DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

GROUP PROJECT REPORT for

Design of a passive exoskeleton suit system on carrying heavy load for backpacker

by

Aaron Blanco, Jack Pledger, Sam Gray, Naimur Lamim Ruhid, Rory Henderson, Jayvratsinh Jadeja

Student ID: 1911261, 1820772, 1805565, 1948928, 1906405, 1940686

Supervisor: Quan Long

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1 Introduction (1906405)

1.1 Context for the project

Exoskeletons are becoming more important in our society. They have many applications, such as aiding in moving heavy objects, helping people with weakened muscles walk again, military applications and making manual labour tasks easier. While many exoskeletons have focused the use of motors and other powered components, these are limited by their electric power source [1]. This means they require a constant power source to function. As a result, there is room in the current market for a simpler exoskeleton that is entirely passive (having no power source). Many exoskeletons are expensive, complicated, and not available for everyday use. An exoskeleton that is passive and simple will have a greater chance of being mass-produced, as it could be less costly to manufacture, purchase, and maintain. In addition to this, without the restriction of an electronic power source, the exoskeleton could be used in any location as there is no need for a power source. This will, in turn, extend the usability of the exoskeleton and make it a more viable tool for everyday work in the labour market, as well as military and leisure used. Concomitantly, manual labour jobs will become less laborious [2], people will be able to walk with heavier loads for longer [1].

1.2 Aim and objectives for the project

This project aims to design a lightweight passive exoskeleton that can aid an averaged size, able bodied and active person in carrying a load of 40kg without using any powered components. In this regard, the exoskeleton must be entirely passive in its ability to aid the person in walking a short distance.

For this exoskeleton to be successful, it needs to be both lightweight and strong [1]. It needs to be lightweight so that wearing the exoskeleton suit does not significantly slow down the user while trying to move. Similarly, the exoskeleton also needs to be strong so that it can withstand the increased loads that the user will be carrying, as well as impacts caused by knocks and falls the user experiences.

The exoskeleton produced must be able to maintain a high level of manoeuvrability for it to be viable [3]. In this project, joints for the waist, hip, knee, and ankle are all being considered. These joints will be made to be as close to the manoeuvrability of the human body as possible while still being simple in design, lightweight, inexpensive to manufacture, and easy to maintain. It should also be noted that some of the manoeuvrability of the exoskeleton suit will be limited to avoid injuries to the user. This will replicate similar constraints of the human body.

Arguably one of the most important aspects of the exoskeleton after its passive nature is its cheap construction and possibility of easy maintenance and manufacture. This will increase the rate at which it is adopted and make it more available to everyday people for their jobs and leisure activities – when compared to current exoskeletons.

To help keep the weight of the backpack off the user's legs and on the exoskeleton, the load will be transferred to the ground via the exoskeleton. The exoskeleton suit will be supported separately to the user and therefore aid in transferring the load of the backpack to the exoskeleton and ground. In this project, aspects of the exoskeleton which involve the arms will not be considered.

When creating an exoskeleton for the everyday person it is important to consider how it will work for everyone. For the exoskeleton to be usable for everyone, it will be designed with adjustment in mind. This will allow a one size fits all exoskeleton to be designed, shipped, and subsequently sold to the users which they can adjust on arrival and growth. This is especially important for exoskeletons as the joints of the exoskeleton need to line up with the joints of the user, as this will help with the use of the exoskeleton and help prevent injuries. The legs will all be adjustable to allow everyone between the 5th and 95th percentiles to use the exoskeleton [4].

To effectively assist people walking the biomechanics of the human body had to be considered. The action with which people walk is very complicated, but mainly requires the movement of the leg about the pelvis/hips, bending at the knee and a rotation of the ankle [1]. Therefore, as previously discussed, the exoskeleton will allow for movement in all these areas with maximised manoeuvrability to allow users to walk unrestricted.

2 Literature Review (1911261)

2.1 Ergonomics of exoskeletons

Two of the most important aspects that an exoskeleton must achieve are comfort and safety. Comfort refers to the ability to wear the exoskeleton for a long period of time and understanding the ergonomics of the human body will greatly influence how the exoskeleton is designed. The exoskeleton must be compatible with human biomechanics. Several factors can contribute to the kinematic incompatibility between a wearable exoskeleton and a real human limb. Incompatibility can occur due to the variability of biomechanical parameters between different people. Also, the unpredictability of joint axis locations and body segment sizes can lead to a disturbed interaction between an exoskeleton and the human operator, depending on the exoskeleton design. Causes of kinematic incompatibilities between humans and exoskeletons can be classified into two groups: Macro-misalignments and micro-misalignments. Macro-misalignments occur if exoskeleton joints used for interacting with specific human joints, or joint groups are oversimplified. Oversimplification, in this case, means that the degrees of freedom of an exoskeleton joint are less than the number of degrees of freedom of the corresponding human joint. This is the case for all wearable exoskeletons that feature 7 degrees of freedom, and this will be considered moving into the design of the exoskeleton [5].

2.2 Hip Joint

When designing the waist, it is best to allow it to freely rotate in the direction the user turns so that they are not constrained. Inspiration from the Mawashi Uprise Passive Load-Bearing Exoskeleton seen in Figure 1 contributed to the design of the waist part of the exoskeleton. The exoskeleton Mawashi created is designed to increase a soldier's protection against

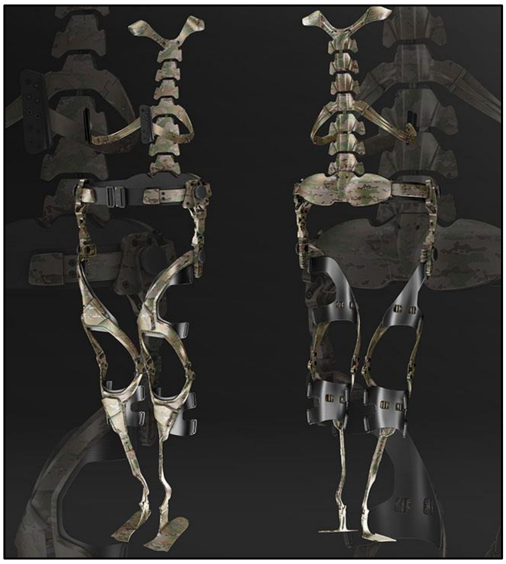

Figure 1: Image of exoskeleton created by Mawashi [9]

injuries that strongly hamper their capacity in the theatre of operation. It has a complex exoskeleton structure made of high strength titanium, has an ultralight design, and provides a minimal degree of resistance to movement [6]. A key feature extracted from Mawashi's exoskeleton was their sliding belt mechanism for waist rotational degree of freedom. The purpose of the sliding mechanism is to allow freedom of movement while taking the load off the back and transferring it to the waist.

2.3 Knee Joint

There are many possible design approaches for the knee joint. One important aspect is that the joint is designed to support the load while not restraining movement. Looking through examples of both passive and non-passive exoskeletons, the knee joint is often designed with a simple hinge to connect both the upper and lower leg sections giving one degree of freedom, as shown in Figure 2.

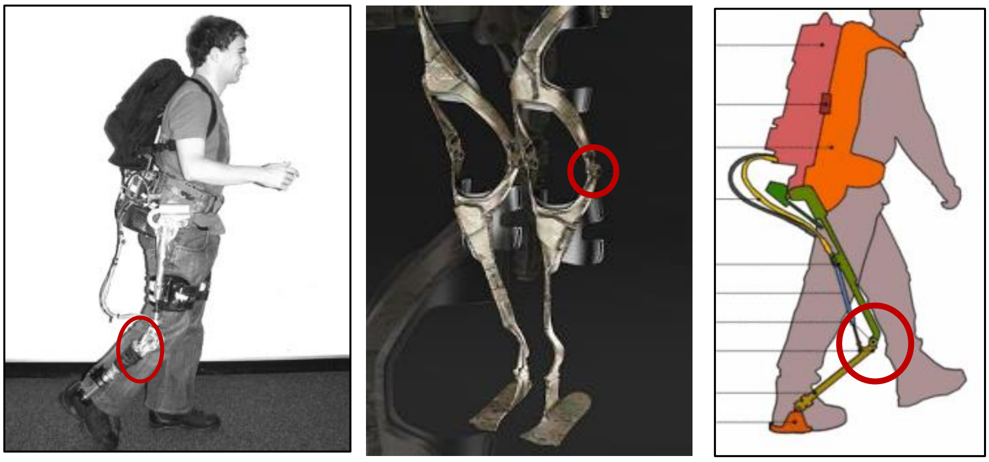

Figure 2: Circled parts of the images demonstrating the different ways the knee joint can be designed [6] [7] [8].

2.4 **Ankle Joint**

The ankle plays a key role in walking, running, and standing. It allows a person to keep their balance from the rotation of the ankle. When carrying the weight of a 30-40kg backpack, the user will need to be able to stay upright on any terrain. Some solutions investigated rotating the ankle towards and away from the floor. One article focused on creating a passive exoskeleton that attempts to improve the way humans walk by using a suspended spring mechanism [9]. This mechanism encountered a time-delay problem which occurred during state-switching due to the deformation of the trigger spring. This normally worked when the user would walk at a low speed. The problem tends to become more obvious as walking speed increases and so their aim of the design was to create a Passive Ankle-Foot Exoskeleton to address the problem of time delay and perform the function of automatic state-switching based

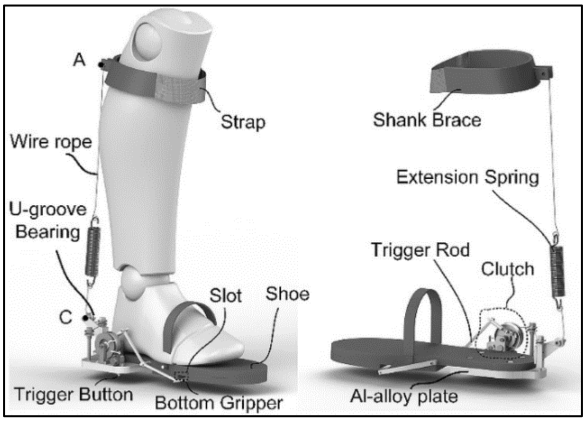

Figure 3: Passive ankle-foot exoskeleton [9]

on mechanical identification of the current gait stages. These features of the exoskeleton look promising, but this is not what this project aims to do. As the exoskeleton only allows one degree of freedom. This is the case with most of the exoskeletons that have been analysed and a custom ankle joint will be designed that matches the freedom of movement of the human ankle.

2.5 **Backpack Interface**

The backpack interface is an essential part of the passive exoskeleton because it will connect the items the user is carrying to the exoskeleton. The interface could make use of an existing backpack and build the exoskeleton around it. Alternatively, a custom backpack can be designed with a complex counterbalance system that moves up and down while walking. The exoskeleton can be designed with a platform to hold up the backpack, or have a structure built around the backpack to hold it in place. This may be the most practical idea as this way, any backpack would fit with the exoskeleton. This may reduce the cost of manufacturing which in turn can make the exoskeleton more affordable for the consumer.

