Design and testing of portable upper limb exoskeleton prototype

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Executive Summary - AB & TS

The Upper Limb Exoskeleton (ULE) Prototype project aimed to examine the possibility of using an exoskeleton on the upper extremity limb for power amplification purposes. This paper investigates the relevant literature and design proposal for a prototype ULE that will be designed to increase the ability of the user in carrying the extra load for the same amount of force exerted by the elbow, especially targeted towards people working in manual labour within the industrial, military, civilian and rescue sectors. With this point of consideration, the ULE prototype will be designed and tested to determine the limits of the performance and efficiency of the prototype, using various masses starting from 100 g, 500 g, 1 kg, 2 kg, and 5 kg, for the 90° 1-DoF movement pivoted around the elbow joint.

The proposed design is a combination of various sensors on a central microcontroller design that executes predetermined commands, to run the exoskeleton based on chosen motor and actuator amongst various considerations. For the current purpose of design and testing, an Arduino Uno Rev 3 is to be used as the central CPU processing incoming signals from an EMG sensor, an IMU sensor and a pressure sensor to control a Trinamic PD42-3-1070 motor that actuates the planetary gear to enable the rigid forearm hardware to move as required. After the initial phase of design and testing, the prototype is to be refined based on the results of the testing in terms of actuation and CPU design. For the completion of the project, underlying knowledge regarding electronics, mechanics, biomechanics, and material science, was required so various research papers were taken as the foothold to support our findings and choices, which had been distributed between the two researchers of the project, Thomas Sonneveld and Atul Bhattarai.

Thomas was responsible for researching types of exoskeletons, actuators design and development, whereas Atul was responsible for researching sensors and microcontrollers, and circuit diagrams. Some topics such as existing exoskeleton technologies, human kinematics were a joint effort to ensure filtering the choices for the equipment used in the prototype. The project is funded by Victoria University, under the supervision of Dr Daniel Lai.

Background Information and Introduction - AB & TS

Over the past few decades, advancements in robotics have revolutionized several industries such as manufacturing, medical and military [1]. Modern robots can perform tasks such as heavy lifting through powerful mechanisms and highly developed control techniques, but they still do not possess the high intelligence, prescriptiveness or decision making of human intelligence [2]. Exoskeletons are wearable devices that combine the advantages of a robotic device and mechanically interact with the human body through means of power amplification, replacing motor function and assistance [2][3]. They are more frequently used in these industries for assisting workers in lifting heavy equipment to rehabilitating stroke patients with a limited range of movement. Comparing a serial robot manipulator, where the end effector is controlled by the human operator, an exoskeleton works synchronously with the human joints to perform the desired task [4]. In recent years there has been an increased attraction from biomedical and engineering sectors for rehabilitation and augmentation for people with disabilities [3].

The very first design of an exoskeleton can be traced back to 1890 for Nicholas Yagn's model of robotic exoskeleton which conceptually enhanced the lower extremity of the human limb, to assist in running, walking, and jumping. This first patent was applied in 1890 and was based on a completely mechanical model, with the use of bow springs for movement [5]. The first proper exoskeleton model, called the Hardiman I, was initiated in 1965. This model was supplied with electric and hydraulic power through an umbilical connection. The machine could amplify the wearer's endurance and strength by a factor of 25 [6]. Just these two first models show a drastic change in terms of technology used/conceived to make the exoskeleton. Currently, there are minimal portable upper limb exoskeletons that are commercially available despite extensive research being conducted [4]. Whilst there is a multitude of applications, there are several impeding factors associated with upper limb exoskeleton technologies.

Given a continually developing society with industries that typically rely on hard manual labour, and an ageing population, exoskeletons have the potential to impact several industries to reduce and rehabilitate injuries, amplify the lifting ability, and assist movement of the wearer. Rehabilitation of stroke victims requires orthopedic sessions at different stages of recovery and with the expense of physiotherapy and duration of the training, rehabilitation using exoskeletons can be used as an alternative method for improving motor function, in replace of manual therapy [7]. Due to the multiple DOF that can be achieved with an exoskeleton, an extensive range of exercises' can be accommodated for [7].

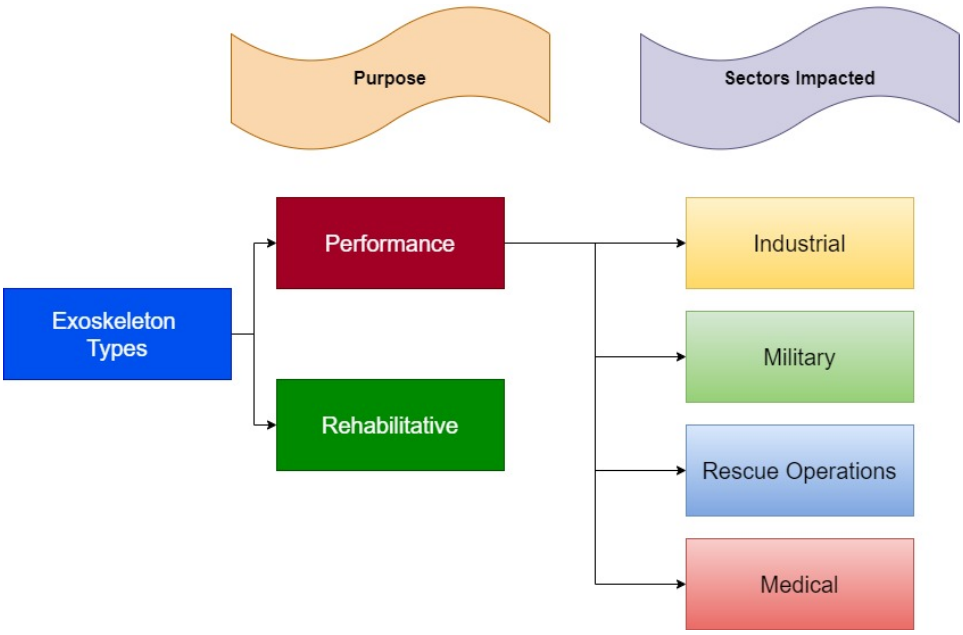


Fig 01: Exoskeleton type based on purpose and relevant sectors

Manual handling injuries in Australian workplaces in 2018 cost 28 billion dollars [8]. Exoskeletons can be applied in industries such as construction, military and civilian/rescue operation sectors that are heavily reliant on the prolonged and repetitive movement of heavyweights and reduce the number of safety incidents and provide relief to the wearer [9]. This project thus aims to design and develop a prototype active Upper Limb Exoskeleton apparatus with a suitable actuator and control system that can assist the wearer's lifting ability within the elbow flexion/extension movement.

Given the complexity in human-to-robot systems, a significant understanding of both the biomechanics of humans and engineering is required to design and develop an operational ULE. The mechanical framework will need to be designed from suitable materials capable of withstanding the stress and wear. To enable unimpeded motion of the wearer, a synchronous movement that reflects the natural human movement is required. To achieve this a combination of sensors such as Electromyography (EMG), Inertial Measurement Unit (IMU) and force sensors, and actuators such as electric motors, hydraulic and pneumatic cylinders can be used. This culmination of electronic sub-systems along with biomechanics, mechanical, and structural engineering, makes exoskeletons a widely explorable technology, with various branches and different purposes. Thus, a significant fundamental understanding and literature review to understand their operation and suitability to design and develop a ULE is required.

Literature Review - AB & TS

There is currently no standard in designing and developing exoskeleton systems and several ways to categorize them are based on their application, structure, actuation method, active or passive, musculoskeletal extremity, and Degrees of Freedom (DOF) [4]. To determine the prototype design, it is necessary to go through a variety of literature and research articles to develop a framework to work with. These materials are defined through several headings as discussed below.

Exoskeleton Technology

Technologies by Type - AB

Partial/ Extremities exoskeleton

Extremities, in this case, are considered as the upper and lower limbs of human anatomy. These exoskeletons help improve human movement in terms of exerting strength to improve human gait or arms movement. Partial exoskeletons have seen the most improvements over the past two decades in terms of research and development. Exoskeletons such as BLEEX [10], LOPES [11], Alex III [12], RoboKnee [13], are some of the examples of lower extremity exoskeletons developed to facilitate rehabilitative as well as non-medical purposes. Similarly, upper extremity exoskeletons like CADEN-7 [14], Rupert IV [15], ARMin III [16], have been considered the state of the art technologies in rehabilitation exoskeleton development.

Full-body exoskeleton

Full-body exoskeletons are essentially a combination of both extremities' exoskeletons. While most existing exoskeleton technology remains confined to limb exoskeletons, there have been a few improvements for full-body powered exoskeletons over the past decade. These exoskeletons combine mounted arm, back support, arm support structures, crouching and standing support, into a single powered "exosuit" that provides power, endurance, and precision of machines in sync with human intelligence, instinct, and judgement [17]. Guardian XO of SARCOS is one of the most prominent examples of a battery-powered full-body exoskeleton promoting work efficiency and reduced load [18].

AI enhancement

The exoskeletons discussed so far are human-controlled. Considering the possibilities for the future, we can apply machine learning technologies to design an artificial intelligence-driven exoskeleton. Using microcontrollers in conjunction with implanted electrodes to monitor muscle responses, brain activity, the machine will be able to perform a lot of capabilities on its own without human intervention. Considering that exoskeleton movements are paternal, adaptive learning can be set up as shadow training techniques for the machine to record premade movements and follow the same trajectory for the general purpose [19]. Usage of sensors is also a defining feature for AI-enhanced exoskeletons. Since exoskeletons are not binary results, fuzzy logic needs to be implemented to determine the status quo of the exoskeleton performance and results [20].

Technology by Mechanism - TS

Exoskeletons are considered either passive, which rely on mechanical springs or gravity assistance, or active, which utilizes an external power source such as a battery to power an electric motor or pneumatic actuator. Active exoskeletons allow the users lifting power to be augmented however the limited exoskeleton technologies make it difficult to develop portable systems.

In rehabilitation, stationary exoskeleton systems are advantageous as weight, the number of components and their size has minimal impedance to the wearer. Typically, they are mounted to a wall, bracket and in some cases wheelchairs. As a result of increased components and size is that stationary systems have the potential to deliver significantly higher torque. A comparative study by Manna, et al. [7] compared forty-six types of exoskeletons, see Figure 02, and categorized them by structure and actuator type and found that stationary exoskeletons with an electric motor actuator are more popular compared to other systems. Portable exoskeletons, whilst limited by weight and various other factors that do not impede portable systems, offer a significant advantage by allowing the wearer to move freely.

