMG sensors, and thus translate to actual movement. One major reference we used was a robotics supplier, "goBILDA". In a YouTube tutorial, we saw how an external motor control was used for a large, brushed DC motor with a 1x15A Go- Build-a controller, enabling multiple motor connections through Y harnesses. The controller supplied 15A continuous power from a 12V, 3000mAh battery, managed via a white jumper on Arduino's pin nine. The tutorial introduced code like “set ESC power” for speed and direction control, and mapping power variables to the PWM range [7]. These insights were applied to Exo-Arm. Incorporating EMG technology was equally intricate. We referenced Nikhil Agnihotri's article, "Designing an Arduino-based EMG monitor," utilizing an AD8226-based sensor and Arduino UNO to assess muscle and nerve health through electrical signals. Components included Arduino UNO, AD8226 sensor, electrode pads, cables, batteries, and wires. Circuitry involved powering the sensor with batteries and connecting its output to an

Arduino analog input, with an Arduino sketch facilitating EMG data reading and visualization [8]. Overall, these resources excelled our Exo-Arm project, combining sophisticated motor control and advanced EMG integration.

Exo-Arm Components and EMG Signal Processing

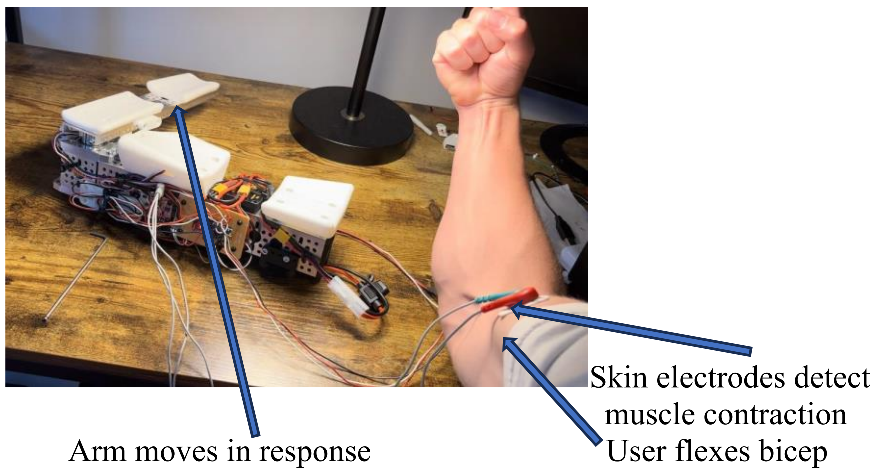


Figure 1
EMG signal to arm movement

Once a user flexes their biceps, Figure 1, the skin electrodes detect the change in voltage and the EMG signal is sent to an Arduino nano. The Arduino takes this raw signal and runs it through a smoothing algorithm and returns a clean signal.

The raw EMG signal appears, Figure 2:

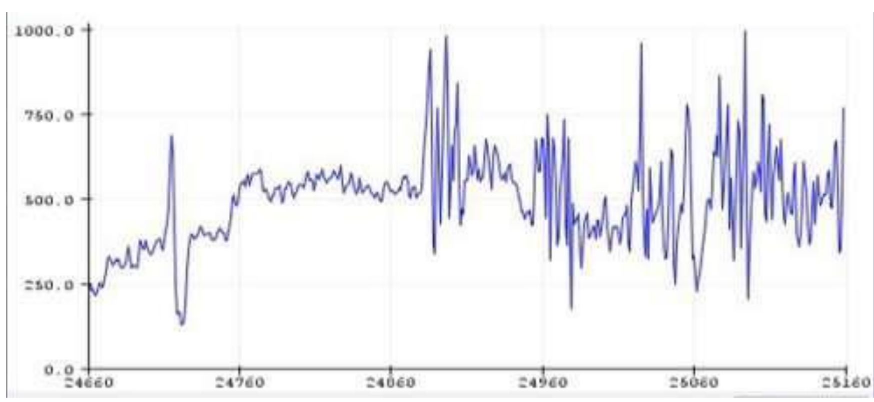


Figure 2
EMG raw signal

The region with heavy signal noise represents a user flexing the muscle group being observed while the flat regions represent muscle relaxation. Visually it is trivial to understand when a user is activating the muscle group. However, to use this plot for motor control the signal must be sufficiently smoothed to avoid jerky motor movement. For the smoothing algorithm a 50-point moving average was used. This resulted in the following signal.