2.6 **Ground Contact**

When it comes to the exoskeleton, the device must be able to attach from the upper body all the way down to the feet. There are several mechanisms to secure the exoskeleton to the foot. For example, a clamp can be connected to the back of the heel, an insole can be worn on the inside of the users' shoes, or a piece of metal can be connected underneath the heel of the shoe with grip added to it. There are various solutions and in the later stages of the design, this will be finalised.

2.7 **Adjustability**

Exoskeletons are usually made to fit a specific person which makes them ineligible for a wider market. However, for this project's design, adjustability within a range of sizes will be investigated. The following section analyses how this can happen.

2.7.1 **Waist**

An exoskeleton needs to be able to attach itself to the user's waist and so tactical belts were researched as they would be the most durable and compatible with the exoskeleton. Tactical belts have many uses and one of them is being able to carry many types of equipment, one of them being a firearm, on top of holding your trousers up. Before choosing a tactical belt, you must understand that they aren't all built the same, so you must be careful when choosing one. There are three main types of tactical belts which are: rigger belt, gun belt and heavy-duty belt. A rigger belt is specifically designed to aid rappelling. These are ideal for rock climbers or for people into similar sports. Some features that stand out for this type of belt is being ease of access, how the pockets are organised and the amount it can carry – both large and small items. The next kind of belt is a gun belt. These hold you holstered gun and weaponry parts without sagging. They are often made from leather as they need to be stiff. These belts are often reinforced with stiffeners and adopt cobra buckles which are a set of Swiss designs that lead the industry for their durability and convenient features. The last belt is the heavy duty. These are designed to hold different types of gear other than weaponry. Things such as flashlights, batons, sprays, and handcuffs. You see these kinds of belts used by police officers; however, this doesn't stop it from being useful for other purposes [10]. A belt that is being considered is the Condor LCS Cobra Gun Belt as shown in Figure 4. This is a gun belt that is constructed with heave duty webbing and reinforced with additional layer of scuba webbing to handle heavy loads. The belts exterior features proprietary LCS material with non-traditional MOLLE slots to stabilise attachments. This belt is versatile and can be used in conjunction with an inner belt or as a stand-alone. This makes it suitable to be used with an exoskeleton [11].

Figure 4: Condor LCS Cobra Gun Belt made by PRESTIGE TACTICAL

2.7.2 Upper and lower leg

Two methods of leg adjustability were considered. These methods can be seen in adjustable crutches or cam lock camps (Figure 5). The mechanism used in adjustable crutches or a bike

Figure 5: Crutch and bike clamp

clamp that is used to adjust the height of the seat of the bike can be used.

A crutch can withstand at least 60kg of mass which makes it ideal for the design of the exoskeleton as the load the user will be carrying will be around 30-40 kg. This also applies to the bike clamp as it can withstand the load of a person sitting on it, which also makes it ideal for the design.

2.8 **Body Connection**

An exoskeleton needs a way to attach to the body. So, this section will investigate the different ways this can be done. There are two common methods of connecting the body to an exoskeleton, both of which are some form of strap.

2.8.1 **Velcro Straps**

Velcro has a wide range of uses and has a strong grip. Velcro can be used for various situations such as a general use or heavy-duty. A heavy-duty Velcro strap consists of a metal buckle which allows the strap to support a greater load. This strong grip a Velcro strap has makes it a suitable option for our exoskeleton.

2.8.2 Backpack Straps

Just like Velcro straps, another alternative is the straps used in backpacks. These can be used to fasten a backpack to the body. Backpack straps work by looping straps through a plastic buckle, which allows them to be adjustable and stops the straps from coming loose. Backpack straps are used in hiking bags which are often heavy and holds loads from 20-30kg. This makes them good at holding large loads and suitable to attach the body to an exoskeleton.

2.8.3 Linear Spring Clamp

Figure 6: Phone clamp for phones and tablets

The idea of the spring clamp was considered as a method of connecting the exoskeleton to the foot. The spring clamp is both adjustable and holds the user’s phone in place, as shown in Figure 6. This made it appealing for use in the design as it will allow the wearer of the exoskeleton to use different sized shoes. Further detail on how the design of the clamp will be altered to make it compatible with the exoskeleton will be shown in a later section.

3 Specification (1948928)

Table 1: Design specification

Operation • The device must permit users to carry 30-40kg in a backpack • The product must allow rotational movement for walking • The product needs to be designed to the same DoF as human joints	Dimensions • The exoskeleton should be adjustable in all aspects, to suit a range of different sizes i.e., between the 5th and 95th percentile for height and waist diameter
Materials • The chosen materials must be durable • The materials must not corrode easily to harsh environmental conditions • The materials must be cost effective and easily sourced	Aesthetics • The device should be kept as lightweight as possible for comfort • The product can have a protective finish to improve protection characteristics
Life Expectancy • The product is expected to have a life expectancy of at least 5 years before components need to be replaced	Environment • The exoskeleton should be operational in mud, snow, and rain • The device must be able to work in various terrains e.g., mountain, desert, swamp etc.
Use • The product should not be restrictive in movement i.e., stiff joints • The device should be able to withstand general wear and tear	Usage Hazards • The product cannot collapse under use causing harm to the user • The product must be removed if the user is feeling discomfort • The product cannot be used by a person under influence of drugs/alcohol
Maintenance • The exoskeleton must be designed for low maintenance • The product should have easily accessible components which can be cleaned/replaced when needed	Recycling • Majority, if not all, of the parts should be made from materials which can be recycled and/or recycled materials
Manufacture Methods • The product must be manufactured using a high quality and cheapest option to keep costs low • The exoskeleton should incorporate off-the-shelf components for easy assembly	Market • This product is aimed at soldiers and private contractors • The product can be sold to the general public for day-to-day use
Engineering Standards • The product must follow ISO 14001 for the environmental management • The product must follow ISO 9001 for quality control in manufacturing • The product must follow ISO 45001 for Health and Safety management	

4 Concept design and selection (1805565)

4.1 The ankle joints

Concept 1:

Concept 1 consisted of a ‘leg’ section and a ‘foot’ section connected by a single hinge to provide one degree of freedom. The design also includes a spring under tension to aid with plantar flexion of the foot to aid the wearer with walking. A rough sketch of the design showing the leg and foot components, compression spring and hinge can be observed in Figure 7a. The advantages and disadvantages of this concept were considered in Table 2.

Table 2: An overview of the advantages and disadvantages of ankle joint concept 1

Advantages	Disadvantages
- Compression spring may reduce the load on the wearer while they walk, enabling them to walk more comfortably for longer distances - A mechanism could be included to adjust to force from the compression spring based on the weight of the wearer and the load from the backpack - Single hinge mechanism is simple and could be manufactured easily, therefore minimising manufacturing costs	- Inclusion of the compression spring in the design requires more components, therefore increasing manufacturing costs - The single hinge mechanism only allows for one degree of freedom in the form of a single axis of rotation. This is fewer degrees of freedom than the human ankle joint, which may hinder the ankle mobility of the wearer

Concept 2:

Concept 2 consisted of a ‘leg’ section and a ‘foot’ section connected by a ball and socket joint. The ball and socket joint provides three degrees of freedom in the form of three axes of rotation of the foot component relative to the ankle joint. This matches the rotational freedom of the human ankle joint. A rough sketch of the design showing the leg and foot components, and the ball and socket joint can be seen in Figure 7b. The advantages and disadvantages of this concept were considered in Table 3: An overview of the advantages and disadvantages of ankle joint concept 2

Table 3: An overview of the advantages and disadvantages of ankle joint concept 2

Advantages	Disadvantages
- The ball and socket joint allows for axial rotation about three axes, matching the rotational freedom of the human ankle joint, therefore this design would be less hindering on the ankle mobility of the wearer - This concept requires fewer components than concept 1 as it does not feature the spring	- This concept is a purely passive joint, meaning less load will be carried by the exoskeleton compared to concept 1. As a result, a greater proportion of the load from the backpack will be

mechanisms of concept 1. This will make the design less costly to manufacture.	subject upon the wearers body.

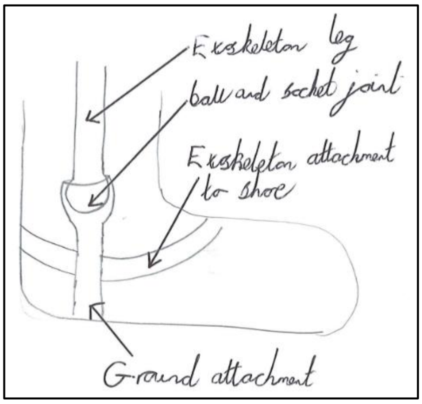

Figure 7a: Ankle joint concept 1

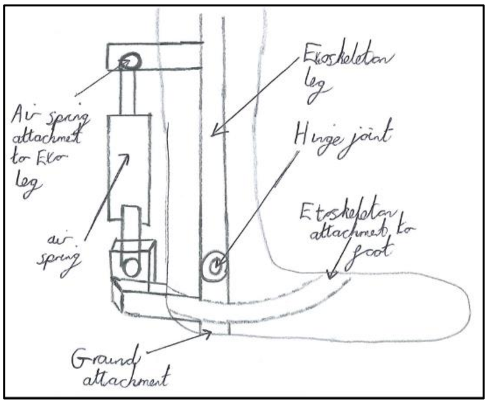

Figure 7b: Ankle joint concept 2

4.2 Backpack Interface

Concept 1:

Concept 1 featured a frame with a solid base, and a mesh to secure a backpack or other items carried by the wearer. The design includes draw strings to close the opening at the top of the meshing, to prevent items from falling from the backpack. A sketch of the design showing the load bearing frame and mesh is shown in Figure 8a. The advantages and disadvantages of this concept were considered in Table 4: An overview of the advantages and disadvantages of the backpack interface concept 1

Table 4: An overview of the advantages and disadvantages of the backpack interface concept 1

Advantages	Disadvantages
- A range of backpacks or other items could be put in the mesh allowing a greater range of items to be carried using this design - The mesh could easily be replaced without replacing the whole exoskeleton if the mesh became worn or damaged	- Items secured in the mesh may move as the wearer walks. The moving mass may make walking difficult as the centre of mass of the wearer and bag would move as the bag moved - The backpack must be removed from the exoskeleton to retrieve items from the backpack

Concept 2:

Concept 2 features a solid, collapsible base on which a backpack sits. The base supports the weight of the backpack. Short vertical support pieces prevent the backpack from sliding off the base while the wearer is walking. The backpack straps must be worn by the wearer to prevent the backpack falling off the base, and to keep the backpack in contact with the wearers back.

A sketch showing the foldable base is shown in Figure 8b. The advantages and disadvantages of this concept were considered and are summarised in Table 5.