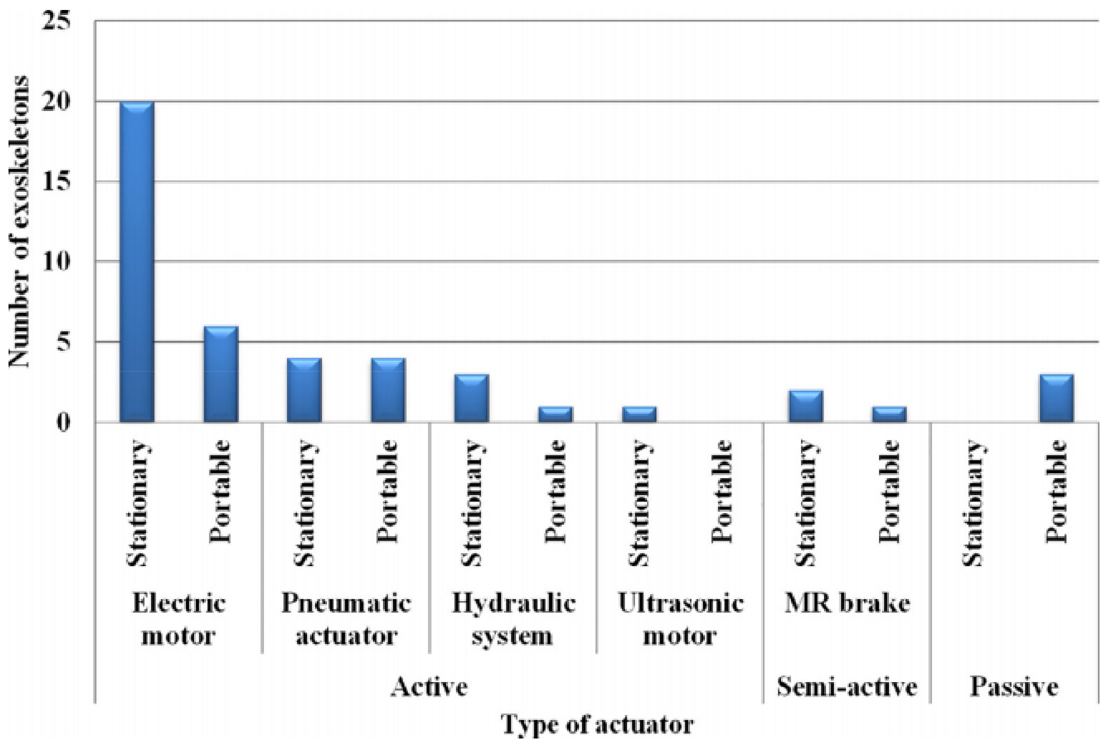


Figure 02 : Statistics of various actuators used in portable and stationary exoskeletons [7].

Technologies by Design - AB

Exoskeleton technologies can be classified based on their support structures. They can be either rigid or soft based on the material composition. Rigid exoskeleton systems have their Degree of Freedom less or equal to the ones required to complete a specific task, and soft exoskeleton systems provide a hope to design wearable assistive devices, not unlike typical human garments, with embedded sensing and actuation to work in sync with our muscles and provide additional power [21]. While soft wearable robots are designed for comfort and portability, rigid wearable robots are more geared towards more accurate and quick delivery of force and torque at the necessary output. In a study done with rigid and soft models Rehab-Exos, a rehabilitative-type exoskeleton arm module, it was found that rigid model performance is better in terms of maximum torque output, and efficiency, whereas soft model performed better in holding its weight, and power consumption [22]. However, for a design model, rather than going to extremes on a singular model it is better to combine both rigid and soft designs for optimum performance of the exoskeleton, as these two design approaches are more complementary to each other than substitutive. Rigid structures for the limb portion and a soft fabric-like design for joints would ensure maximum movement capability while still being confined to desired torque output levels.

Actuators in Exoskeletons - TS

Actuators play a significant part in the operation of any exoskeleton regardless of the operational specifications and type. Depending on the actuation, whether it be active, semi-active or passive, and the DOF required for the specific limb(s), several factors need to be considered when determining the actuator for a ULE. For a portable ULE, the weight and portability of the actuator will impede the wearer and may result in early fatigue if heavy components are required, as opposed to a stationary ULE, where weight and size of the actuator can be ignored. Having a high bandwidth enables quick responses in the actuator if there is a sudden change in torque, speed, or position. The power-to-weight ratio is one of the key factors in actuator selection as certain types can produce higher torques but require several more components and portability starts to become limited. As an increase in components occurs the construction, control, and design start to become more difficult and begin to cost more. Some conventional types of active actuators used with active ULE’s are hydraulic, pneumatic, and electric motors [7].

Electric Motors

Electric motors are one the most used actuators with active exoskeletons as they are easy to control, have high bandwidth and provide a quick and precise response [3][4][7]. Most exoskeletons use a direct drive motor which is placed at the joint such as an elbow or knee [7]. Two common types of electric types are brushed Direct Current (DC) and brushless DC. Of the types of electric motor, brushed Direct Current (DC) motors are preferred as they require less complex control circuits [7][23]. Brushless DC motors however provide a better power-to-weight ratio than brushed but require additional components such as an encoder for the control circuit [7]. As seen in the force-feedback experiment conducted in [23], haptic rendering in both brushless and brushed DC motors were quite similar. A motor that can be considered a brushless DC motor and suitable for robotic applications is the stepper motor [24]. They are used in industrial applications and offer precise control [25]. A stepper motor receives an electrical pulse, from and translates the change within the stator windings into discrete changes of the position of the rotor [26]. This discrete change is referred to as a step, hence the name “Stepper motor”. The magnetic alignment between the stator and rotor allows the stepper motor to achieve the positioning of the stepper motor [26]. One ability of the stepper motor is that it can maintain a steady position with a given load [24]. They are widely used within industrial sectors as they are low cost, produce high torque at low speed and have simple construction [25].

Electric motors generally have a low power-to-weight ratio compared to other actuator types [3][4][7]. To improve torque, a larger motor can be used however as the size increases, the portability and wearability will decrease. Another solution is to combine electric motors with gears or other actuating types such as cables, however, this can introduce other issues and require additional components [7][23].

Hydraulic

Out of three conventional actuators used in exoskeletons, hydraulic actuation provides the highest power-to-weight ratio [4][7][27] and has a high bandwidth [28]. Despite having high bandwidth, hydraulic actuator control is nonlinear and is not as precise as an electric motor. Hydraulic actuators are made up of a pump, reservoir, motors and valves, and work by injecting fluid under high pressure, typically the fluid is pressurized at a range of 15-25 MPa [28], into a hydraulic cylinder to achieve a push and pull movement [7]. With additional components being required in these systems, the portability of these types of exoskeletons is reduced, more space is required to allow for all the components and current commercially available systems are quite heavy [3]. Systems like the NEUROExos, an active elbow rehabilitation exoskeleton, utilize hydraulic cylinders driven by a 1.1kW AC electric motor, in combination with Bowden cables, non-linear springs and a planetary gear, which cannot be easily relocated when being operated [7]. Construction of hydraulic systems is generally complex and even carefully designed systems suffer from fluid leaks which results in pressure loss and produces a less efficient motion [7][27]. Fluid leaks also pose the risk of contamination which compromises the safety of the system and require extensive maintenance [4].

Pneumatic

There are a variety of forms of pneumatics such as pneumatic cylinders, artificial muscles such as the McKibben Muscle [30] and air bladders [3]. The pneumatic cylinders operate in a similar way to hydraulic systems but instead of oil, compressed air is used to achieve the push and pull movements [7]. Artificial muscles act in a similar way to natural muscles by pressuring layers of braided nylon with CO_2 which cause the braided material to expand, resulting in the axial length contracting [7]. Both pneumatic cylinders and artificial muscles have a high power-to-weight ratio compared to electric motors, but not as high as hydraulic systems [4][7]. Other benefits are that they are not as prone to hazardous environments [3], offer a lower impedance and weigh less than electric motors [3], and are simpler to construct, cheaper and lighter than hydraulic systems [28]. Some of the disadvantages are that they have low bandwidth (5kHz) [27], mostly stationary systems as they require pneumatic pressure and control of the system is complex and can sometimes suffer from hysteresis. To overcome the hysteresis additional components such as valves and regulators can be introduced however this will reduce portability and increase cost and maintenance [4].

Planetary Gear - TS

Planetary gears are an actuation mechanism commonly used in applications such as wind turbines, car turbines and robotics [31]. They offer significant advantages in a wide variety of applications such as their high torque-to-weight ratios in compact spaces, high-speed reductions, load sharing and can offer several gear ratios [32]. The name "Planetary" is derived from its similar motion to that of the solar system in that the planet gears revolve around the inner sun gear. The planetary gear is made up of several spur gears which are the sun gear, planetary gears, a planetary carrier, and outer ring (An internal gear) as seen in Figure 03 below [33]. A typical planetary gear will be driven at the sun gear delivering torque to the planet gears which will be fixed to a carrier, and then rotate around the sun gear while meshing with the outer ring.

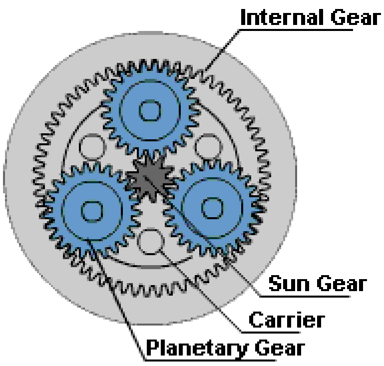


Figure 03 : Planetary gear [34].

Sensors - AB

One of the major features separating the exoskeleton from other robot infrastructures is the direct human-robot interaction ability it shows. Such human-robot interactions can be better optimized with the use of sensors to increase the performance and efficiency of the machine. An exoskeletal module can be differentiated into three major divisions: sensing module, decision module, and execution module [35]. The sensing module is responsible for gathering the raw data and information, the decision module takes account of pre-existing and pre-programmed algorithms and uses the raw data and information to send an executable command to the execution module, in terms of actuating the exoskeleton limb. Considering the sensing module of human-robot interaction, it can be broadly classified into cognitive human-robot interaction, and physical human-robot interaction [36]. The physical human-robot interaction takes into account the kinematic and kinetic data and stresses experienced by the system, whereas the cognitive human-robot interaction takes the muscle activity, brain activity, eye movement, etc as raw data.