This signal allows for motor control by setting a threshold which must be past for motor activation. Thus, when a muscle is sufficiently flexed, the motor engages, assisting this movement. This muscle activation would occur when a user is lifting a heavy object.

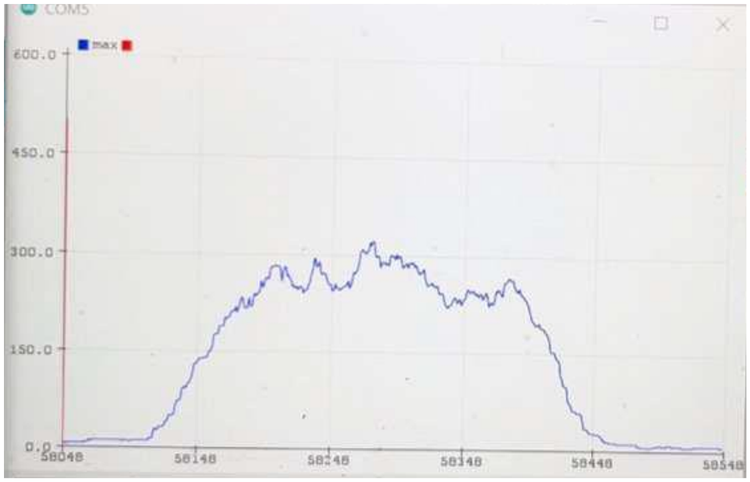
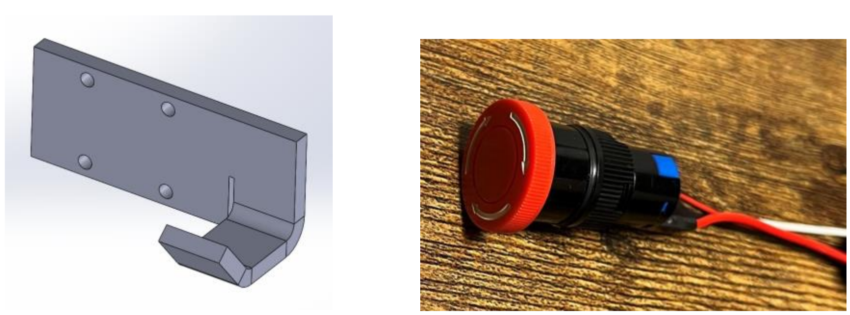


Figure 3
EMG smoothed signal with threshold

Figure 3 shows a smoothed EMG signal that would result in motor movement as the EMG signal passes the set threshold of 150.
Once the clean signal passes a given threshold a signal is sent to the motor controller which activates the electric motor.

The motor turns a worm gear which changes the axis of rotation by 90 degrees and adds an additional 1:28 ratio to the 1:19.2 ratio of the stock gear box.

Safety Features
The arm movement is limited by end stops placed at full extension and contraction of the arm. The end stops are switches placed such that they are contacted by "end stop contacts" at the set limits, Figure 4:



(a) (b)

Figure 4

(a) End stop; (b) Switch stop-motor.

End Stops
In the Arduino code these are referred to as the variables “upper” and “lower”. Reference the code for more information regarding how these end stops affect motor control, Figure 5:

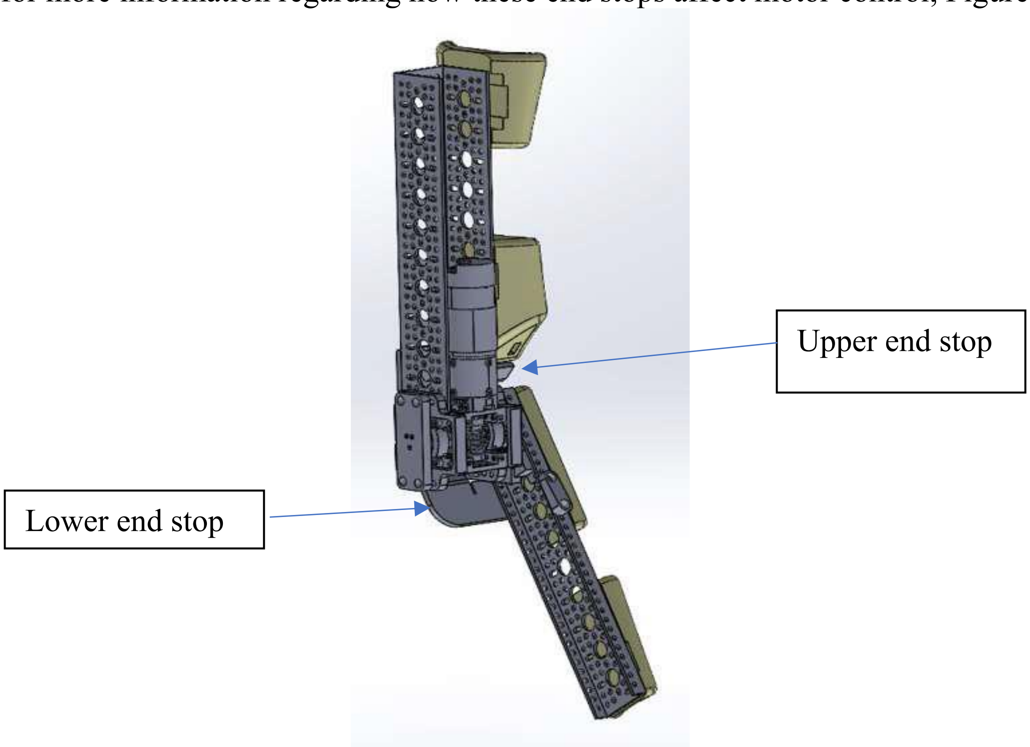


Figure 5 Lower and upper end stops.

Motor, worm gear and electrical components
Several critical components were sourced from a robotics supplier “goBUILDA”. Several of which were the battery, motor controller, motor, and worm gear assembly. Sourcing these components from a single supplier makes for easier assembly and higher confidence as these components were all intended to be used together. For more information regarding the motor controller programming reference the above Arduino code. The battery supplies 3000 mAh at 12 volts which allows for extended remote use of the Exo-Arm. For this application it is desirable to have low RPM’s and high torque for both user safety and lifting capability. To fulfil this, several gear assemblies are used to reach a proper speed. First, there is a gear assembly attached to the motor. goBUILDA offers several different options for this to fit a myriad of cases. For this application a motor with a 19.2:1 gear ratio was chosen. With this gear assembly attached, Figure 6, the motor delivered 24.3 kg.cm (338 oz-in) of torque at 312 RPM. It was desired for this speed to be reduced further. Additionally, the angle of rotation needed to be rotated by 90 degrees. For these reasons, the following worm gear assembly was purchased from goBUILDA.

Figure 6 Worm gear assembly

This gear assembly adds an additional 28:1 gear ratio to the system. This results in a final torque of 680.4 kg.cm (9,464 oz-in) of torque at 11.14 RPM. Based on early estimates of typical arm movement this is a desirable speed. At a length of 12 in, approximately the length of a typical forearm, this assembly would be able to lift a maximum of approximately 20lbs.
In Figure 7 is shown the assembly with its components and Figure 8 shows the final prototype in the fully extended and fully contracted positions.