Table 5: An overview of the advantages and disadvantages of the backpack interface concept 2

Advantages	Disadvantages
- The collapsible base can fold into a small area to allow easier storage and transport of the backpack when not in use - Items can be retrieved from the backpack without removing it from the exoskeleton	- Only backpacks of a specific size and shape would be compatible with this concept design as the base of the backpack must fit snuggly on the collapsible base in order to prevent the backpack moving while the exoskeleton is in use - The mechanism to allow the base to fold away will require several components that need to be precisely machined. This will increase the manufacturing cost of the exoskeleton if this concept is used in the final design

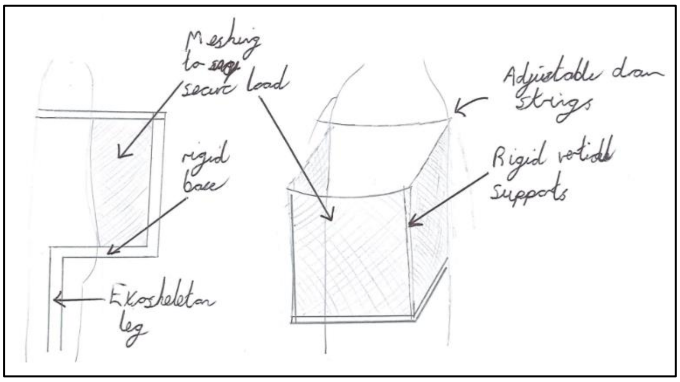

Figure 8a: Backpack interface concept 1

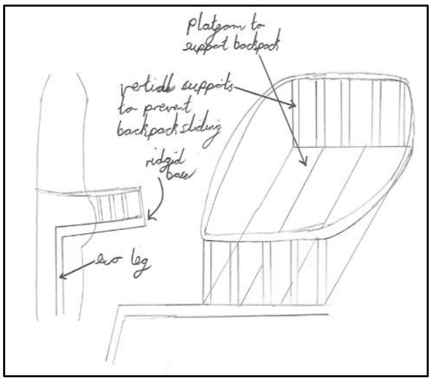

Figure 8b: Backpack interface concept 2

4.3 The Knee Joint

Two design concepts were considered for the knee joint. The first was a simple passive joint with a single hinge to provide one degree of freedom. This matches the degree of freedom of the human knee joint. The second design concept also consisted of a single hinge providing one degree of freedom, but also featured a compression spring to aid with extension of the knee. This spring was included to aid with walking with a heavy load. Figure 9a and Figure 9b display the concept design for the knee without, and with the compression spring respectfully. The advantages and disadvantages of the two concept designs were considered, and are summarised in Table 6

Table 6: Advantages and disadvantages of the two concept designs for the knee joint.

Concept 1 Advantages	Concept 1 Disadvantages
- This concept is very simple as it only includes one hinge and no compression spring. As a result, it could be manufactured for little cost, helping to minimise the	- This design concept does not include any components to aid with extension or bending of the knee. Therefore, it will provide less aid to the wearer as they are walking than a design with a spring or other

overall manufacturing cost of the exoskeleton - The simple nature of the joint will increase the reliability of the joint and reduce the maintenance required on the joint	component to aid with extension of the knee - As the design consists of an upper and lower leg component configured with one component in front of the other, a bending moment will be induced on the shaft that the components pivot on – Analysis must be conducted on this shaft to ensure the strength is sufficient if this concept is used in the final design
Concept 2 Advantages	**Concept 2 Disadvantages**
- The concept features a compression spring which aids with leg extension, this will take some of the load of the wearer's legs while walking, enabling them to walk longer distances more comfortably while carrying the 40kg load - Compression spring force could be adjusted based on the weight of the wearer and the load being carried by the wearer to configure the exoskeleton for different wearers and loads	- Inclusion of the spring adds additional complexity into the design by increasing the number of components required to manufacture the knee joint. This will increase the cost of manufacturing the knee joint, increasing the overall cost of manufacture for the exoskeleton. - Joint would need to be designed with sufficient strength to withstand forces induced on the joint by the spring

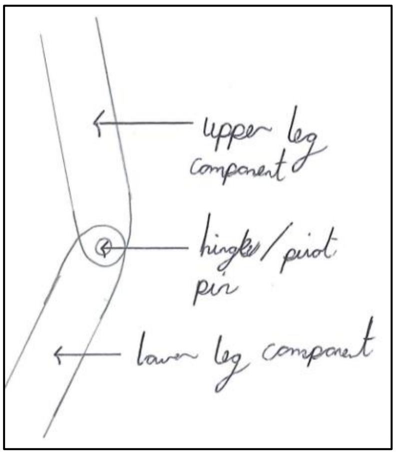

Figure 9a: Knee joint concept 1

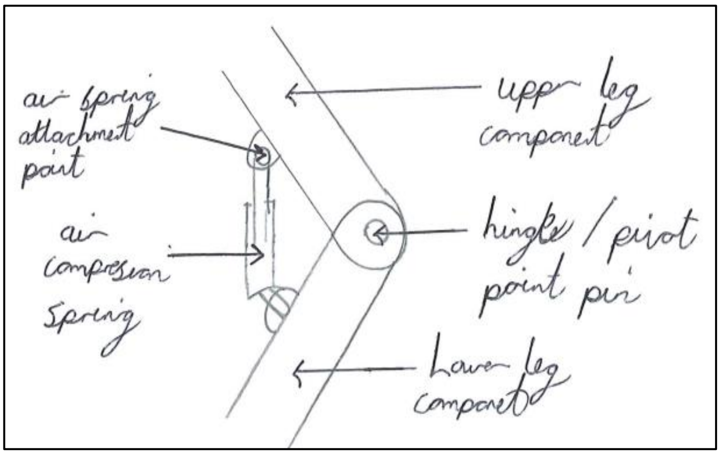

Figure 9b: Knee joint concept 2

4.4 The Hip Joint

Concept 1:

Design concept 1 for the hip joint featured a simple single hinge, allowing for one degree of freedom. The hinge was fixed in place on the waist section of the exoskeleton. A sketch of this concept design is displayed in Figure 10a. The advantages and disadvantages of this concept are shown in table 7.

Table 7: An overview of the advantages and disadvantages considered for hip joint concept 1.

Advantages	Disadvantages
- The design is simple, as a result it could be manufactured for a low cost, helping to minimise the overall cost of manufacturing the exoskeleton - The waist component of the hip joint could be manufactured from sheet metal, again helping to minimise manufacturing costs	- This concept design only gives one degree of freedom as the design uses only a single hinge. The human hip joint is a ball and socket joint with three degrees of freedom. As a result, this concept design would restrict the hip mobility of the wearer, possibly making walking with the exoskeleton challenging

Concept 2:

Design concept 2 for the hip joint featured a rail system to allow a plate with a rose joint to move around the outside of the hip joint. This mechanism allows for unrestricted rotation of the hip joint. The plate contains a hinge with a rose joint, to provide a large degree of rotation in one axis, and a small degree of rotation to for abduction and adduction of the leg. Furthermore, it aids with rotation of the hips or legs. Figure 10b displays a sketch of this concept while table 8 shows an overview of the major advantages and disadvantages of this design concept.

Table 8: An overview of the advantages and disadvantages considered for hip joint concept 2.

Advantages	Disadvantages
- Rotational freedom of this concept matches the rotational freedom of the human hip joint. Therefore, this design should provide little / no hindrance to hip mobility of the wearer - Most components in the design could be manufactured from sheet metal, helping to reduce manufacturing costs of the hip joint	- This concept is significantly more complex than concept 1, requiring significantly more components. As a result, this concept design would be significantly more expensive to manufacture than concept design 1 - The component that the rollers contact would need to be precisely machined in order to allow smooth operation of the rolling mechanism

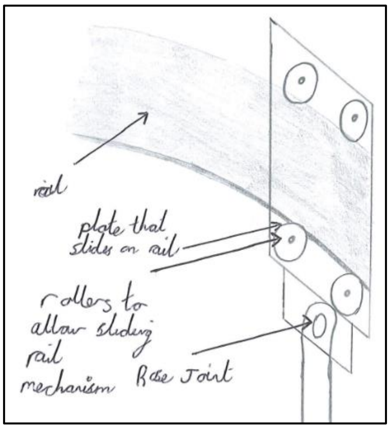

Figure 10a: Hip Joint Concept 1

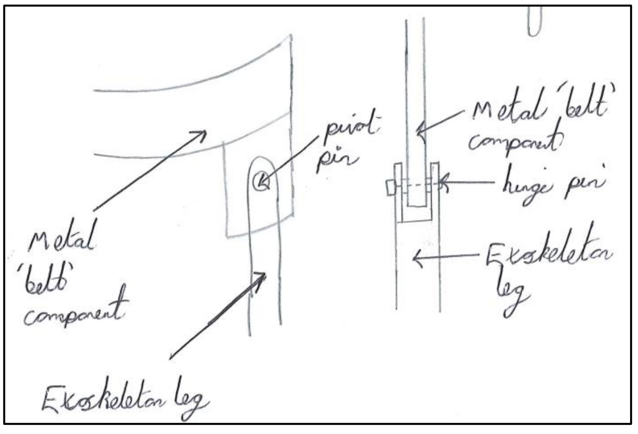

Figure 10b: Hip Joint Concept 2

5 Theoretical Calculations (1906405)

5.1 Material Selection for the Leg Structure

Table 9: Shows the materials that were researched and considered for use as the main material of the exoskeleton structure. The material properties, as well as their estimated cost is also shown.

	Tensile Yield Stress, MPa	Compressive Yield Stress, MPa	Young's Modulus, MPa	Cost, £/m^3	Density, kg/m^3
Carbon Fibre	1230	736	9.99E+04	£1,428,000.00	1410
Aluminium	276	280	6.80E+04	£45,166.60	2698.9
Steel	350	427.6	2.00E+05	£48,680.92	7800
Acrylic	75.4	120	3.10E+03	£26,276.60	1190
Polycarbonate	61.6	77.2	2.40E+03	£14,496.26	1210
PDCPD	54.2	76.4	2.08E+03	N/A	1050
Phenol formaldehyde resin	55	250	8.00E+03	£39,508.85	1420

Materials which are lightweight, readily available, cheap, resistant to weather and have high compressive yield strength were researched for use in the exoskeleton.

Using the equations below, Table 10 was produced to assess the viability of each of the materials from Table 9.

$$Minimum\ area\ required = \frac{F}{\frac{\sigma_{Compressive\ yield\ strength}}{FoS}} = \frac{392.4}{\frac{\sigma_{Compressive\ yield\ strength}}{10}}$$

$$Volume = Minimum\ area\ required * length = Minimum\ area\ required * 0.45$$

Table 10: Shows the minimum area required, volume, cost and weight of the materials assessed. This allows these values to be compared so a material can be chosen. The colour coding shows the best results in green and the worst in red.

Material (compression)	Area required, m^2	Volume, m^3	Cost, £	Weight, Kg
Carbon Fibre	5.33E-06	2.40E-06	£3.43	3.38E-03
Aluminium	1.40E-05	6.31E-06	£0.28	1.70E-02
Steel	9.18E-06	4.13E-06	£0.20	3.22E-02
Acrylic	3.27E-05	1.47E-05	£0.39	1.75E-02
Polycarbonate	5.08E-05	2.29E-05	£0.33	2.77E-02
PDCPD	5.14E-05	2.31E-05	#VALUE!	2.43E-02
Phenol formaldehyde resin	1.57E-05	7.06E-06	£0.28	1.00E-02

From Table 10, it was assessed from the relative weight and cost of the materials (given their compressive yield strengths) that aluminium would be the most suitable material to use. Aluminium was the third lightest material at (1.7×10^{-2} Kg - for the given volume) and tied for the second cheapest (£0.20 - for the given volume). As a result, aluminium is in a perfect middle ground considering weight and cost. Aluminium also has the benefit of being recyclable after the product has reached the end of its life cycle. Many people may not trust the strength of acrylic and therefore aluminium is a better choice. Carbon fibre was not chosen, as its significant cost outweighed the advantage of it being 5 times lighter than aluminium. Steel was not chosen despite it being the cheapest as it is 1.89 times heavier than aluminium and it is paramount that the exoskeleton is lightweight to not impede the movements of the user.