Physical Human-Robot Interaction

Kinematic sensor

Kinematic sensors include potentiometer, gyroscope, accelerometer, encoder, electrogoniometer, IMU, etc. These devices take the movement of the exoskeleton based on their position and provide spatial coordinates, movement speed, angular direction as raw data, to be processed for better exoskeleton control.

Kinetic Sensor

Kinetic sensors in this case refer to devices like strain gauge, piezoresistive sensor, force/torque sensor, etc. These devices can send out electrical signals of different voltage levels by imitating a voltage divider circuit based on their maximum resistance produced by strain, pressure, force, etc. These signals in turn can be yet again used to determine the torque the actuator needs to produce to counteract the held weight.

Cognitive Human-Robot Interaction

Electromyography

Electromyography refers to mapping the muscle response or electrical activity in response to the nerve's stimulation of muscles [37]. While this used to be considered an exclusive clinical examination, now it can be used to explore the constant stress experienced by the muscles in human anatomy under different postures. These postures would create a baseline for a comparative study with the muscle activity while wearing an exoskeleton, thereby testing endurance and efficiency limits.

Microcontrollers/Microprocessors

In today's age, no electrical device is without the use of microcontrollers. From phones, keyboards to the heating kettle in a kitchen, everything has microcontrollers placed in them to make their work more efficient. Microcontrollers are small programmable CPUs that are self-contained in a small chip, which performs a single job/task as pre-programmed by the user repeatedly. Microcontrollers work in sync with other equipment and electric circuits on a Printed Circuit Board (PCB) to control and monitor different system behaviours [38][39].

Microcontrollers consist of some basic peripherals as presented below:

CPU

The CPU is the brain of the microprocessor. The CPU consists of Arithmetic Logic Unit (ALU) and Control Unit (CU), and is responsible for performing arithmetic operations, managing data flow, and generating control signals for other peripherals depending on the sequence of instructions coded in by the programmer.

Memory

Any sequence of computation requires two types of memories. The program memory (Read Only Memory), which contains the execution codes for the microcontroller, and the data memory (Random Access Memory), which stores temporary data and information while executing various instructions.

Peripherals

Microcontrollers have other peripherals that help in executing instructions. The most significant ones being Pulse Width Modulation (PWM), Analog to Digital Converter, (ADC) and Digital to Analog Converter (DAC). The PWM helps control average power delivered by the electrical signal by discretizing the said signal into various parts. The ADC converts analog signals from the sensors to digital inputs that the CPU can recognize to carry out instructions, whereas the DAC converts the executed instruction of the CPU to analog signals for external devices.

Input/Output Ports

Microcontrollers come with ports that help them communicate with the external environment. Sensor input signals and actuator movement are determined through these ports upon completion of built-in executable instructions.

Clock generation

A clock generator is an electronic oscillator that produces a clock signal for use in a circuit's operations. They govern the baud-rate of serial communication signals, the amount of time needed to perform signal conversions, the speed of execution of a program, etc.

Timers/Counters

Timers/Counters are an important feature of the microcontroller. They control all counting and timing-based operations of the microcontroller. Their functions include pulse generation and modulation, clock control, etc.

Serial communication

The microcontroller can communicate with other external devices and peripherals using the serial communication port. Most of the serial communication of microcontrollers is done through UART, but ports such as I2C and SPI are also seen in some microcontrollers.

Interrupt Mechanism

The interrupt mechanism is one of the most advantageous features of the microcontroller. All contingency events can be pre-programmed to execute as soon as the event transpires, whether the event is internal, external, software or hardware related.

Like the microcontrollers, microprocessors are also used in electronic systems to control several instructions using viable coding. Microprocessors can be used in the same way as microcontrollers but there are key differences that are mentioned below.

Table 1: Comparison of microcontrollers and microprocessors on various fields[40]

	Microcontrollers	**Microprocessors**
Application	These are generally designed for a specific task and only used for a certain task as designated by the programmer. It is considered the heart of an **embedded system** where only small functions are required to be performed.	These are used in applications where the tasks/executions are not predefined and require a lot of data to be handled. It is considered the heart of a **computer system** where a lot of processing power is required to simultaneously handle tasks.
Structure	CPU, Memory, Input/Output peripherals, timers etc. are all integrated into a singular chip. The circuit structure is fixed and cannot be changed by the user once designed.	It only contains the CPU. All other devices like timers, memory, input/output ports etc. need to be connected externally for processing. Users can customize the size of memory and input/output ports as per their need.
Clock speed	These have a considerable speed in the range between 1 MHz to 300 MHz depending on the architecture.	They boast higher speed in terms of GHz with top of the cream technological advancement.
Memory	The volatile memory and flash memory have less storage space, each limited between 2 to 256 kB and 32 kB to 2 MB respectively.	Since external volatile and flash memory can be connected, the storage space is user-defined.

Interface	The most common peripherals for microcontrollers include I2C, SPI and UART.	The most common peripherals for microprocessors include USB, UART, and high-speed ethernet cable.
Bit size	They come in 8-bit, 16-bit or 36-bit.	They come in 32-bit or 64-bit.
Cost and Power	They are cheaper in terms of cost and consume less power.	Due to external devices connected, their power consumption and cost is higher.

There are multiple things to consider when looking for a processing unit for projects. Depending on the requirement of the project, microcontrollers can be low-powered but more focused on data inputs, with minimum parallel processing required. High-end projects can also be considered, using higher power microcontrollers, with multiple calculations, for example: building a Personal Computer prototype. Considering the market for microcontrollers, 3 major ones are initially looked at for this project: Arduino, Raspberry PI, and BeagleBone. Arduino is the only proper microcontroller considered whereas Raspberry PI and Beaglebone align more towards being microprocessors.

Arduino

Arduino is the most prominent beginner-level microcontroller in use. For this project, Arduino UNO was considered as a model. Arduino UNO uses the ATMega328P [41] microcontroller running at 16 MHz. With 32 kB Flash memory, of which 0.5 kB is used by the bootloader, Arduino UNO has 16 general input/output pins, out of which 6 of them can be used as analog inputs, and 6 can be used for PWM output. Operating between 6-20 V at limits, Arduino UNO has 2 8-bit timers or 1 16-bit timer. It can be operated using C programming, and once the code is written, it just needs to be uploaded to the board where it can iterate theoretically infinite times as long as the power is supplied.

Raspberry PI

Raspberry PI is a complete minicomputer. Looking at the newest Raspberry PI 4, with its quad-core Cortex-A72 64-bit System-on-a-chip [42] processor, it offers a greater range of processing power and speed when compared to Arduino UNO. It supports 2 mini-HDMI ports for 4k video output, along with two USB 2.0 port and 40 general input/output pins. At 1.5 GHz clock speed, the Raspberry PI can also support ethernet connection capabilities, and in the latest model a connection to the Wi-Fi. While all these extra peripherals cause its power consumption to rise quite a lot with a minimum current supply of 3 A, it can be considered as a viable option for the project if we were to include multiple exoskeleton schematic. Raspberry PI operates on the Linux operating system.

BeagleBone

BeagleBone is very similar to Raspberry PI. Boasting 46 general port input/output pins, BeagleBone Black with its TI AM3359 [43] processor chip is more powerful and versatile in terms of working with multiple operating systems like Android, Linux, Cloud9 IDE etc. At 1GHz clock speed, it supports USB 2.0 Type A, mini-USB 2.0 client port, dedicated micro HDMI port for audio and video output, and works amazingly with the Internet of Things application.

Considering these options and matching the microcontrollers with our objective, the team decided to go with the Arduino Uno R3 model for the prototype. Since, this is the first design considered, later microcontrollers can be looked to being custom built to suit our purposes better.

Human Mechanics - AB & TS

A rigid body has at most six different degrees of freedom. They are elevation/heaving, straying/strafing, walking/surging, yaw, pitch and roll. Considering the flexibility of the human body due to joints and muscle ligaments, the upper limb exoskeleton can be segmented to control two different sets of movement mechanics. One would be acting on the elbows, for the pitch movement of the forearm, moving up to 90 degrees angle from its normal 180 degrees state. The second state of movement would be the roll movement of the wrist, pivoting side to side at 180 degrees from facing palm downwards. These two sets of movement are considered to be enough for the aim of the project, however other mechanical movements can be considered for the future path of the project. These movements need to be monitored using sensors, like IMU, pressure sensors, EMG sensors, to constantly check the muscle response and activity of the test user so as not to overstrain what they would need to do.

Muscles work in pairs as they can only contract and move the limb in one direction [44]. The bicep is a flexor muscle and as it contracts will result in the forearm rising, whereas the tricep is an extensor muscle and as it contracts causes the arm to fall back to the person's side [44]. If we consider the arm to be operating in an X-Y plane where the only movement occurring is that of the bicep contracting and moving the forearm from rest at the side of the body to perpendicular with the body we can assess the forces acting on the arm and torque occurring at the elbow joint. Figure 04 below shows a diagram of the forces occurring within the arm in a static position as a mass is held perpendicular to the body.