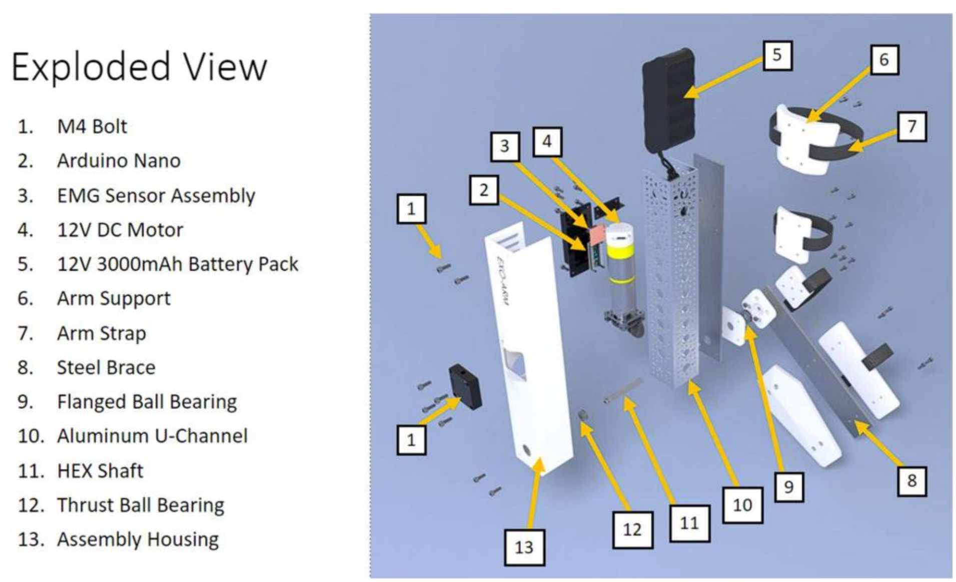
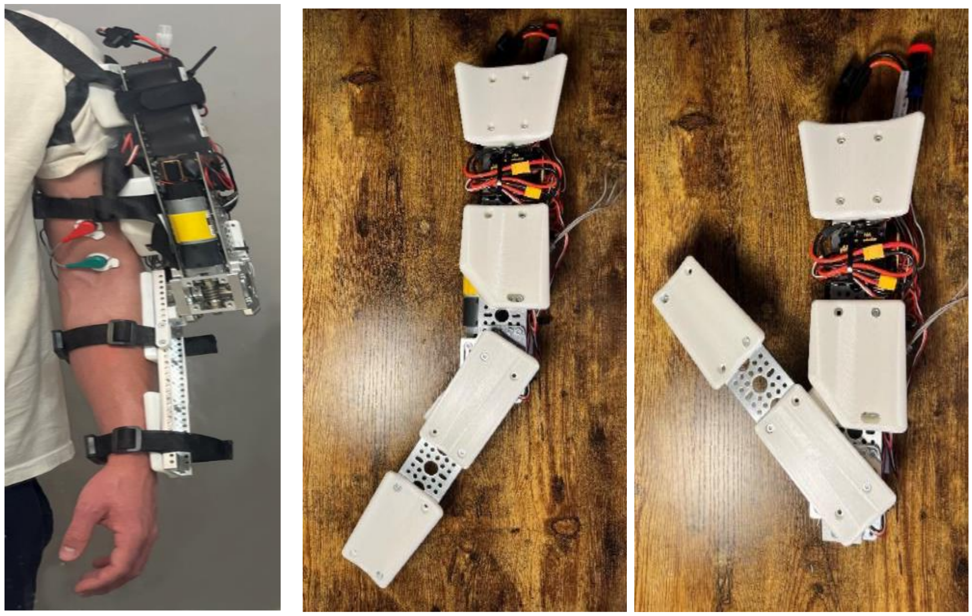


Figure 7 CAD assembly-exploded view.



(a) (b) (c)

Figure 8

(a) Final prototype; (b) Fully extended position; (c) fully contracted position.

Trajectory Planning

In this section we determine the trajectory for the function θ(t), the angle in time t of the forearm at the actuated revolute joint. We select the angle as a cubic polynomial, smooth curve function, Equation 1:

$$\theta(t)=A_0+B_1 t+C_2 t^2+D_3 t^3 \quad [\text{deg}] \tag{1}$$

Therefore, the angular velocity is, Equation 2:

$$\dot{\theta}(t)= B_1+2 C_2 t+3 D_3 t^2 \quad [\text{deg/s}] \tag{2}$$

The polynomial generates joint's control variables between initial time t_0 and final time t_f.
The initial and final values for position θ(t) and velocity $\dot{\theta}(t)$ are, Equation 3:

$$\theta(t_0)= \theta_0 \;;\; \dot{\theta}(t_0) = \omega_0; \quad \theta(t_f) = \theta_f \;;\; \dot{\theta}(t_f) = \omega_f \tag{3}$$

In biomedical area for rehabilitation applications, the initial and final angular velocities are zero since a smooth motion is desired for patient's elbow.

$$\theta_0 = 0 \text{ deg} \;;\; \omega_0 = 0 \text{ deg/s}; \quad \theta_f= 90 \text{ deg}; \;\omega_f = 0 \text{ deg/s} \tag{4}$$