5.2 Determining the dimensions of the leg structure

To determine the optimum dimensions of the inner and outer sections of the leg structure to keep the exoskeleton lightweight, low profile and cheap an iterative program was devised. The program takes these initial values: thickness of 10mm, widths of 20mm to 50mm with 5mm intervals and width and thickness ratios of 0.1 to 0.9 with 0.1 intervals. The thickness and width ratios determine the dimensions of the inner section relative to the outer section. This is shown by the equations below.

$$Inner\ width = outer\ width * width\ ratio$$

$$Inner\ thicknesss = outer\ thickness * thickness\ ratio$$

Using table 1, the minimum required area can be calculated using the equation below.

$$Area = \frac{Force}{\sigma_{compression/FoS}} = \frac{392.4}{\frac{280}{10}} = 32.70mm^2$$

The area of the inner thigh and outer thigh both must be greater than or equal to 32.70mm^2. In the program, the area of the outer thigh (A1) is calculated using the equation below.

$$A1 = (width * thickness) - ((width * width\ ratio) * (thickness * thickness\ ratio))$$

The area of the inner thigh (A2) is calculated using the equation below.

$$A2 = ((width * width\ ratio) * (thickness * thickness\ ratio))$$

The widths, width ratios and thickness ratios that produce A1's and A2's which are greater than or equal to 32.70mm^2 are kept by the program and used to form the graph below.

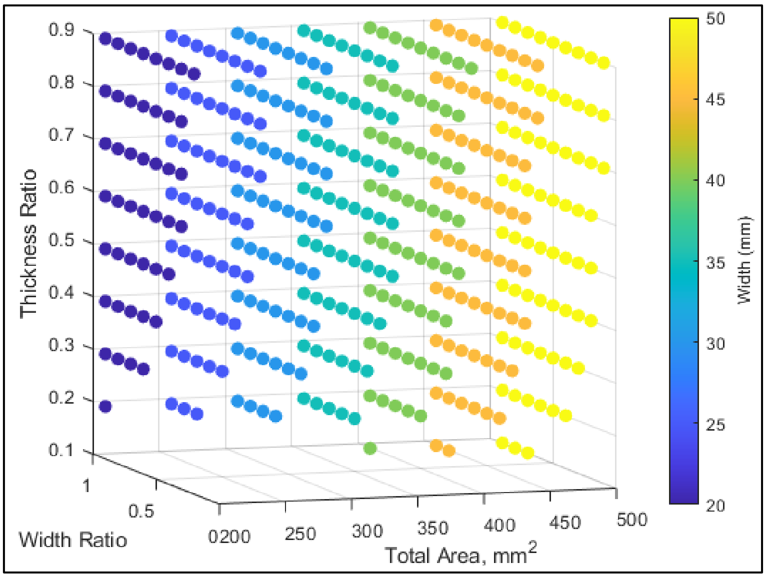

Figure 11: Shows the results from the program.

All the points on the graph represent a possible combination of width, width ratio and thickness ratio which could be used for the leg structure dimensions. However, this only accounts for material failure due to the load. Therefore, Finite Element Analysis (FEA) with some of the options from the smallest total area (shown by the equation below) were tested to see if they would buckle under the load. Using the smallest total area will keep the cost of the exoskeleton down while giving it a low profile and making it lightweight. This iterative process of FEA will not be shown for conciseness; however, the chosen values will be shown for completeness.

5.3 Analysis of Leg Structure

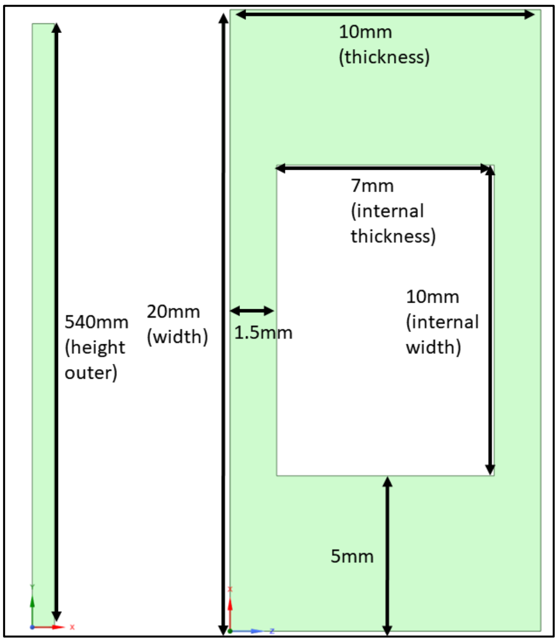

Figure 12: Shows the dimensions for the outer thigh model

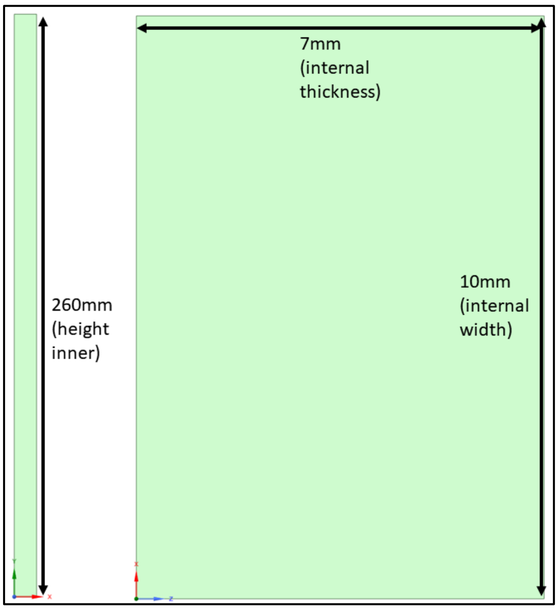

Figure 13: Shows the dimensions for the inner thigh model

Three different models for the leg structure were used. These are the whole thigh, outer thigh, and inner thigh. The dimensions of which are shown in Figure 12, Figure 13 and Figure 14. The dimensions were derived from the 5th and 95th percentiles of both men and women for thigh length (depending on which was smaller/larger respectively) from macoshdesign.com (2022). The 5th percentile represents the smallest the exoskeleton needs to be and the 95th percentile represents the largest the exoskeleton needs to be. This encompasses the largest number of people without unnecessarily increasing the cost and making the design complex. The whole thigh model shown in Figure 14 is used to represent the leg structure when it is built and at its maximum extension. For simplicity the part that tightens the outer thigh and inner thigh models together is not modelled – instead, they are modelled as one solid piece. Using the maximum height of the leg structure allows the worst-case scenario to be assessed to ensure the leg structure is safe and can support the 40kg load. Figure 15 Shows the FEA set-up for the outer thigh, which is also used for the inner thigh and whole thigh. The fixed support is shown at A in blue (at the bottom of the y axis). The 392.4N force (used to represent the 40kg load carried by the exoskeleton) is shown at B (on the hidden surface) in red acting in the direction of the red arrow (shown) in the negative y-direction. In practice, the 392.4N load will be smaller than this, as the user will take some of the load (as shown in the literature review).

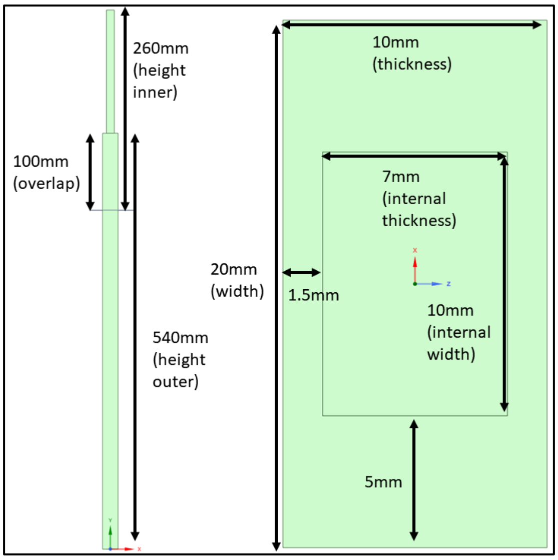

Figure 14: Shows the dimensions for the whole thigh model

The leg structure is assumed to be made from isotropic aluminium which has a Young's Modulus of $6.8\text{x}10^{10}$ Pa, a Poisson's Ratio of 0.36 and a compressive yield strength of $2.8\text{x}10^{8}$ Pa. For the Mean Stress Theory, the Goodman equation is used. The design life of the leg structure will be assumed to be $1\text{x}10^{9}$ cycles. Five modes of eigenvalue buckling will be investigated.

Convergence plots for the total deformation and equivalent stress were created for both the whole thigh as well as outer/inner thigh, however, these have been omitted for conciseness. The element sizes were determined using suitable convergence criteria and are shown in Table 11 as well as the other mesh parameters.

From these models, to assess the suitability of the chosen dimensions, the following results will be collected and analysed: maximum stress in the y axis, maximum deformation in the y axis, factor of safety and life. In addition to this, the five modes of eigenvalue buckling will be assessed to determine if the leg structure will buckle.

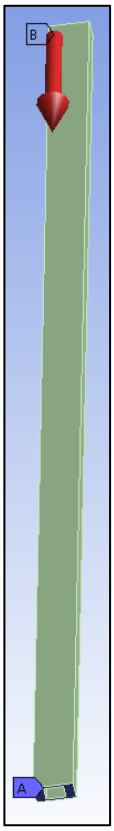

Figure 15: Shows the FEA setup

Table 11: Shows the mesh parameters for the FEA simulation

Model	Element size (mm)	Equation	Element shape
Whole thigh	5	Quadratic	Square structured
Outer thigh	2	Quadratic	Square structured
Inner thigh	2	Quadratic	Square structured

5.3.1 Results and Discussion

For the outer thigh, the maximum normal stress in the y-direction is -6.0527 MPa, which is less than the compressive yield strength of aluminium and is therefore safe. The maximum deformation in the y-direction is -2.3947×10^{-2} mm, which is negligible and therefore safe. The factor of safety is 15 and the minimum life is 1×10^{8} cycles – both of which are more than enough for the exoskeleton's lifetime and use. In terms of the eigenvalue buckling the results for the five modes of buckling tested are shown in Table 12 Since all the values are greater than 1 no buckling is expected with the 40kg load and the factor of safety for mode 1 of eigenvalue buckling is 2.0283. The outer thigh leg structure is strong enough for its purpose.

Table 12: Shows the eigenvalue buckling results for the outer thigh FEA model.