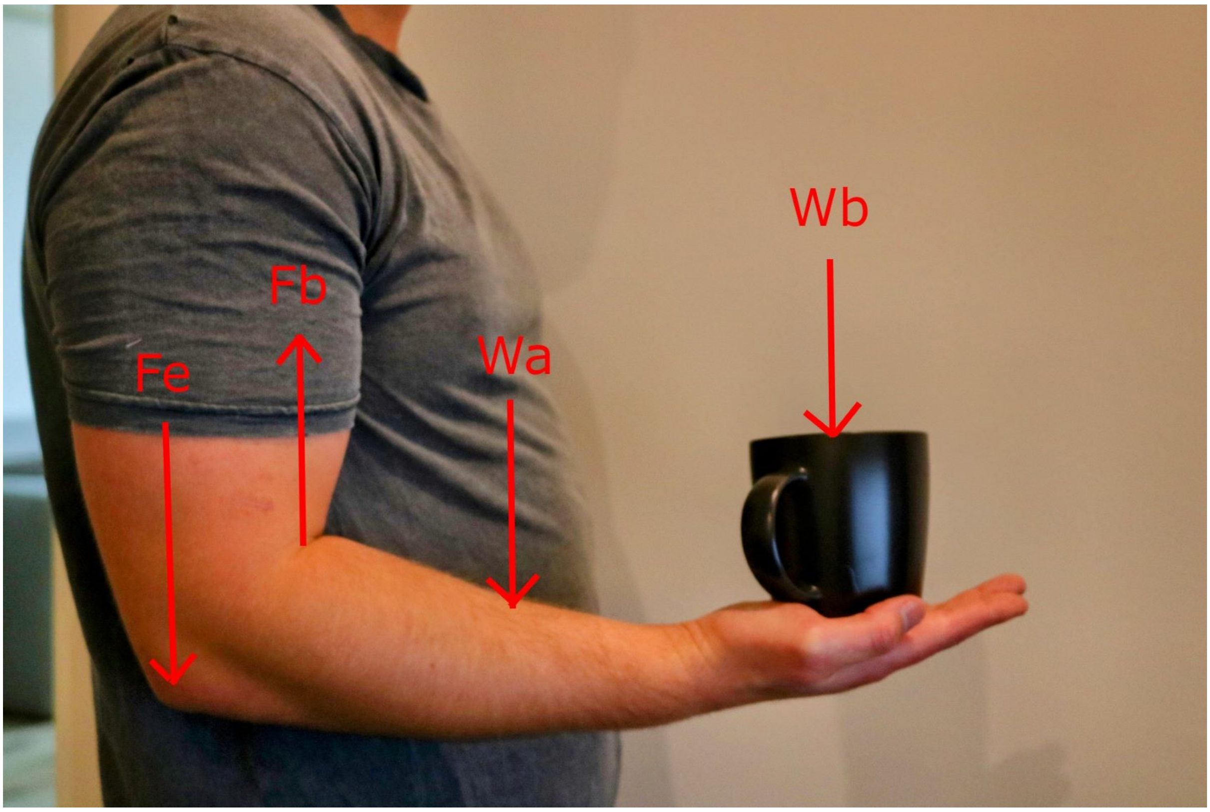


Figure 04: Diagram of forces acting when lifting an object

The forces acting on the elbow joint can be defined by the following;

$$Fb = Wa + Wb + Fe$$

Where;
$Fb = \ Force\ exerted\ by\ the\ bicep$
$Fe = \ Force\ exerted\ on\ the\ elbow$
$Wa = \ Weight\ of\ the\ forearm$
$Wb = \ Weight\ of\ the\ mass\ in\ the\ hand$

Applying the second condition of equilibrium,, the torque exerted on the elbow can be reduced to;

$$Telbow \ = \ Tarm + Tmass$$

Where;
$Telbow \ = \ Fb \times L_1 \times sin\theta \ = Torque\ produced\ at\ elbow\ by\ the\ bicep$
$Tarm \ = Wa \times L_2 \times sin\theta \ = Torque\ produced\ by\ the\ weight\ of\ the\ forearm$
$Tmass \ = Wb \times L_3 \times sin\theta \ = Torque\ produced\ by\ the\ weight\ of\ the\ mass\ held$

The maximum value of torque occurs when the acting force is perpendicular to the fulcrum, in this case, the elbow.

Aims and Scope of project - AB & TS

This project aims to develop and design a portable ULE that works synchronously with the flexion and extension of the elbow and surrounding muscles and amplifies the wearer's lifting potential.

There are several design considerations for this project which include but are not limited to the following:

- Safety of the wearer.
- Portability and wearability.
- Control and responsiveness.
- Low-cost.
- High power-to-weight.

The desired outcomes of this project consist of the following:

- An extensive literature review on wearable ULE, actuation types and mechanisms, control systems, sensors and human movement.
- Design a suitable ULE framework from 3D printed materials that can be easily attached to the user and support various components.
- Design a suitable actuation system to be controlled via several sEMG, force and IMU sensors.
- Conduct a series of tests through physical processes and software techniques.

The desired project deliverables consist of the following:

- An operational prototype ULE that can assist the user's movement within the flexion and extension of the elbow.
- An actuation system that can improve the users lifting capacity without increasing the human effort required.
- Develop a suitable control system to control the ULE synchronously with the human body.

Project Methodology - AB & TS

Given the complexity of designing, developing, constructing, and testing a ULE, the project has been separated into two focus areas which are the control systems and sensors, and mechanical framework, actuator, and actuation mechanisms. To undertake the project suitable literature of the current industry, exoskeleton technologies and human mechanics has been reviewed and applied to the design and development of the upper limb exoskeleton. This methodology outlines the project deliverables and goals to be achieved.

With no standard in designing and developing exoskeleton systems, a systematic design approach has been used. The engineering design process was broken down to several methodical steps that were followed to establish the prototype [45]. For this project, an eight-step engineering design process was adapted with the aim to achieve the desired project outcome [45]. The following outlines the various steps to be followed for the project:

- **Define the problem**
- **Research**
- **Discuss**
- **Establish the requirements**
- **Develop**
- **Design and Evaluate**
- **Test**
- **Iterate**

The Problem

The project assigned to the design team is to develop and design a portable ULE to assist the wearer when performing tasks involving elbow movement. There are currently a limited range of cheap portable upper limb exoskeleton designs available for commercial use and no standard in developing or designing exoskeletons. Whilst this can be problematic when addressing project deliverables and stakeholder requirements, it allows for a multitude of technologies to be explored and applied to prototype development.

A study conducted by Yu et al. [8] developed an exoskeleton capable of handling 50kg in refractory construction by connecting to a piece of existing worksite equipment, which reduced the stress and muscle fatigue experienced during extended periods of heavy lifting. Similarly, this project aims to develop a prototype hoping to achieve something similar, albeit on a smaller scale.

This project is currently in the second year of progression and was previously investigated by Behan et al. [46] but due to the COVID-19 pandemic, they could not access university facilities and were limited to framework design with AutoCAD Inventor, software simulations of a 3D prototype, finite element analysis and partial embedded system design. This stage of the project will utilize the previous findings and designs, and further develop the prototype and aim to complete the mechanical framework, construction, embedded control system and validation and testing.

Research

Existing upper limb exoskeleton technologies are dominated by stationary systems and factors such as mechanical framework, bandwidth and control and actuators contribute to the limitations within this engineering field [29]. The complexity in the human movement and achieving a somewhat synchronous motion of the mechanical structure that does not inhibit the user is a significant issue. To achieve synchronous interaction with the elbow joint requires high bandwidth and a complex control system capable of driving an actuator with a high power-to-weight ratio. Comparison of multiple microcontrollers were done to decide upon a suitable microcontroller for the exoskeleton. Similarly, multiple sensors were considered as attachments for analog inputs to design a control function for the actuator as future milestones.

Discussion

As this project has been assigned by the university to the design team, no external stakeholders or customers are currently involved in design input, deliverables or outcomes. Therefore the prototype design will need to be aimed at a select target group and anticipate requirements by investigating similar technologies during the research phase. For this project the current and potential stakeholders to be included in any design decisions are the following;

- Project supervisor
- Design team
- Victoria University
- Future customers
- Industry partners

Project Requirements

As there is currently no industry partner or customer to outline the requirements for this project, the design team under the guidance of the project supervisor has determined a set of requirements for the prototype. Based on the current literature that has been reviewed several considerations have been made to enable a functional, cost-effective ULE. One of the major obstacles to be challenged for our system would be the utility of the exoskeletal system. The upper-limb exoskeleton should be lightweight, comfortable to wear, and portable enough to move around with ease. The ULE is designed for power amplification purposes, so its usability will primarily focus on physical workforce occupations. It is paramount that long arduous activities conducted with the help of the ULE have no side effects to the user in the immediate or the long run. Thus along with its utility, it is necessary to consider and employ safety mechanisms to the system to reduce possible risks. This can be in terms of considering wire safety, actuator control based on skeletal capabilities, power consumption levels, and so forth. The ULE also needs to have a proper control system in place, with a proper interrupt handling mechanism for pre-coded eventualities for quick responses to triggered events. The use of sensors along with monitoring and analysis are necessary to create actuating control for better implementation of the system mechanism. All these things are to be considered while the system being as inexpensive as possible. As a prototype model, the current ULE is designed to increase the user's lifting capacity for the same amount of force applied as they would without the use of the ULE. Considering the lower level of investment, and funds collected, all the materials used will be tailored to the bare minimum standard to fulfil our basic needs, requirements and expectations from the system. However, once the prototype is completed and tested, upgrading its peripherals for better performance is to be considered as well.

Development

While the system needs to be efficient, as a prototype, it is required that we aim for the low return of investment cost model. Considering the choices for microcontrollers, the cheaper Arduino Uno R3 model has been chosen, which requires a small processing power as well as can handle smaller data streams from the sensors, which seems like the most appropriate choice for our purpose. The material chosen for the exoskeleton hardware is primarily polylactic acid (PLA) for experimental prototype purposes. These portions would be supported with straps, to ensure that it is modifiable to a certain extent, for tests with multiple users. Since most of the material used is 3D printed, the entire system is light weighing less than 2.5 kg, including the supporting electronics (PCB and wire connections) and actuating materials (mounting platforms, gears, motors). The actuation mechanism chosen was a permanent magnet stepper motor as they are easy to control, have high bandwidth and construction is much simpler than that of a hydraulic or pneumatic system. As the actuator will need to be driven to discrete angles and maintain a steady position under load, a stepper motor would be most suitable. The control of the actuating motor is entirely dependent on the sensors employed, which will be monitoring and sending data streams to the microcontroller in real-time to ensure that the system is compliant with the user needs. For the safety of the user, the mounted outer ring of the gear is meant to be stopped/locked between the 0° at full extension, and 90° as complete flexion of the arm. This is to be done in proper synchronisation using the IMU sensors to monitor spatial coordinates of the apparatus. EMG sensors are also to be used to constantly detect the muscle responses of the human arm, to monitor base levels as well as strain levels experienced by the arm during work done.

Project design

With the project currently in its second year, the initial design for the prototype ULE will be based around the CAD designs provided by the previous years design as shown in Figure 05 below.