The path constraint equations (1) and (2) for the initial and final values from Equation 4 provide the coefficients in cubic polynomial shown in Equation (5)

$$A_0=0 \;;\; B_1=0 \;;\; C_2=67.5 \;;\; D_3=-22.5 \tag{5}$$

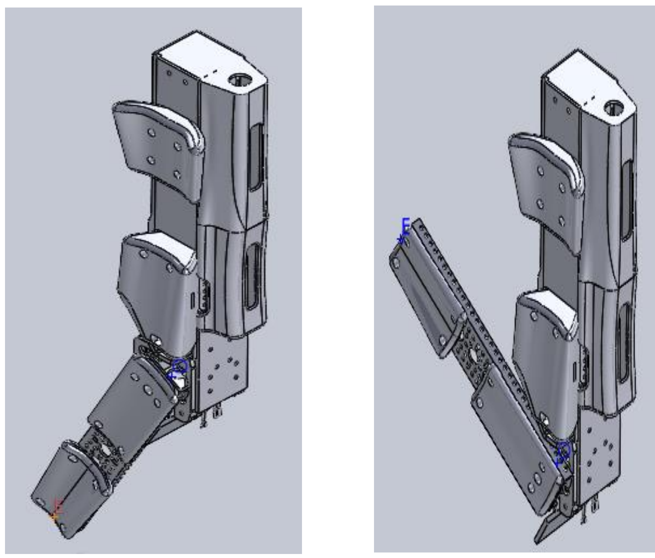
Equations (1) and (2) for trajectory planning are

$$\theta(t) = 67.5\, t^2 - 22.5\, t^3 \qquad [\text{deg}] \tag{6}$$

$$\dot{\theta}(t) = 135\, t - 67.5\, t^2 \qquad [\text{deg/s}]$$

Motion Simulations with SolidWorks Motion

The team of students created the SolidWorks assembly for Exo Arm, Figure 9. The time interval for simulation is considered two seconds, within interval $t_0 = 0$ to $t_f = 2$ sec.

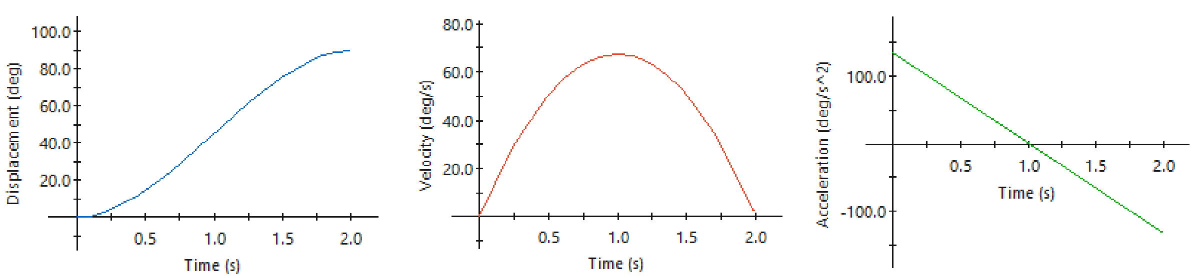


(a) (b)

Figure 9

End effector E on the initial and the final positions (a) fully extended; (b) fully contracted.

The SolidWorks Motion graphs for the desired input for angular position, angular velocity, and angular acceleration for actuating joint are shown in Figure 10.