Mode	Load Multiplier
1	2.0283
2	8.9156
3	18.213
4	50.342
5	78.976

For the inner thigh, the maximum normal stress in the y-direction is -9.7419 MPa, which is less than the compressive yield strength of aluminium and is therefore safe. The maximum deformation in the y-direction is -2.14×10^{-2} mm, which is negligible and therefore safe. The minimum factor of safety is 9.9924 and the minimum life is 1×10^{8} cycles – both of which are more than enough for the exoskeleton's lifetime and use. In terms of the eigenvalue buckling the results for the five modes of buckling tested are shown in Table 13. Since all the values are greater than 1 no buckling is expected with the 40kg load and the factor of safety for mode 1 of eigenvalue buckling is 1.8123. The inner thigh leg structure is strong enough for its purpose.

Table 13: Shows the eigenvalue buckling results for the inner thigh FEA model.

Mode	Load Multiplier
1	1.8123
2	3.6957
3	16.272
4	33.091
5	44.981

For the whole thigh, the maximum normal stress in the y-direction is –5.7644 MPa, which is less than the compressive yield strength of aluminium and is therefore safe. The maximum deformation in the y-direction is -3.5763×10^{-2} mm, which is negligible and therefore safe. The minimum factor of safety is 14.019 and the minimum life is 1×10^{8} cycles – both of which are more than enough for the exoskeleton's lifetime and use. In terms of the eigenvalue buckling the results for the five modes of buckling tested are shown in Table 14. Since all the values are greater than 1 no buckling is expected with the 40kg load and the factor of safety for mode 1 of eigenvalue buckling is 1.1237. The whole thigh leg structure is strong enough for its purpose.

Table 14: Shows the eigenvalue buckling results for the whole thigh FEA model.

Mode	Load Multiplier
1	1.1237
2	4.2599
3	6.1496
4	16.216
5	18.597

Overall, the leg structure is safe for use. However, the failure load in the form of mode 1 eigenvalue buckling (shown by Figure 16) is shown by the equation below.

$$Fail\ load_{Eigenvalue\ buckling} = Load * Load\ Multiplier_{mode\ 1} = 392.4 * 1.1237 = 440.94N$$

The maximum backpack mass is shown by the equation below.

$$Max\ Mass = \frac{Max\ Load}{9.81} = \frac{440.94}{9.81} = 44.948Kg$$

This means that the leg structure can be overloaded by roughly 5Kg before failure and this is a decent factor of safety given this is at the maximum extension (only affecting the 95th percentile of the tallest men) and the maximum load of the exoskeleton will be stated as 40Kg. If this ever proved to be an issue in testing, the maximum height of a user could be reduced to help prevent this issue. In addition to this, the percentage error of an exoskeleton loaded with a 45Kg backpack as opposed to a 40Kg one is shown by the equation below.

$$Percanetage\ error = \frac{44.948 - 40}{40} x100 = \ 12.37\%$$

5.3.2 Conclusion

Given the results of the FEA, it is clear to see that the design dimensions of the exoskeleton are safe for use, as there is a decent factor of safety, and the exoskeleton will not fail under its intended use conditions.

While the leg structure could be made stronger by increasing the width and thickness dimensions this goes against two of the key design points of the exoskeleton - keeping it lightweight and low profile. In addition to this, it also keeps the cost down.

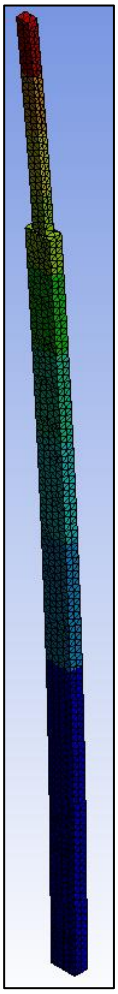

Figure 16: Show mode 1 of the eigenvalue buckling (the whole thigh model is shown)

6 Final Design and FEA

Figure 17: The full exoskeleton assembly. Legs sections have been shortened for clarity

6.1 Backpack Interface (1940686)

6.1.1 Design

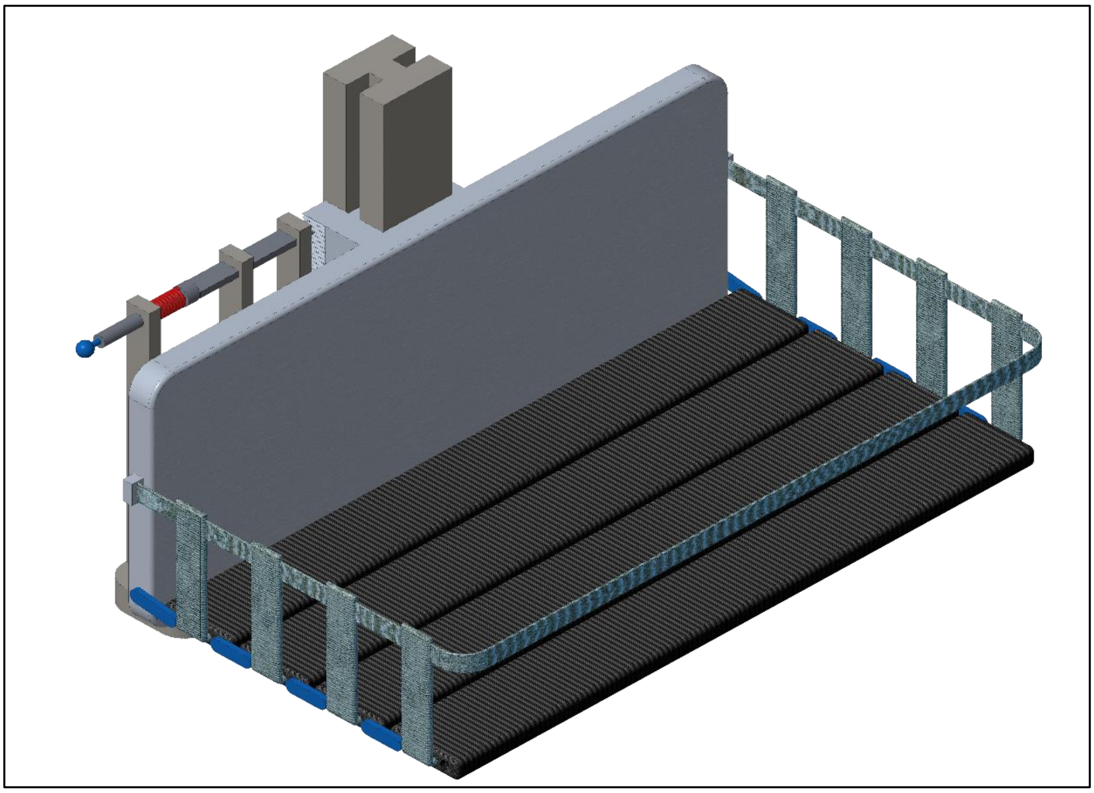

Figure 18: Backpack Support Final Design

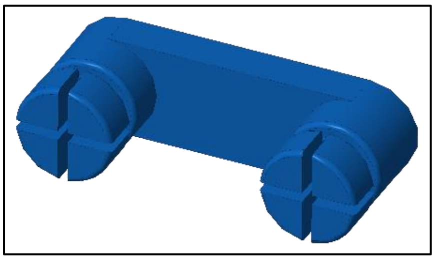

Figure 20: Rotational clip

Figure 19: Strap Buckles

The design shown in Figure 18 is a clean and modified version of the initial sketch shown above in the concept selection section of the report. Here an ‘ɪ’ shaped bracket is used as the main support to carry the load as it provides good structural strength which is less prone to bending. The sliding mechanism is used to make the platform adjustable with the help of a rack on the back side of the adjustable plate. The teeth on the rack have an average gap of 0.75mm to provide maximum adjustability to the user with a range of 10 cm in height. A rod with a triangular end point locks the adjustable plate in a fixed position acting as a pin. Too make sure the pin stays stationary a spring is placed in between the pin and the bottom part of the assembly. To support and lift the backpack from the bottom multiple 7.5 mm cuboidal plates are used, those plates are further attached with 22 mm clips shown in Figure 20. These clips allow rotational motion making the design more flexible to adapt according to the shape of the backpack. Lastly, the fabric-like material seen in Figure 18 represents straps that will connect the bottom plates to one another and further connect to the adjustable plate. There will be strap buckles (as shown in Figure 19) at the end of each strap so it can be tightened around the backpack to hold it in place.

6.1.2 Analysis

Structural analysis was performed on the design using ANSYS mechanical in which the materials that were used are Aluminium Alloy for the pin, adjustable plate and rotational clips, Stainless steel for 'I' shaped bracket and the bottom attachment which attaches to the waist, carbon fibre (395 GPa) for cuboidal bottom plate, and lastly backpack straps will be purchased from market which are generally made of Nylon 66. The test was carried out with a 50 kg (500 N) load exerted downwards on the cuboidal carbon fibre plates.

As it can be seen from Figure 21 the maximum deformation experienced under a 50 kg load is 9.44 mm which mostly happens at the end of the straps and at the last cuboidal plate as they are far from the adjustable plate where the straps are attached.

Looking at Figure 22 we observe that most of the stress is experienced by the rotational clip attached to the adjustable plate as it connects the lower assembly of cuboidal plate to the system. The stress experienced by the clip ranges between 66.667 MPa to 233.33 MPa which is below the yield strength of Aluminium Alloy which has a yield strength of 280 MPa. With these results we can easily conclude the backpack holder will be able to lift more than 50 kg of load.

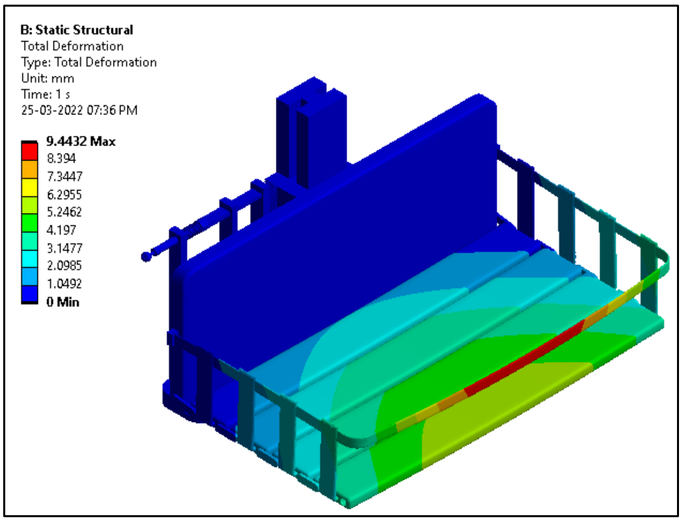

Figure 21: Total Deformation results from ANSYS of Backpack Holder

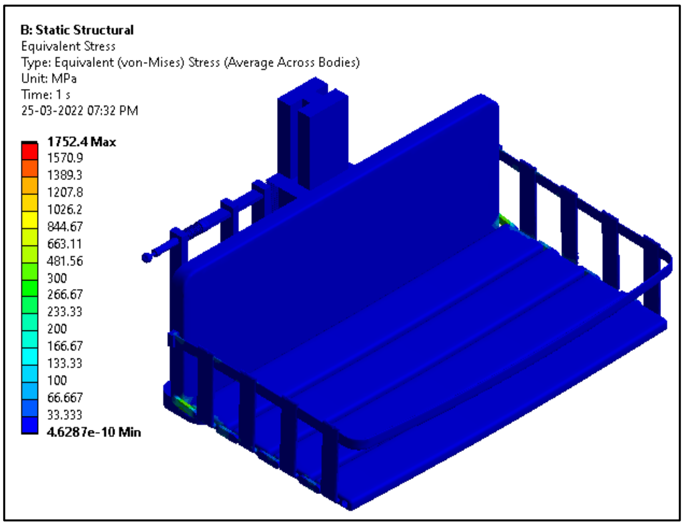

Figure 22: Equivalent Stress results from ANSYS of Backpack Holder.