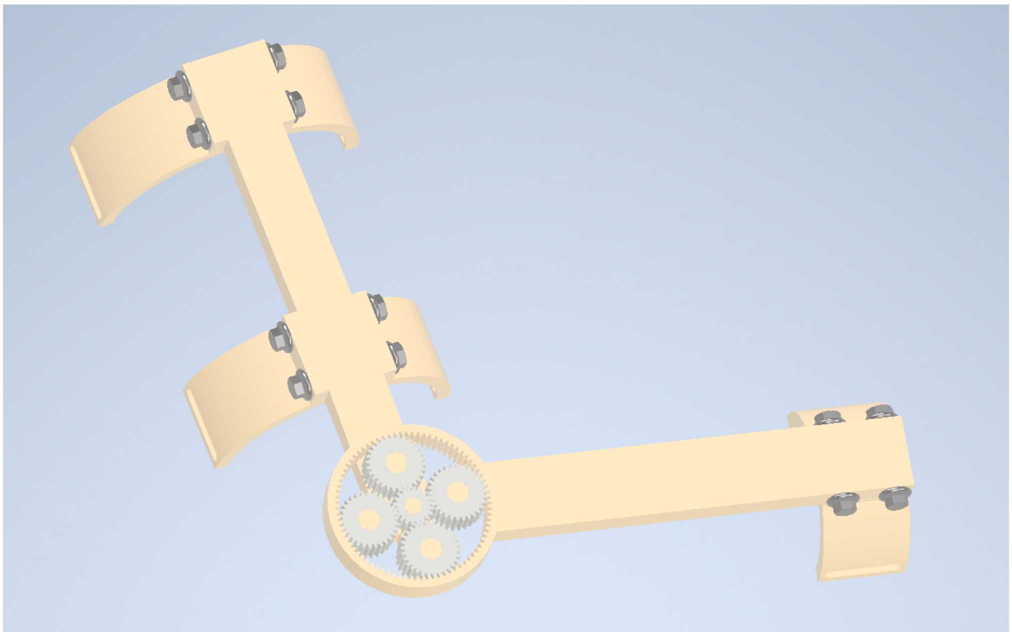


Figure 05 : Current Exoskeleton framework design.

The current design has utilised a planetary gear system at the elbow to drive the brace attached to the forearm. The brace attached to the upper arm will act as a planetary carrier and fix the planetary gears. The sun gear in Figure 05 is shown only as a concept, and the final design will have the sun gear driven by the stepper motor. This arrangement allows the outer ring to rotate around the planetary gears, with the proposed design having a ratio of 1:4. Whilst this does provide a speed restriction, given the limitations in electric motors with power-to-weight ratios, the planetary gear will also decrease the torque required by the motor to assist during operation.

The purpose of the exoskeleton design is to increase the users lifting capacity when performing a bicep flexor movement. As the arm moves from the 0° position (Parallel to the body) to the 90° position (Perpendicular to the body), the torque at the elbow continues to increase. If the static forces and torques acting on the arm at varying angles are analyzed, we can calculate the approximate holding torque that will occur in the elbow. Whilst the forces and torques are dynamic throughout the flexor movement, the maximum torque in the elbow will occur when the arm is perpendicular to the body. A MATLAB calculation was conducted to determine the additional mass that can be held in a static position at a varying position with the assistance of the exoskeleton. For the MATLAB calculations, a male with a weight of 85kg and 178cm has been considered to determine the weight of the forearm and hand. The percentages of total body weight for the forearm was 1.87%, 1.5895 kg, and the hand was 0.65%, 0.5525 kg [47]. The motor selected was a Trinamic PD42-3-1070 stepper motor which has a maximum holding torque of 0.44Nm and a 1. 8°step angle. A motor of this size was selected to allow for a safety factor during operation, thus the maximum operating torque considered will be 0.22Nm. The mass of the exoskeleton framework that will be affecting the torque of the elbow was 0.069 kg.

The first calculation conducted was to determine the holding torques that would be at the elbow joint in an unloaded bicep flexor movement at a varying angle which can be seen in Figure 06 below.

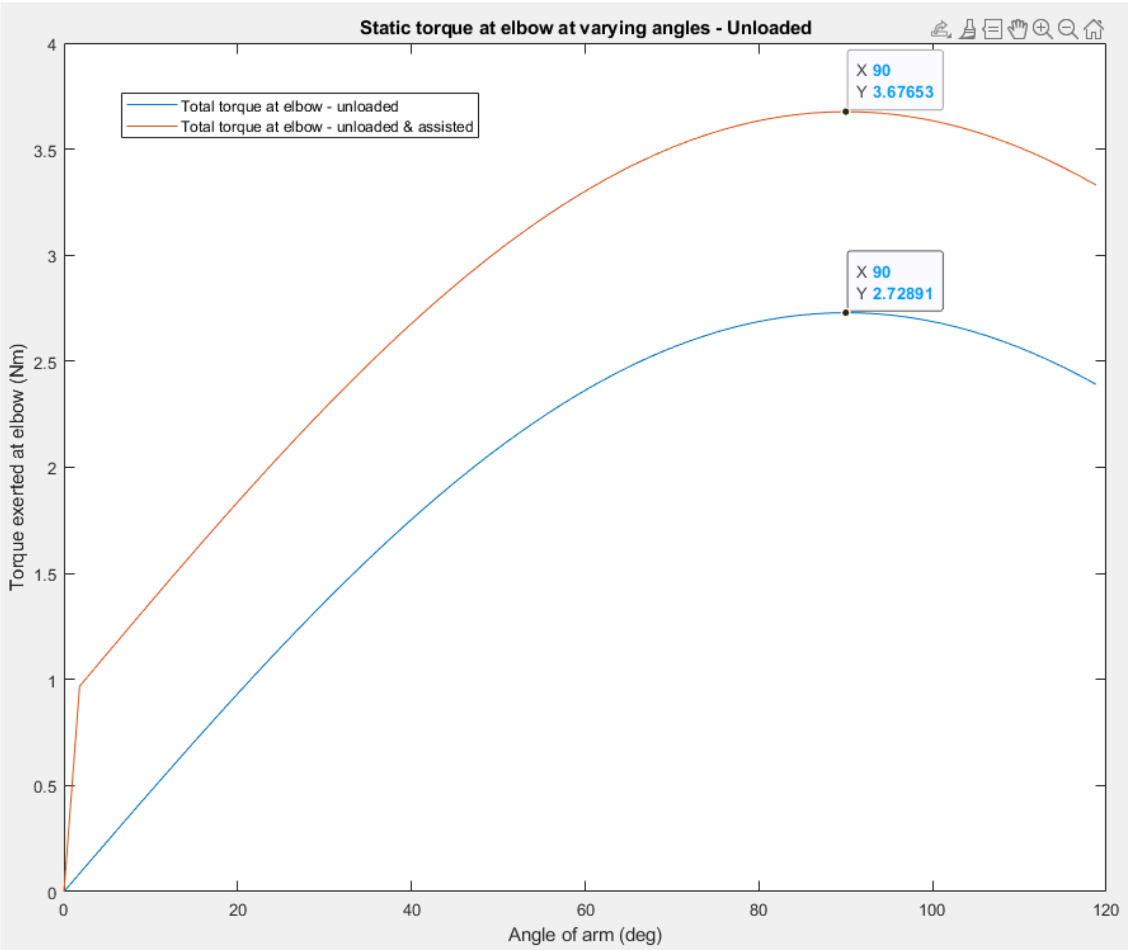


Figure 06 - Unloaded static torque at the elbow at varying angles.

The second calculation determined the static torques that would be acting at the elbow when a mass of 0.5kg was held at varying angles, and the third calculation combined the torque at the elbow produced the same lift with the additional torque produced by the motor and exoskeleton frame to determine the additional mass that could be held. With the addition of the exoskeleton, the total torque generated at the elbow when the arm would be perpendicular was 5.01129 Nm. Taking this value, it could then be determined that for the same torque generated by the user in a 0.5kg lift, with the exoskeleton fitted, the user would be able to lift an additional 0.332 kg. The below figure shows the torque produced at the elbow during a 0.5kg unassisted lift and the additional torque that the exoskeleton would provide the wearer.

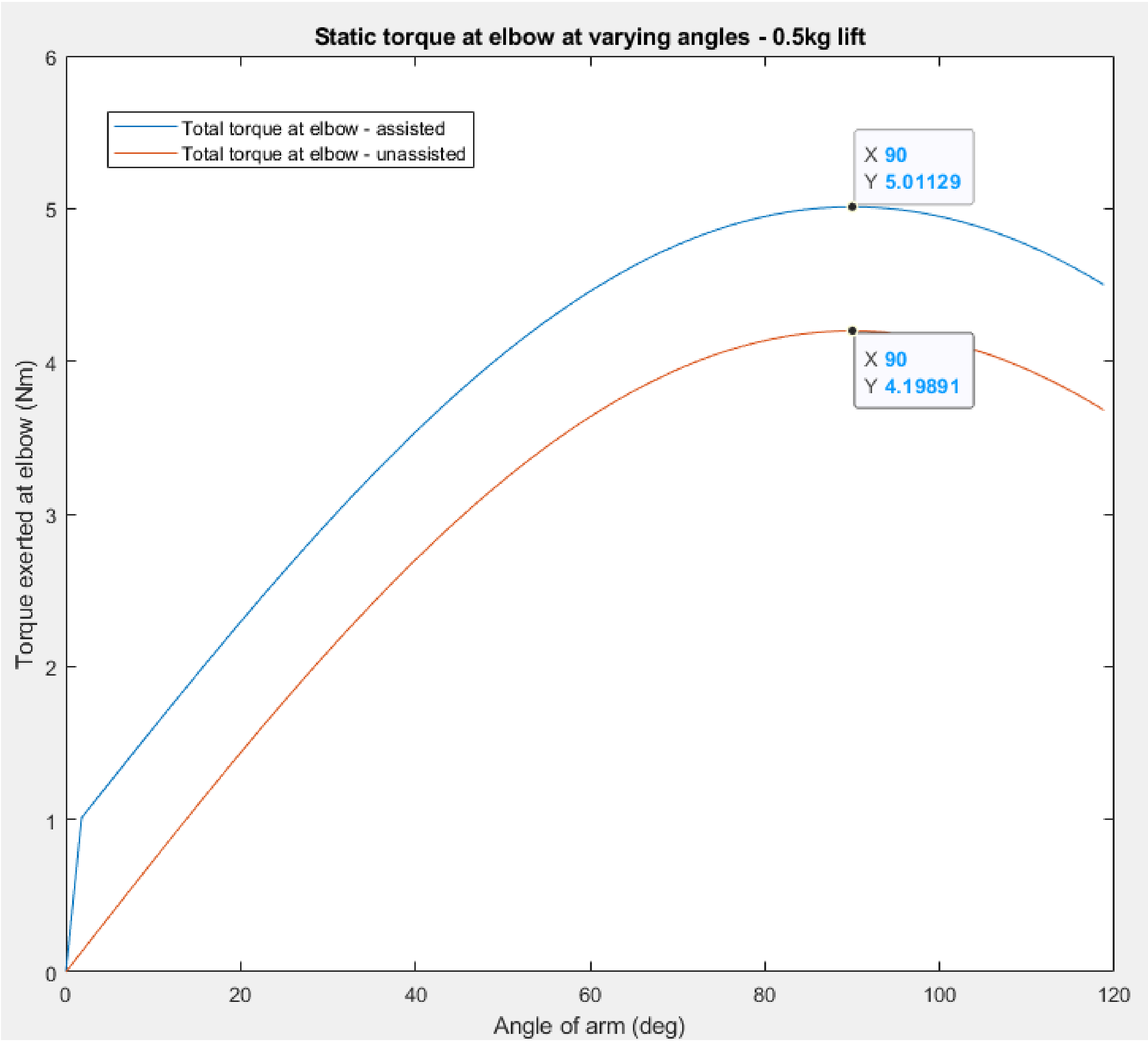


Figure 07 : 0.5kg unassisted and assisted lift static torque at the elbow.