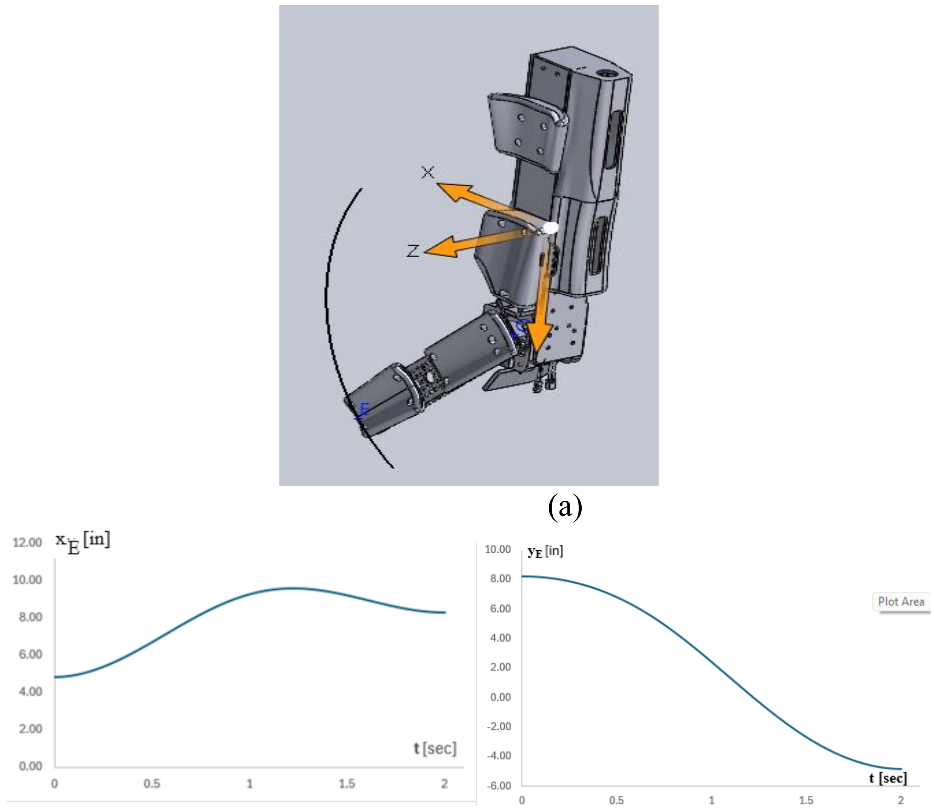


(a) (b) (c)

Figure 10

(a) Angular displacement; (b) angular velocity; (c) angular acceleration

The output path and the coordinates x_E, y_E function of time for effector E located on the elbow of Exo-Arm are shown in Figure 11.



(a)

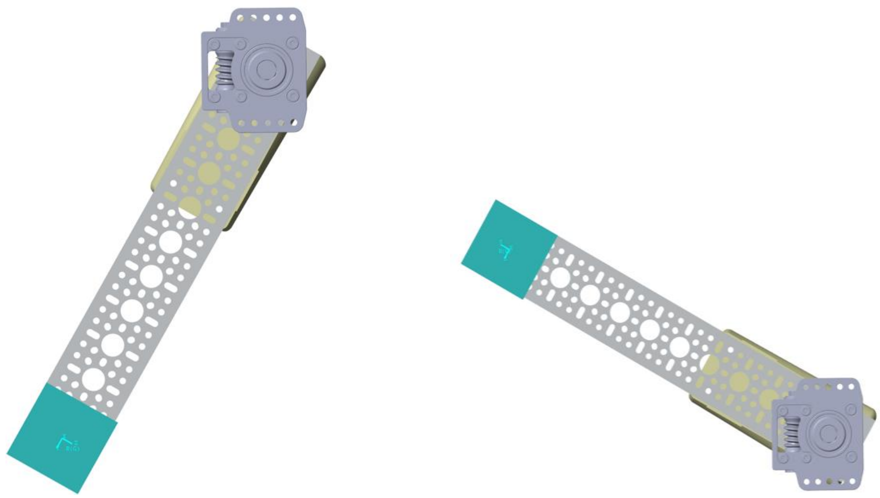
(b) (c)

Figure 11

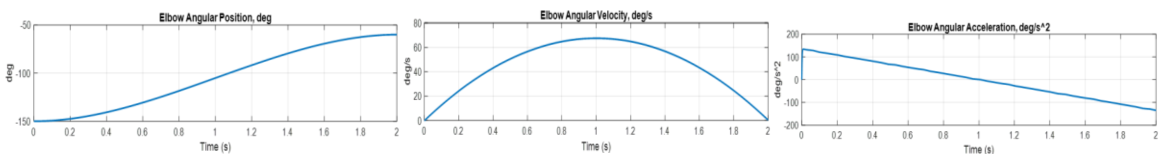
(a) End effector E path (b) x_E-displacement (c) y_E-displacement

Dynamic Simulations with Matlab Simulink

The team of students working on Exo Arm developed a Simulink model Figure 12 (a). The input was the desired actuation, Figure 12 (b)-(d). The output of simulation is the plot of the torque needed to move the user's arm at the desired angular displacement and angular velocity, from completely relaxed to 90-degrees angle while lifting F=20 lbs of weight.



(a) (b)



(c) (c) (d)

Figure 12

(a) Simulink model in fully extended position; (b) Simulink model in fully contracted position c) Angular displacement; (d) angular velocity; (e) angular acceleration

The elbow's mass and moment of inertia, are shown in Table 1:

Table 1 Mass and moment of inertia

Mass properties of IT-Forearm
Configuration: Default
Coordinate system: -- default --

* Includes the mass properties of one or more hidden components/bodies.

Mass = 0.72 pounds

Volume = 19.92 cubic inches

Surface area = 279.55 square inches

Center of mass: (inches)
X = 2.88
Y = 6.99
Z = 6.11

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.