6.2 Waist (1820772)

6.2.1 Design

Figure 23: An overview of the waist and hip assembly

The waist and hip assembly are a major part of the exoskeleton design, providing the main attachment point to the user and transferring load from the back to the legs. The system must be able to adapt to the user's movement and have a large range of adjustments to fit multiple wearers while remaining lightweight. Following the literature review, the design of Mawashi's UPRISE exoskeleton appeared to meet these criteria, utilising its unique rail system to provide unrestricted movement to the hips and torso while still transferring force to the legs. This inspired the design of this exoskeleton, which follows the concept of the rail system but with reduced cost and complexity to lower the overall price. Using a combination of 3mm and 4mm sheet metal for the main structure combined with several readily available parts, the assembly can be easily manufactured without specialist tools. The overall assembly is shown in Figure 23.

The waist mechanism is articulated in three main parts, with the rear plate to support the weight of the backpack and a rail on each side to support the hip joint. Figure 24 shows a close-up of the joint. The parts are attached with an M8 bolt through interlocking tabs, limiting the system to a single degree of freedom, and transferring the weight of the backpack through the joint. The bolt can be tightened without affecting the mechanism due to the configuration of the tabs. A nylon lock nut is used to prevent the bolt from loosening due to movement and vibration.

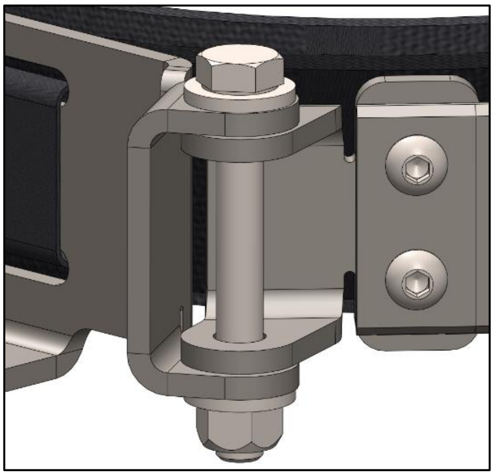

Figure 24: A close-up of the rail cross-section

The rail and follower are designed to be as simple as possible while remaining reliable and free moving. The rail has a machined profile on each edge to create a V section, which allows the V groove bearings to securely travel along the path as shown in Figure 25. This is the only part that requires precise machining which will increase manufacturing costs, but it is necessary to guarantee the smooth operation of the mechanism. Four bearings hold the follower in place to ensure it cannot rotate or slip off the rail. The bearings are secured to a plate that holds them at a constant angle, matching the curve of the rail. The raised sections on both ends of the rail act as end stops, keeping the follower within its limit of travel and preventing it from falling off.

Due to the tight tolerances required in this area, weld nuts are pre-attached to the plate. This ensures the position of the bearings is correct within the holes, even after disassembling or replacing them. The vertical spacing between the bearings has a tolerance of ±0.5mm which would be specified to the manufacturer. Weld nuts also have the benefit of reducing the overall part count of the system, easing assembly, and ensuring they do not fall off or get lost. They can also be used in hard-to-reach areas with limited access to tools. For these reasons, weld nuts are also used in other areas in the assembly.

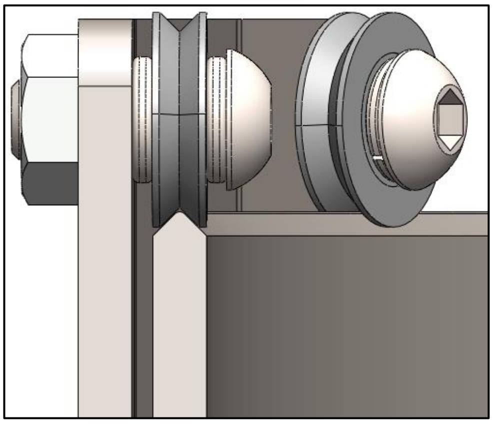

Figure 25: A close-up of the rail articulation

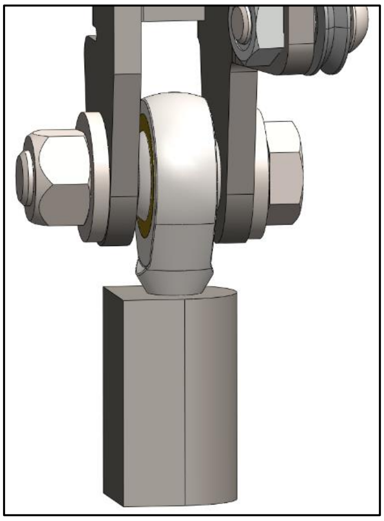

Figure 26: A close-up of the hip joint

The hip uses a rose joint to provide rotational freedom in all axes as shown in Figure 26. The main rotational axis is unrestricted, with the others having a lower range of motion. This increases the joint's ability to conform to the user's movement while remaining restricted enough to prevent collapsing. The rose joint is secured with an M8 bolt and nylon lock nut to prevent loosening. Attachment to the leg is provided by a threaded boss which is welded to the upper section of the leg. This allows for easy assembly without extra fixings.

When designing with sheet metal, tolerances are especially important to consider. Modern manufacturing techniques allow for a high amount of accuracy, but some variation will always be present, and the tolerance will depend on the type of feature. The edge profile of a part, including the outer perimeter and interior holes, will normally have a small amount of variation due to the reliable techniques used to cut the shape. This can include CNC laser, plasma or water jet cutting. Typical tolerances are within ±0.2mm. Larger variation is found in the position and angle of bends due to the greater variability in the process. Angles within ±1° and positions within ±0.5mm are usually standard [12]. Higher accuracy can be achieved but will usually come with additional manufacturing costs in order to perform checks. This has been considered when designing the waist system, with tolerance only specified where it is needed. This includes the rail profile and bearing spacing. Non-essential parts have been designed to accommodate for inaccuracy.

Certain design practices must also be followed for sheet metal parts, such as the proximity of holes and bends. A hole will deform if it is too close to a bend, so these features have been given adequate space as to not interfere. Tooling clearance has also been considered, for example where bends form a U shape, space has been left to allow the bend tool to retract after the operation.

Specific steel grades have been selected for the components. DC01 steel is a widely used European standard that is available in thicknesses up to 3mm and has good forming properties. Due to its low cost and reasonable strength, it is a good option for most of the sheet metal pieces.

6.2.2 Analysis

After analysing the pieces using FEA, it was found that the rear plate did not have sufficient strength when made from 3mm DC01 steel. For this reason, the material was changed to 4mm S275, another commonly used steel with slightly better mechanical properties and availability in thicknesses larger than 3mm.

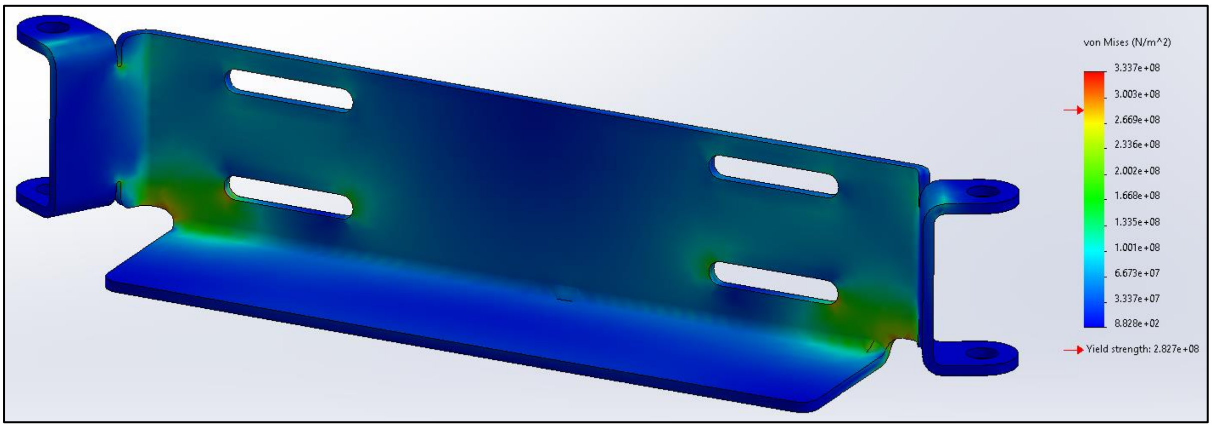

Figure 28: FEA results for 3mm DC01

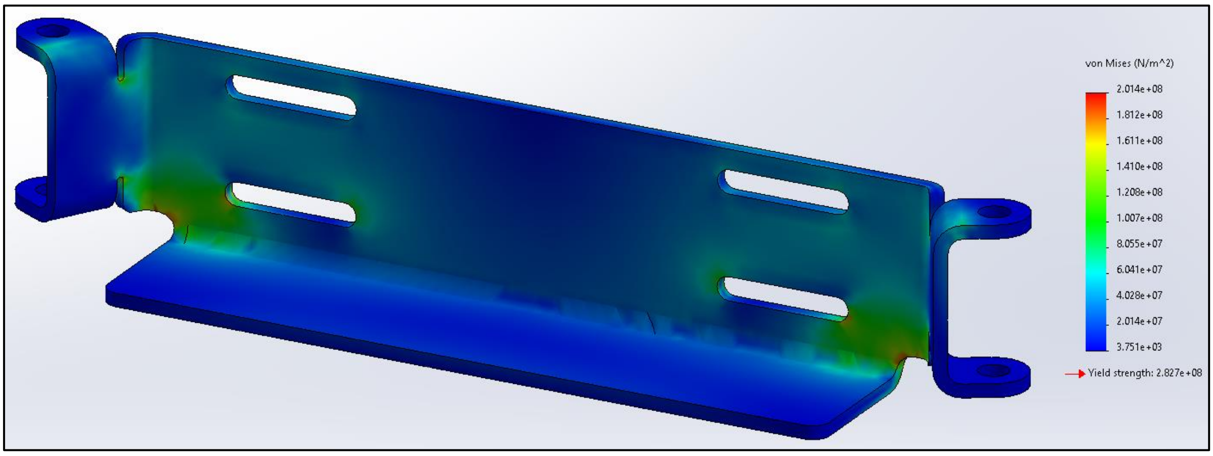

Figure 27: FEA results for 4mm S275

Figure 28 and Figure 27 show the FEA results for the rear plate using 3mm DC01 and 4mm S275 steel. The parts were tested with a simulated 100kg load resting on the rear mounting flange. This exceeds the 40kg load specified in the project requirements but ensures a factor of safety of at least 2 for static loading. Additionally, dynamic loading such as the movement of the backpack while walking could put additional force on the system. As shown, the DC01 material showed regions of stress which are higher than the yield strength of 283MPa, as well as a maximum deformation of 1mm. The results for S275 steel show significantly decreased maximum stress, as well as a maximum deformation of only 0.5mm. The mass increased from 628g to 835g, a difference of approximately 30%. FEA was also used to evaluate the rail and follower as these are subjected to significant forces. Both parts showed acceptable strength when using 3mm DC01 steel.