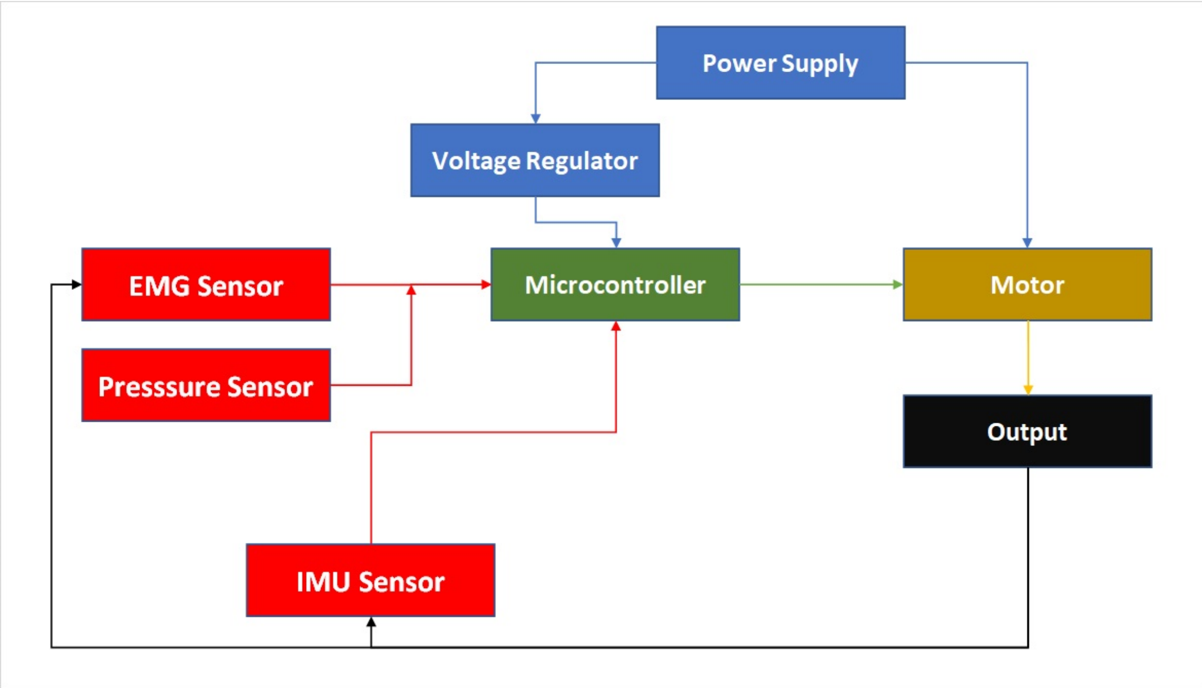


Figure 08 : Block Diagram proposed for the circuit board

The above diagram shows the major electronic components of the circuit board. A singular power supply of 24 V is connected to the circuit to power all the electronics. A voltage regulator is introduced to reduce the supplied power in parallel to feed the microcontroller circuit, to protect the circuit from burning out with excess power. Once the motor is switched on, the pressure sensor activates to measure the amount of force being experienced on the palms of the user. The EMG sensor picks on the muscled twitch of the forearm on user movement and compares it to a pre-calibrated value of muscle stress to determine the purpose of the muscle tension, whether it is a simple movement or an act of lifting an object. The microcontroller takes both of these analog inputs into account to execute the rotation required by the motor to perform the on-hand task. As the motor outputs in moving the attachment to the forearm, the IMU constantly calibrates its position and sends the signals to the microcontroller as events, to trigger maximum motor torque once the determined angular displacement is reached.

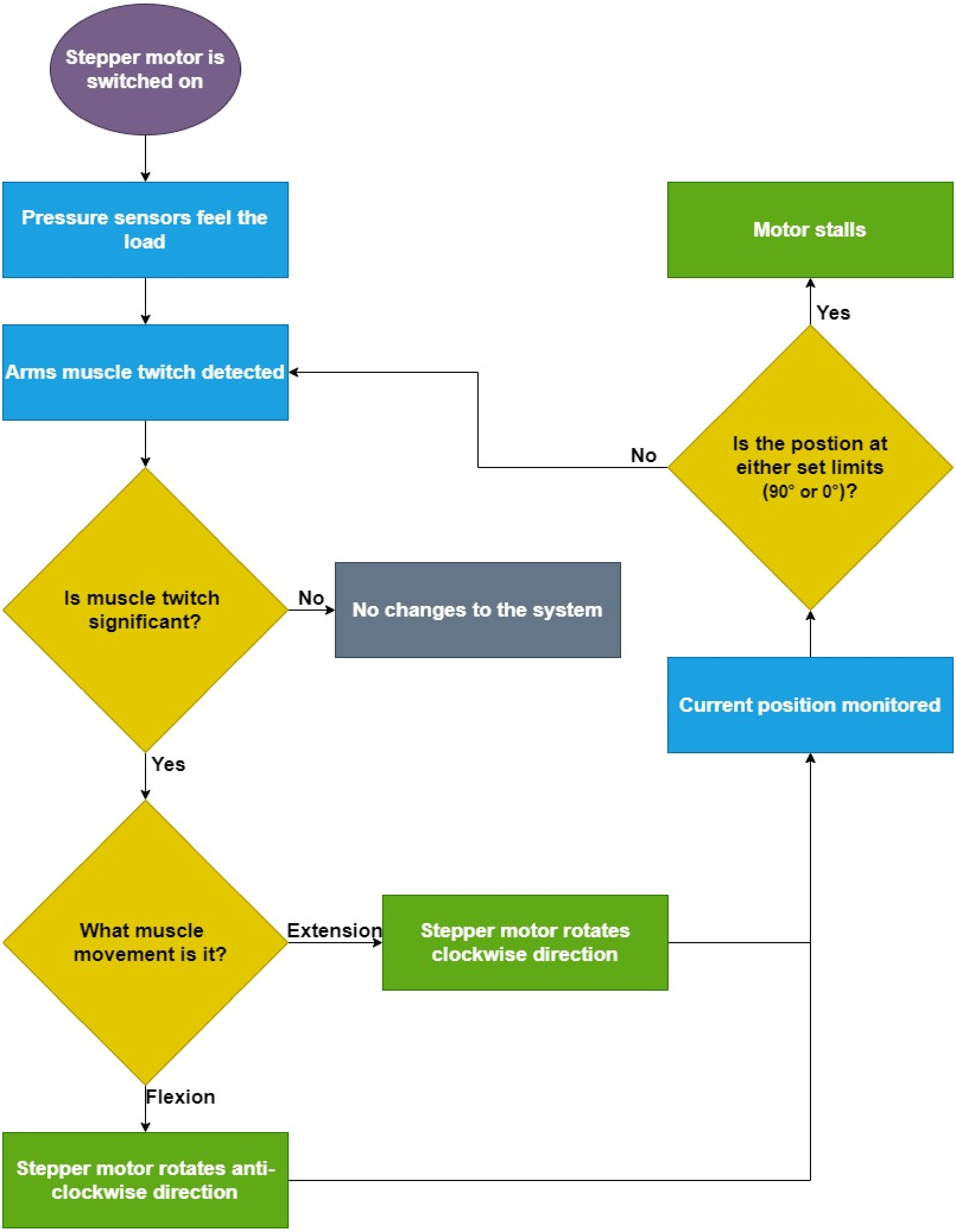


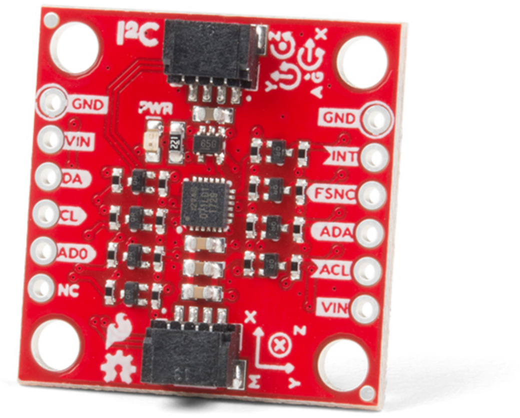
Figure 09 : Algorithm of the exoskeleton working mechanism

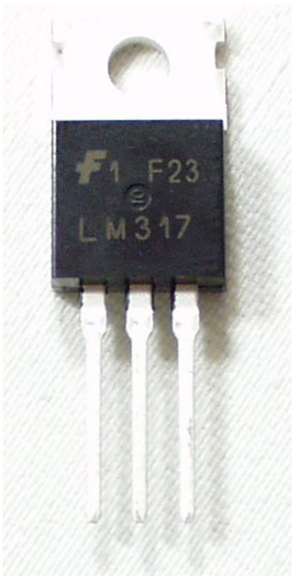
Types of equipment chosen:

Table 2: Equipment list and descriptions.