Ix = (0.48, 0.85, 0.23)	Px = 1.50
Iy = (-0.80, 0.53, -0.28)	Py = 11.72
Iz = (-0.36, -0.05, 0.93)	Pz = 11.95

Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system. (Using positi

Lxx = 9.39	Lxy = 4.15	Lxz = 1.19
Lyx = 4.15	Lyy = 4.37	Lyz = 1.97
Lzx = 1.19	Lzy = 1.97	Lzz = 11.40

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system. (Using positive tensor notation.)

Ixx = 71.43	Ixy = 18.65	Ixz = 13.85
Iyx = 18.65	Iyy = 37.20	Iyz = 32.70
Izx = 13.85	Izy = 32.70	Izz = 52.56

The Simulink diagram is shown in Figure 13:

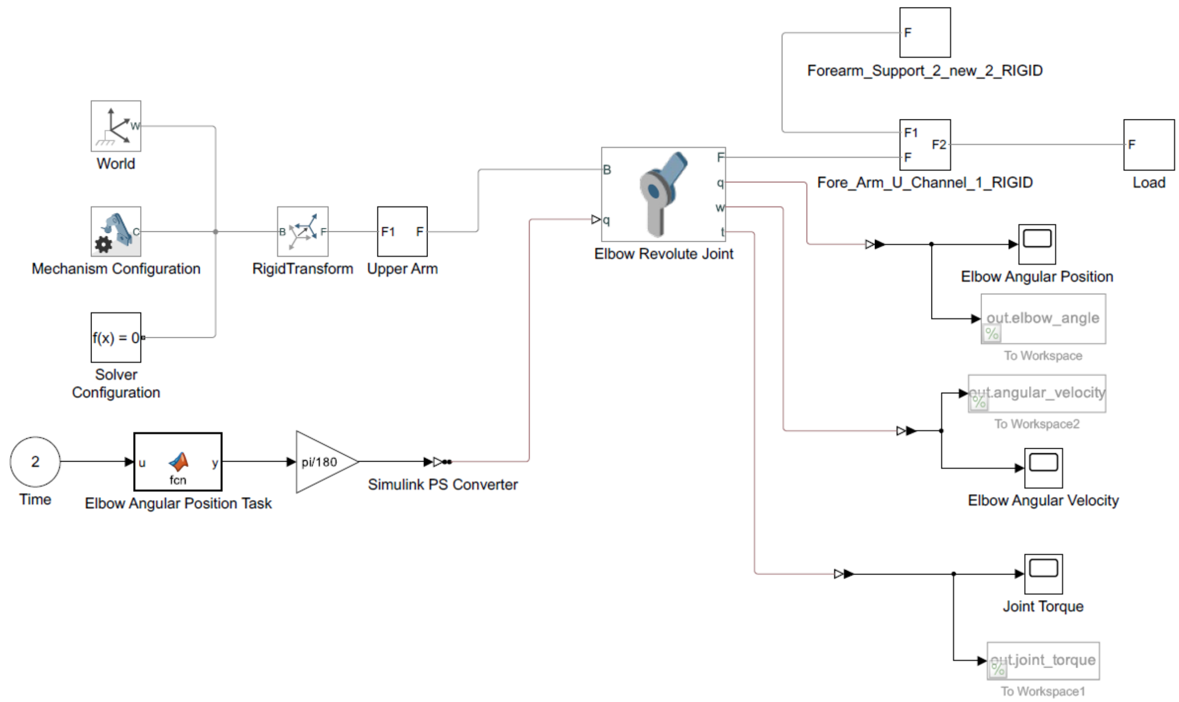


Figure 13. Simulink diagram

As result, is obtained the plot of the torque required, Figure 14, to move the user's arm at the desired angular displacement and angular velocity, from completely relaxed to 90-degrees angle while lifting F=20 lbs of weight.