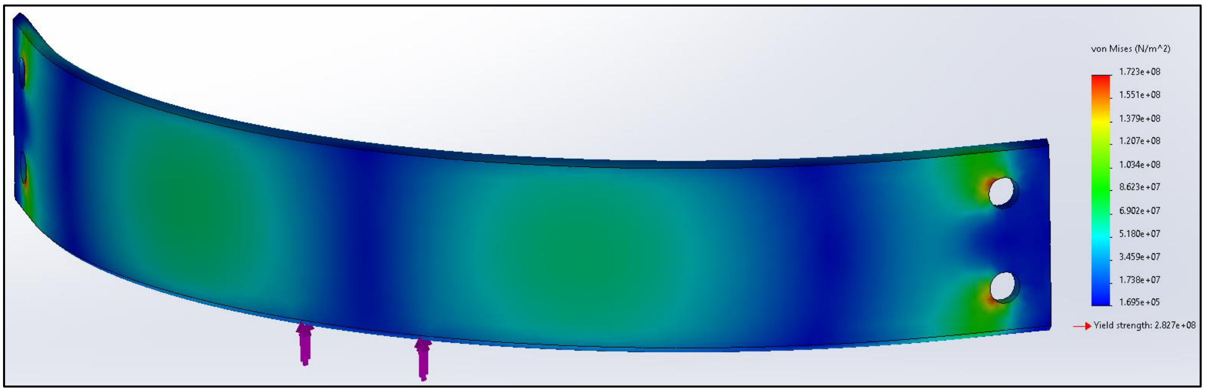

Figure 29: FEA results for the rail

Figure 29 shows the rail subjected to a 1000N force in the centre of its length, approximately simulating a 100kg load being supported by a single leg. The force was located at the centre of the rail, which would be the point of maximum bending stress. A maximum deformation of 0.2mm was observed, and the maximum stresses are significantly below the yield stress.

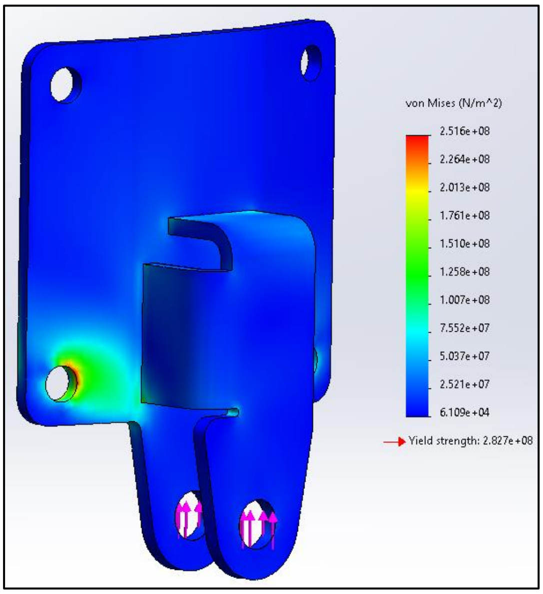

Figure 31: FEA results for the follower

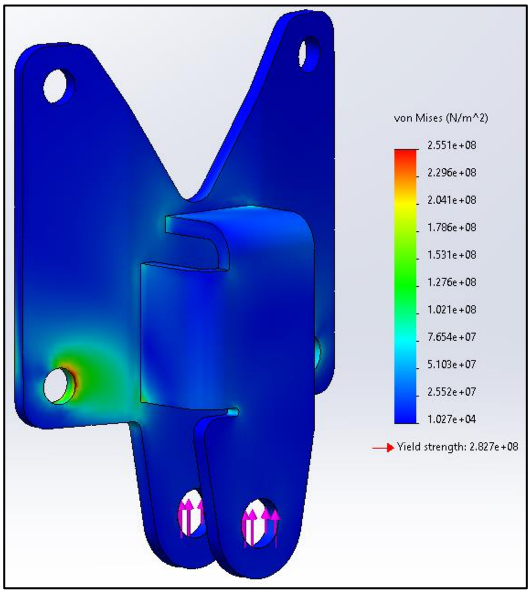

Figure 30: FEA results for the follower with additional weight saving

Similarly, Figure 31 shows the follower subjected to a 1000N vertical force on the hip joint. All the force is transferred to the lower bearings, as these are the only point in contact with the rails. A maximum deformation of 0.16mm was observed. Stress concentrations can be seen at the weld points between the two sheet metal pieces, which are joined with a single-sided fillet weld along the horizontal and vertical edge. A very small area around the bearing mounting holes is nearing the yield strength of the material, but the area would need to be significantly larger before the part would begin to yield. Based on these results, a small weight saving was made in an area of very low stress. The FEA results for this part are shown in Figure 30. There is effectively no difference in maximum stress and no additional stress concentrations, with an overall weight saving of approximately 40g.

The mechanism is designed to be easily serviceable by the user. All parts can be replaced with a minimum amount of work, especially possible wear components such as the bearings and rail. Assembly and disassembly can be performed with common tools, allowing field repairs if a malfunction were to happen during use. With all parts being open and accessible, the mechanism can be cleaned easily. This increases its effectiveness in harsh environments where water, mud and debris are present.

Allowing the user to replace parts themselves is beneficial for the sustainability of the system. Spare parts can be made available to buy, meaning the whole mechanism does not need to be discarded if a malfunction occurs. Additionally, the sheet metal and fixings can be easily recycled, greatly reducing the waste at the end of the product's life.

Figure 32:The Condor LCS Cobra® tactical belt [11]

Attachment to the user and adjustability is provided by a Condor LCS Cobra® tactical belt, shown in Figure 32. This is a high-quality belt that is designed to be load-bearing and used in outdoor environments. The durable materials and sturdy construction will provide comfort and durability. Alternatively, a custom fabric belt could be designed and manufactured to suit the needs of the project at a lower cost. If the product were to go into mass production this option would be considered but for a limited prototype the time and cost to do so outweigh the benefits.

The Condor belt features MOLLE-compatible attachment points which are used to secure the waist mechanism to the user. MOLLE is a recognised standard for modular tactical gear, meaning other items can also be attached. Short Velcro straps loop through the holes on the belt and sheet metal brackets, securing them together in 4 places. This method of attachment holds the waist assembly securely to the belt whilst also accommodating for a small amount of movement, increasing comfort for the user. The waist mechanism can also be completely removed when it is not needed.

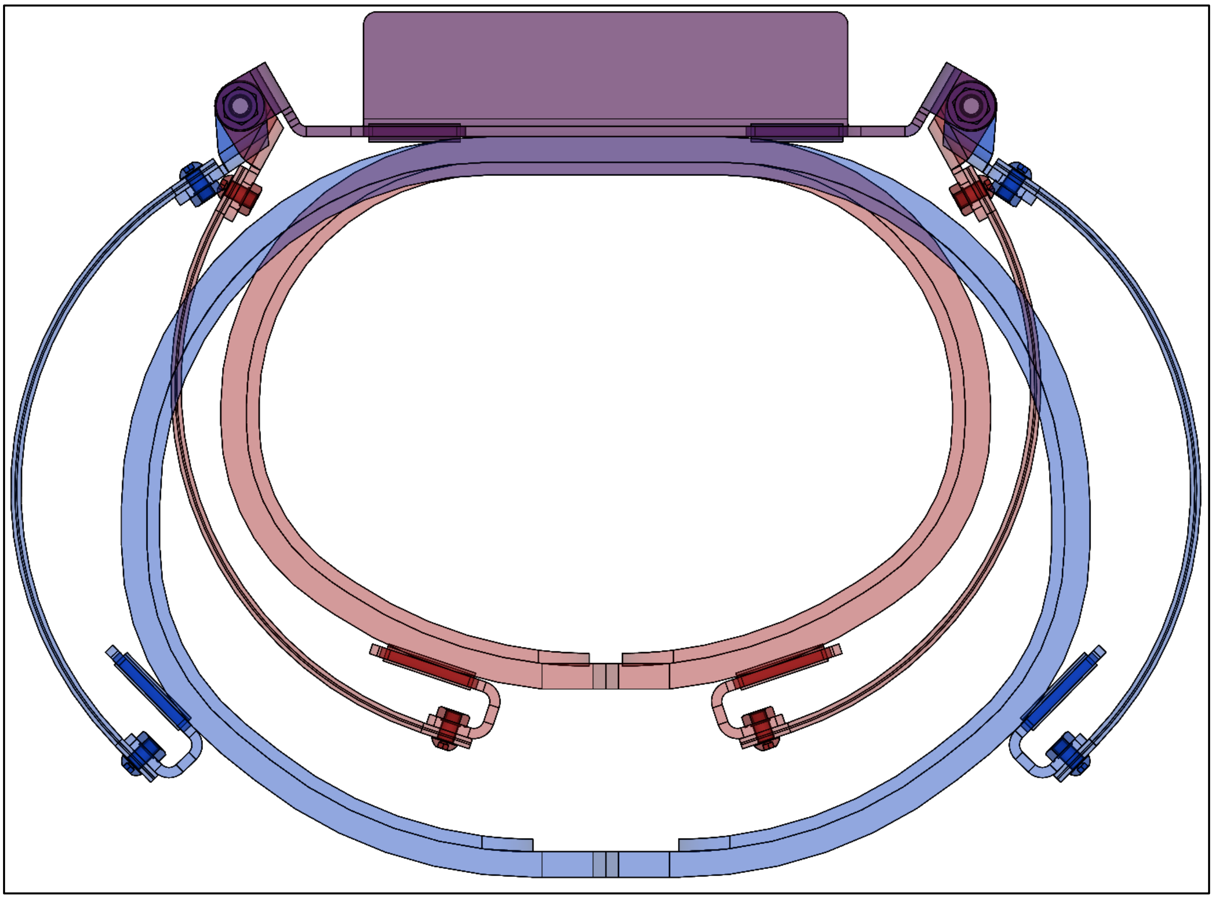

Figure 33: *The belt in smallest (red) and largest (blue) configurations, with the corresponding position of the rails*

The hinges attaching the rails to the rear plate allow the system to adjust to a range of waist sizes, as can the belt itself. *Figure 33* visually shows the adjustment range. Waist circumferences in the range of 76-102cm (30-40in) can be accommodated without significantly affecting the operation of the mechanism. This range was selected based on a 2012 study of US army anthropometrics [13]. The range correlates to the 5th-75th percentile of male waist circumference. The range is shifted towards the lower end of the normal distribution due to the nature of the target audience. People who carry heavy loads and walk long distances are more likely to have a lower waist circumference than average.