 Trinamic PD42-3-1070 Motor [a]	Supply Voltage: **9-24 V** Rated DC current : **1 A** Holding Torque: **0.49 Nm** Mass : **0.35 kg** Common Voltage Input: **5 V** Dimension: **42 mm x 42 mm x 59 mm** Baud Rate: **9600** The chosen motor is suitable for our purpose. It comes with an in-built driver with H-bridge thereby not requiring any external component to be bought for the circuit.
 Arduino UNO R3 [ref from section above]	Operating voltage: **7-12 V** Maximum current output: **0.04 A** Input/Output Channels: **20** Analog Input: **6** Pulse-Width Modulation output: **6** Mass: **0.028 g** Processor: **ATMega328** Speed: **16 MHz** Dimension: **68.6 mm x 53.4 mm** Communication channel: **SPI** **I2C** **UART**

 FlexiForce Pressure Sensor [b]	Pin: **3-pin Male Square Pin** Dimension: **191 mm x 14 mm** Sensing area: **9.53 mm (diameter)** Weighable force: **0-445 N** This pressure sensor, true to its name, is quite flexible. It can weigh and display force between 0-445 N, depending on its sensitivity which can be increased by increasing the size of the feedback resistor. It utilizes an inverting op-amp using thee formula; $V_{out} = -V_T \times \frac{R_f}{R_s}$ where, V_T = Supply Voltage R_f = Feedback Resistance R_s = Sensor Resistance (depending on the Weight)
 Myoware Muscle Sensor [c]	Supply Voltage: **3.1 - 5.9 V** Supply Current: **9 mA** Electrode nodes: **3** This Myoware Muscle Sensor can provide two different outputs: EMG Envelope and Raw EMG. For this project, the enveloped EMG can be used in conjunction with proper Ardunio coding to calibrate, limit and in turn control the movement of the exoskeleton. This equipment comes with an attachment of 3 electrodes, the reference, the middle and the end electrode. The middle electrode is to be placed at the middle of the muscle midline, the end electrode towards the end of the muscle body. The reference electrode is to be placed at a separate location like the bony area of the elbow. This ensures the proper measurement of muscle responses during isometric contractions.

<table>
<tr>
<td>
SparkFun 9DoF IMU Breakout [d]</td>
<td>Supply Voltage: 1.71 - 3.6 V
Kinematic sensors: Gyroscope
Accelerometer
Magnetometer
Communication channels: SPI
I2C

This particular IMU sensor is considered for its versatility. It provides a 6-DoF measurement (9 DoF can be seen as a stretch but seems viable if we are considering dynamic angular movement too). Each of the sensors can be isolated and used as required thereby saving on the power used if some of the kinematic sensors are unrequired.</td>
</tr>
<tr>
<td>
Voltage Regulator LM317 [e]</td>
<td>Output Voltage: 1.2-37 V
Output Current: 1.5 A

This voltage regulator is adjustable depending on the two external resistors used in the circuit to determine the output voltage. Based on the calculation for the LM317 voltage regulator, to receive an output of 9 V to supply to the Arduino board, two resistors of 900 Ω as R1, and 5580 Ω as R2 are required for the given input supply of 24 V.</td>
</tr>
</table>

 RS PRO 24V NiMH [f]	Voltage: **24 V** Charge: **2 Ah** Weight: **1.12 kg** Dimensions: **101 mm x 74 mm x 31.5 mm** Features: **Rechargable**

All the components mentioned in Table 02 above have been included in the Bill of Materials below. The current budget for this project has been determined below in Table 03.

Table 3: Parts and materials list.

Item	Item Type	Retailer	Order Code	Quantity	Cost ($)	Total cost ($)
IGUS iglidur® I150-PF	Print Material	Imaginables		1	106.90	106.90
Ultimaker Tough PLA	Print Material	Imaginables		1	86.90	86.90
Trinamic PD42-3-1070 Motor	Motor	Element 14		1	197.80	197.80
Arduino Uno R3	Microcontroller	Core electronics		1	39.00	39.00
FlexiForce Pressure Sensor – 25lbs	Sensor	Sparksfun		1	21.95	21.95
Myoware Muscle Sensor SEN – 13723	Sensor	Sparksfun		2	37.95	75.90
RS PRO 24V NiMH Rechargeable Battery Pack, 2Ah	Battery	RS Components		1	152.46	152.46
Additional components (Straps, screws, nuts and bolts etc.)	Various	Various		N/A	50	50
Total Cost						**730.91**

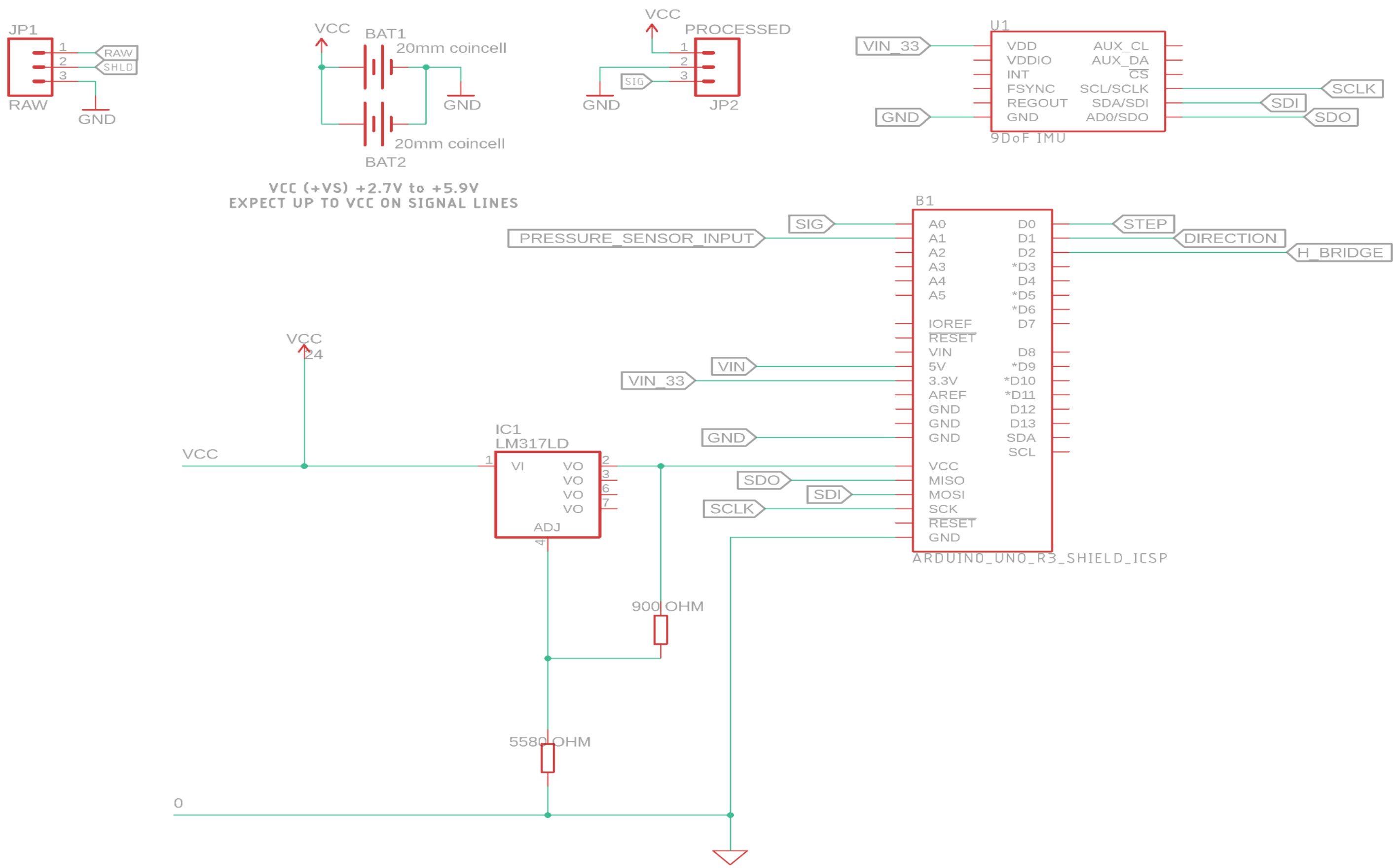


Fig 10 : Proposed Circuit Diagram

Testing

The testing stage of this project will be conducted after the construction of the prototype has been completed. This stage is critical to the project's success and will determine whether the project outcomes have been met. Due to the lack of design and development of exoskeletons, a suitable testing methodology and strategy needs to be adapted from similar studies and implemented. There is currently no strict testing guideline established as this will be explored in further detail during second part of this project.

Iterate

The development of new prototypes can provide unexpected results and outcomes. To meet project outcomes, the eight-step design process outlined in this project needs to be iterated to achieve the best result. Throughout the design and testing phase, issues, flaws, and inconsistencies need to be analyzed and recorded to be addressed in the next iteration.

Due to the complex requirements of an exoskeleton design, multiple iterations would typically occur. However, due to time constraints and resources, only a small number of iterations will be able to be completed, therefore careful planning and time management needs to occur with each iteration to maximize the outcome.

Risk Assessment - AB & TS

With any engineering project, a significant consideration for the safety of the end-user must be practised and adhered to. Young, developing technologies generally suffer from the lack of expertise and thus, adequate safety measures in the early design stages are crucial. Common risk assessment tools include a risk safety matrix, as shown in Figure 11 below, which looks at the severity of the risk and the likelihood of the incident and determines the risk factor which can be denoted by the associated number.

Risk Assessment Table

		Severity of Harm (Impact)		
		Low (L)	Medium (M)	High (H)
Likelihood	High (H)	3	4	5
	Medium (M)	2	3	4
	Low (L)	1	2	3

Figure 11 : Risk Safety Matrix[54].

By applying such a tool in the design stage, it can help identify several potential issues in the early development of the upper limb exoskeleton and minimize the need for rework. Using this alongside a risk assessment form, controls can be implemented to reduce the risk factor. The risk assessment form consists of the risk, risk factor (RF), consequence, mitigation technique and adjusted risk factor (ARF).

Due to the lack of standards for developing and designing exoskeletons [2][4], and the lack of governing bodies in the safety of exoskeletons, the safety procedures of the project will need to be determined and implemented by the design team. To establish a minimal safety standard, consideration of other projects applying similar technologies will need to be analyzed and adapted in conjunction with using tools such as the risk safety matrix and assessment.

Design Risks

With a complex control system, actuators, actuation mechanism and various moving parts associated with Active Exoskeletons there need to be significant considerations for the safety procedures. Table 4 below indicates some of the potential risks that need to be factored in when making design decisions for the project and the appropriate mitigation techniques to minimize the risk factor.