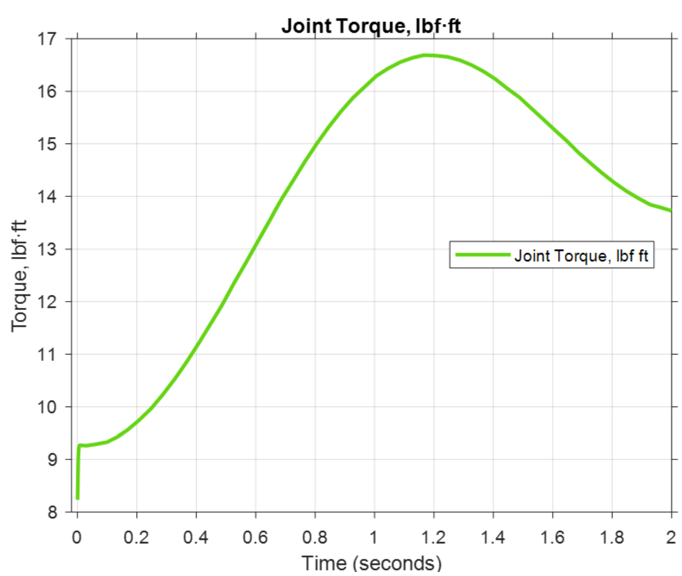


Figure 14 Torque required.

Conclusions

The final capstone project adequately fulfills the main objective, demonstrating the potential for the use of EMG in the design and operation of future orthotic devices. This will no doubt be a useful device for people who suffer from physical disabilities or injuries, therefore for improving their quality of life.

The second objective is fulfilled, the team of four mechanical engineering students improved their undergraduate learning experience by gaining knowledge and hands-on experience in Arduino programming, sensors, and robotics, as pedagogical materials which will help them in their future career as engineers.

The third objective of the project, which will impact the engineering education field, was to present the prototype at the student university's capstone projects show. Many students and faculty participants at the show were interested in detail for this project.

The Exo-Arm project presented a large interest at the town show in Robotics, where other universities and companies presented their projects. After the presentation of Exo-Arm prototype, more than 30 students, parents, and representatives from industry asked for a flier with the project's description.

The senior design project pedagogical learning experience and improving the undergraduate engineering education.

Our capstone design project is the ultimate demonstration of technical capability at graduation and proof of readiness of undergraduate engineering students to apply knowledge absorbed in engineering classes in pieces and segments and integrate it into a real-world engineering project. This particular project is setting higher standards for the capstone design accomplishments in what regards: a) the theoretical difficulties that have been overcome by individual efforts, requiring multidisciplinary investigation of the various aspects involved in the problem to be solved, b) the practical realization of the prototype using at state of the art technology available, c) utilizing state of the art CAD and manufacturing capabilities and d) the demonstration of operation and the continuous improvement for the proposed design. All these accomplishments are practical statements of professional prowess brought to fruition after 4-5 years of academic preparation in particular a demonstration of analytical, design and manufacturing skills developed during the mechanical engineering program. In the case of the Exo-Arm project, the presentation at the Capstone Design Showcase hosted by the University has led to intense discussions and interest from different stakeholders in engineering education: sophomore and junior students, faculty, program administrators, industry advisers.

Faculty arguing the opportunity to develop a program in robotics can make a strong example of this project and propose the adoption of more applied formal and informal education avenues (modify current coursework, introduce elective coursework, organize student club activities) dedicated to maintaining and enhance the education in key aspects of robotics (theory of mechanisms, theory of control, theory of dynamic systems, applied electronics, sensors, and instrumentation). It is relevant to mention that Wentworth is currently evaluating a program in robotics that can be the logical continuation of a unique program of electromechanical engineering still in operation today.

The success of this project can have an impact on students seeking to define their own capstone project as they can be inspired and motivated to come up with equally challenging topics of their own choice. They can also get a glimpse of the technical capabilities to be demonstrated in the capstone project and choose their elective courses with the capstone design in mind, including some recently added planar and spatial mechanisms courses. Another exemplary aspect of this project to benefit students preparing to tackle their final year project is the coordination and cooperation in the teamwork leading to the project prototype. The talent and interest combined in this team made the project possible and the team members complemented each other's skills and interests to cover all areas and project management tasks were kept in check and fulfilled by the deadlines.

Finally, for academic administration and strategic decision makers at the school and university levels, such capstone design projects that present innovative concepts, incorporate modern tools and technologies or complex multidisciplinary analysis can serve as a direction for future expansion of education and undergraduate research and guide the allocation of resources to emerging fields. Such projects can contribute to the development of a more encompassing vision about creating an identity for research oriented undergraduate and graduate work while preserving and retaining the results and knowledge to be perfected in future activities.

Future Work

-Adding multiple EMG sensors spanning various muscle groups would allow for much more dynamic control of the arm and response to triceps flexion

- Better ergonomics, the current arm straps create tension and chaffing for the user and are not comfortable for long term use

Acknowledgement

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