Table 4 – Design Risk Assessment Form

Risk	RF	Consequence	Mitigation Technique	ARF
Electric Shock	3	Electric shock can result in burns, muscle spasms and cardiac arrest.	Using extra-low voltages, insulated material and minimizing physical contact between energized equipment and human skin.	2
Chemical burns	3	Chemical burns from batteries will cause skin deformation and pain.	Avoid placing the battery near the operator.	2
Pinch points	4	Skin could be pierced causing bleeding.	Potential pinch points to be designed away from skin surface and extrusions placed around	1
Poor control system	3	Actuators could drive systems beyond musculoskeletal capabilities.	Spotter, limiter switches, mechanical limiters and "Dead man" switches to be used.	1
Overloading	4	The actuator could fail to result in fire and damaged equipment. Users could drop load and damage other limbs.	Strict mass limit to be adhered to and all testing to be done in a controlled manner.	1
Actuator failure	3	The actuator could drive or fail to drive resulting in injury to the user.	Limit switches, no-load tests before loaded test and monitor actuator condition.	1

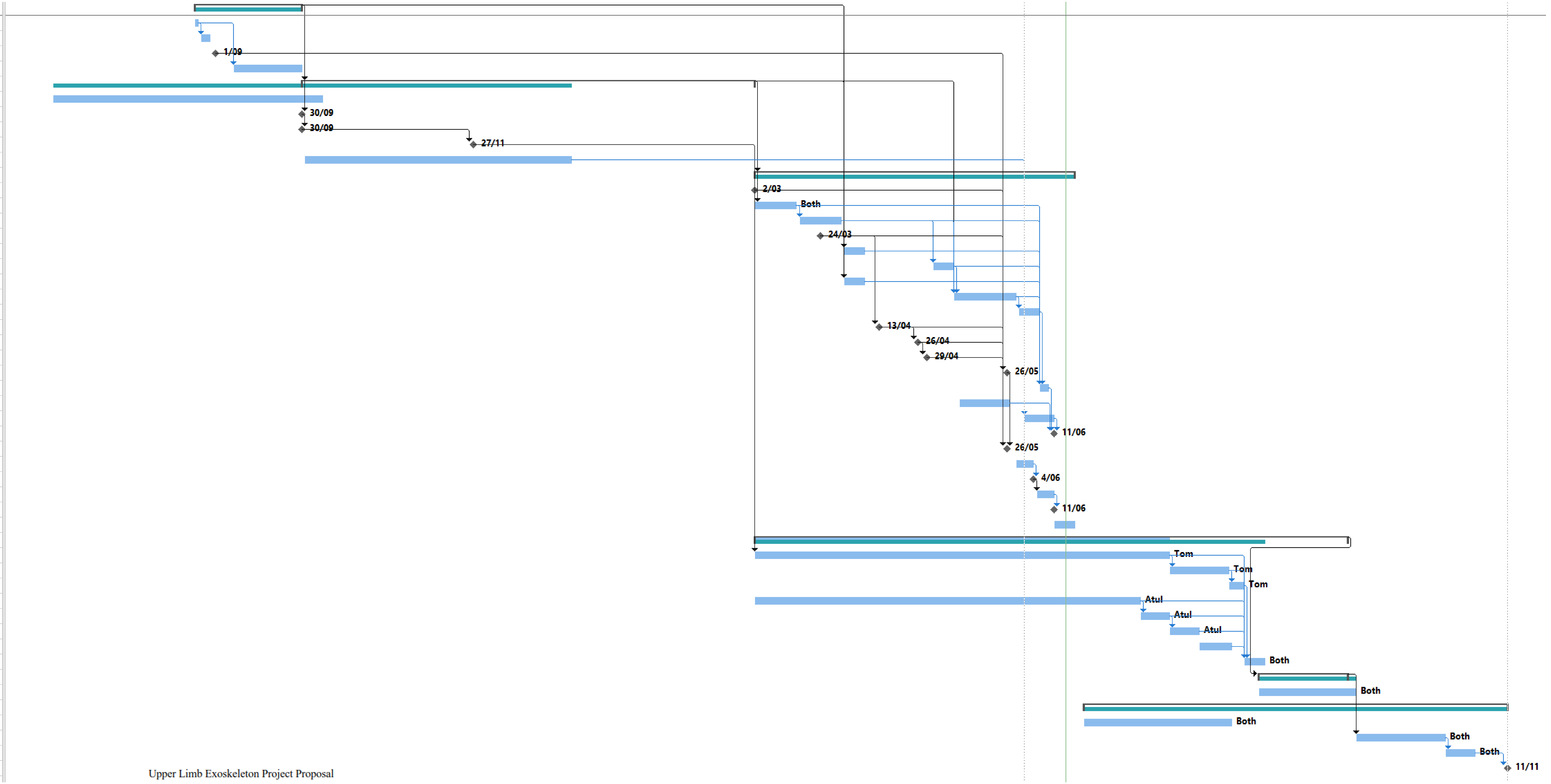
External Risks and Stakeholders

External risks are usually ones associated with stakeholders, lobby groups, customers, global issues and pandemics. Due to exoskeleton technology being reasonably new there are minimal external party issues that need to be factored into the design and development of the project. Thus this project has minimal external stakeholders input during the design and development. To overcome this, however, the design team will need to adopt a target group.

The current COVID-19 global pandemic is an impeding factor on many industries and various research studies. During this time Victoria University had shut down all campus facilities under the instructions of the Victorian government. With the unpredictability of the COVID-19 virus and the possibility of limited to no access to university facilities, careful design choices will be taken to ensure the progression of the project. Should the state be placed into a complete lockdown the project will be reevaluated and the project scope will be readdressed.

Gantt Chart

PLANNING STAGE	**36d**	**Tue 25/08/20**	**Wed 30/09/20**		**Both**
Select research topic	1d	Tue 25/08/20	Wed 26/08/20		
Write small project overview for project supervisor	3d	Thu 27/08/20	Sun 30/08/20	2	
Meeting with project supervisor	0d	Tue 1/09/20	Tue 1/09/20		
Commence research	23d	Mon 7/09/20	Wed 30/09/20	2	
LITERATURE REVIEW	**153d**	**Wed 30/09/20**	**Tue 2/03/21**	**1**	**Both**
Investigate current exoskeleton designs and technology	91d	Wed 8/07/20	Wed 7/10/20		
First meeting with supervisor (Diary Entry 1)	0d	Wed 30/09/20	Wed 30/09/20	1	Tom
Second meeting with supervisor (Diary Entry 2)	0d	Wed 30/09/20	Wed 30/09/20	8	Both
Discuss project history and receive files (Diary Entry 3)	0d	Fri 27/11/20	Fri 27/11/20	9	Both
Collect relevant research papers as references	90d	Thu 1/10/20	Wed 30/12/20		
LITERATURE REVIEW/PROJECT PROPOSAL	**108d**	**Tue 2/03/21**	**Fri 18/06/21**	**6**	**Both**
Meeting with project supervisor (Diary entry 4)	0d	Tue 2/03/21	Tue 2/03/21		
Create base structure for report	14d	Tue 2/03/21	Tue 16/03/21	6	Both
Introduction and Background	14d	Wed 17/03/21	Wed 31/03/21	14	
Meeting with project supervisor (Diary entry 5)	0d	Wed 24/03/21	Wed 24/03/21		Both
Outline scope	7d	Thu 1/04/21	Thu 8/04/21	1,6	
Complete literature review	7d	Sat 1/05/21	Sat 8/05/21	15	
Draft risk assessment	7d	Thu 1/04/21	Thu 8/04/21	1,6	
Draft project methodology	21d	Sat 8/05/21	Sat 29/05/21	6,18,15	
Compile resource requirement	7d	Sun 30/05/21	Sun 6/06/21	20	
Meeting with project supervisor (Diary entry 6)	0d	Tue 13/04/21	Tue 13/04/21	16	Both
Meeting with project supervisor (Diary entry 7)	0d	Mon 26/04/21	Mon 26/04/21	22	Both
Construct first framework design (Diary entry 8)	0d	Thu 29/04/21	Thu 29/04/21	23	Tom
Meeting with project supervisor (Diary entry 9)	0d	Wed 26/05/21	Wed 26/05/21	24	Both
Review current draft version	3d	Sun 6/06/21	Wed 9/06/21	15,14,17,18,19,20,21	
Edit and review of current report	17d	Mon 10/05/21	Thu 27/05/21		
Complete references section	10d	Tue 1/06/21	Fri 11/06/21	11	
Finalise draft copy	0d	Fri 11/06/21	Fri 11/06/21	27,26,28	
Submit diary entries	0d	Wed 26/05/21	Wed 26/05/21	4,13,16,24,22,23,25	
Create Gantt chart using project timeline	6d	Sat 29/05/21	Fri 4/06/21		
Add Gantt chart to project report	0d	Fri 4/06/21	Fri 4/06/21	31	
Final read through and editting	6d	Sat 5/06/21	Fri 11/06/21	32	
Submit project report	0d	Fri 11/06/21	Fri 11/06/21	33	
Report overflow	7d	Fri 11/06/21	Fri 18/06/21		
PROJECT DESIGN AND CONSTRUCTION	**200d**	**Tue 2/03/21**	**Sat 18/09/21**		**Both**
CAD Framework	140d	Tue 2/03/21	Tue 20/07/21	10	Tom
3D print	20d	Tue 20/07/21	Mon 9/08/21	37	Tom
Framework Construction	5d	Mon 9/08/21	Sat 14/08/21	38	Tom
Circuit design	130d	Tue 2/03/21	Sat 10/07/21		Atul
Circuit construction	10d	Sat 10/07/21	Tue 20/07/21	40	Atul
Circuit testing	10d	Tue 20/07/21	Fri 30/07/21	41	Atul
Restesting/Redesigning	11d	Fri 30/07/21	Tue 10/08/21		
Exoskeleton assembly	7d	Sat 14/08/21	Sat 21/08/21	37,38,39,40,41,42,43	Both
PROJECT TESTING	**30d**	**Thu 19/08/21**	**Sat 18/09/21**	**36**	**Both**
Testing of exoskeleton	33d	Thu 19/08/21	Tue 21/09/21		Both
PROJECT REPORT	**143d**	**Mon 21/06/21**	**Thu 11/11/21**		**Both**
Background information and literature review	50d	Mon 21/06/21	Tue 10/08/21		Both
Testing results	30d	Tue 21/09/21	Thu 21/10/21	45	Both
Conclusion	10d	Thu 21/10/21	Sun 31/10/21	49	Both
Submission	0d	Thu 11/11/21	Thu 11/11/21	50	Both



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