The adjustment process is designed to be simple and fast with a minimum number of steps:

- Detach the front connections using the Velcro straps
- Adjust the belt to fit the user's waist size
- Reattach the front connections to the appropriate points on the belt

6.3 Knee Joint (1948928)

6.3.1 Design

The knee joint is a simple rotational part working in one degree of freedom. The principle behind this design is to allow for low friction rotational movement akin to how a human leg works. Figure 34 depicts the general freedom of movement for a human knee joint. The figure shows how far out a human knee can extend, and therefore the joint was designed around this information. Figure 36 shows the assembled knee joint.

Figure 35 is an exploded, annotated, view of the knee joint. It shows all the components necessary to assemble the joint. The top link of the joint is to be connected to the exoskeleton thigh leg. The design uses three M5 bolts and nuts which will attach to the inner leg of the thigh part. The thigh link has a 5mm ± 0.5mm thickness of Aluminum, a length of 60mm ± 0.5mm and a width of 10mm ± 0.5mm. The thigh link is also connected to the main shaft of this part. The design features a press-fit to link to the shaft so the thigh link can rotate smoothly. The main linear shaft used in the knee joint is a 5mm (dia.) x 24mm (length) steel shaft. The linear shaft has a tolerance of h6 which means the shaft is produced with + 0mm - 0.008mm. This component has also been manufactured with a Rockwell hardness of 60 which is the ideal hardness for steel. The linear shaft's main function is to rotate the thigh link independently from the rest of the joint. This works using ball bearings.

The ball bearings are sealed, preventing dirt and dust ingress as well as preserving the lubrication in the bearings. The tolerance for this bearing is h6, which means the bearing will be a snug fit on the shaft. The aim is to slightly press fit the bearings onto the shaft which

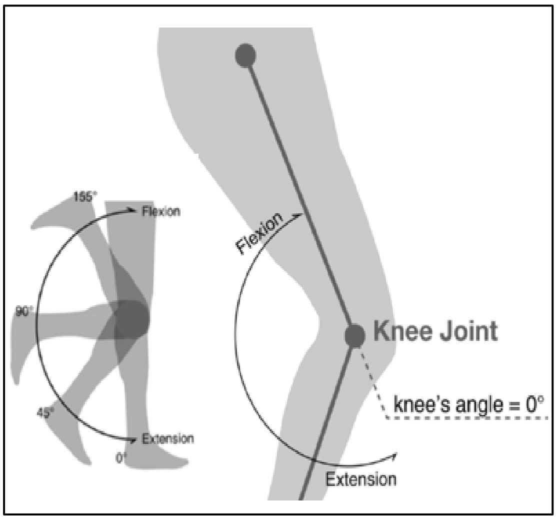

Figure 34: DoF for a Human Knee Joint [18]

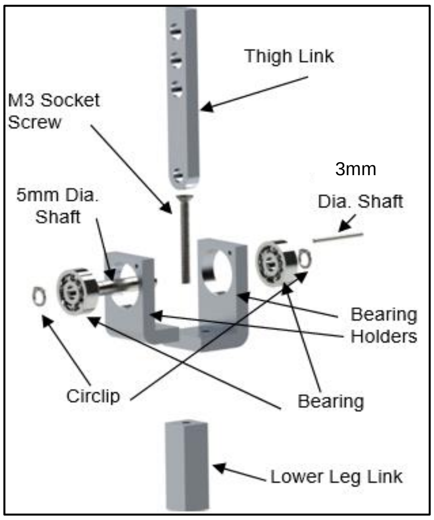

Figure 35: Exploded View of Knee Joint

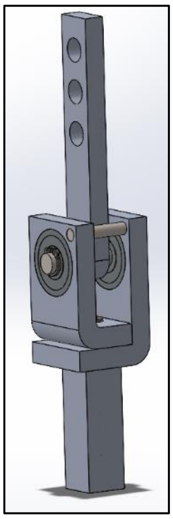

Figure 36: Assembled View

should prevent creep on the shaft. The datasheet for the ball bearing states that the static load is 0.675kN and the dynamic load is 1.729kN. The force that was calculated using FEA is less than both static and dynamic which means the bearings are suitable for this situation.

Even though the bearings are slightly press-fitted onto the shaft, the shaft can slide while in operation. To prevent this, the knee joint design includes two steel circlips attached to the ends of the main shaft. The circlips are designed to fit a 5mm shaft. The circlip requires the shaft to have a groove of 0.2mm which will be machined into the shaft using a lathe.

The bearing holders are the main body for the knee joint. The holders are 5mm thick Aluminum sheet metal folded to an 'L' shape. The sheet metal is folded to an angle of 90° ± 1° with the tolerance of the length, width, and thickness to be ± 0.5mm. The choice for the sheet metal bending was purely for the manufacturability of the bearing holders. It would cost more, and take more time, to use a solid block of metal to machine the part. One bracket is 5mm shorter to accommodate the thickness of the other bracket to place the two as shown in Figure 20.

The holders are secured together using an steel M3 hex socket countersunk screw. The screw will lock into the lower leg link shown in Figure 19. The lower leg link itself is an Aluminum block with a threaded hole through the entire body. This link is to be welded onto the inner lower half of the exoskeleton legs. This allows for the holders to be properly secured while effectively transferring the force.

The smaller shaft connects through the bearing holders shown in Figure 20. The purpose of this shaft is to prevent the knee joint from rotating 360° because a normal knee can only rotate in the positions shown in Figure 34. This feature aimed to create a "locking" function to prevent the user's legs from collapsing into each other while the user is walking. Figure 18 shows that the knee cannot bend past the extension range which is 0° to 45°. To allow for adjustability on different users' knees, the knee joint was designed to allow for an extra 3° of rotation in the extension range. The rotational range of the knee joint is depicted in Figure 37.

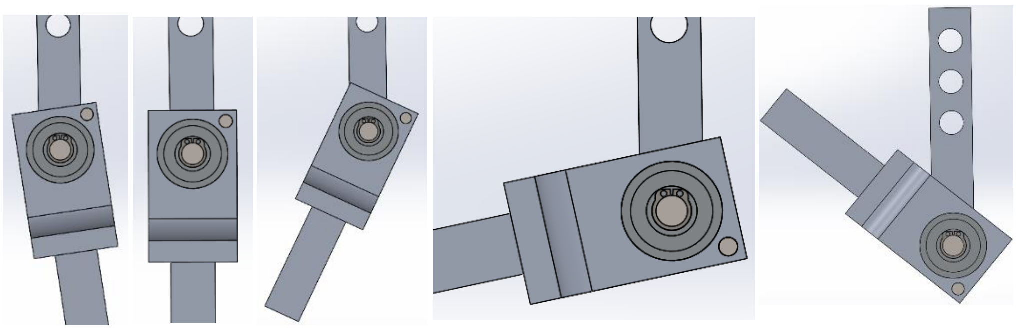

Figure 37: Rotational Range for Knee Joint

6.3.2 Analysis

Modelling the entire knee joint in FEA would require a lot of complex geometry. In order to make the analysis simpler, the knee shaft was the focus of FEA. The areas where the shaft is constrained by the bearings are defined as fixed supports with the force applied in the negative Y axis at the middle section. This is where the thigh link would attach to the main shaft. This configuration is demonstrated by Figure 38.

The force was calculated by multiplying the load of the backpack with gravity. For the min requirement of the backpack load (30kg), the force is 294.3N. Using this force, the total deformation has been calculated and is shown in Figure 39. From the image, the highest concentration of deformation is at the centre. This result makes sense as the main force is acting on the centre while the ends of the shaft are constrained. Regardless, the max value of deformation was 0.000747mm which is infinitesimal and within the elastic range of stainless steel.

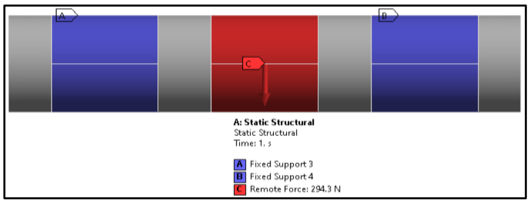

Figure 38: Configuration of Constraints and Force

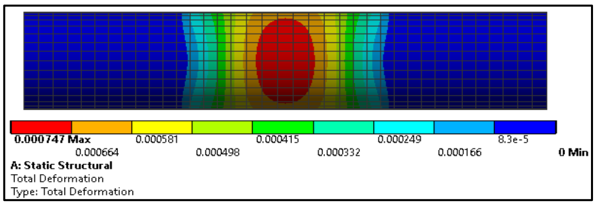

Figure 39: Total Deformation of Knee Shaft at 30kg

The next analysis conducted was the safety factor of the knee shaft over 1 billion life cycles. The results are shown in Figure 40. This figure shows that the lowest safety factor is 1.82 which means if the force was increased by more than 82% the part would fail. To further the analysis, deformation, shear strain, and safety factor for a range of force values were calculated. The project brief stated the load range for the backpack to be 30kg-40kg, however, the analysis was conducted for the range of 30kg-50kg (for which results can be found in Table 15). By doing the extra 10kg, the results can reflect what would happen to the joint if the load was increased before use. This could be due to an unexpected factor during the operation of the exoskeleton. As the results show, the max limit of the specified load (40kg) produced a force of 394.2N which resulted in a deformation of 0.001mm and a safety factor of 1.37. Going further, at 50kg (490.5N), the deformation is 0.00125mm and safety factor is 1.09. To conclude, by increasing to 40kg or 50kg, the knee joint is not affected. Both deformations can be considered negligible, although increasing past an estimated 54kg should cause the part to fail. Nevertheless, the design for the knee joint is suited for the given task.

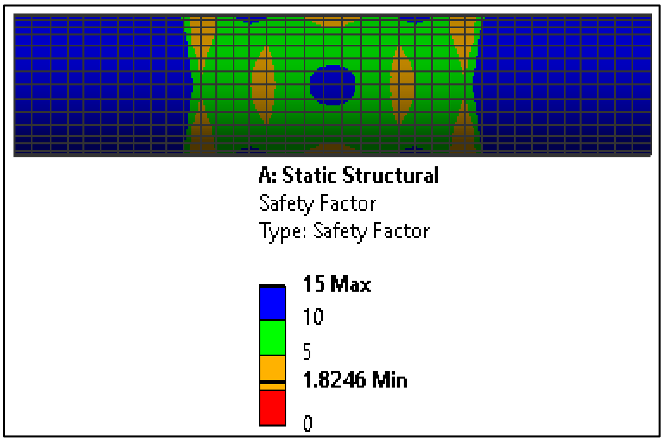

Figure 40: Safety Factor for Knee Shaft at 1 billion Cycles

Table 15: Table of Results for a Range of Backpack Loads

Backpack Load (Kg)	Force (N)	Deformation (mm)	Safety Factor	Shear Strain (mm/mm)
30	-294.3	0.00075	1.82461267	0.000298094
31	-304.11	0.00077	1.765754196	0.000308031
32	-313.92	0.00080	1.710574387	0.000317967
33	-323.73	0.00082	1.658738794	0.000327903
34	-333.54	0.00085	1.609952367	0.00033784
35	-343.35	0.00087	1.563953722	0.000347776
36	-353.16	0.00090	1.520510571	0.000357713
37	-362.97	0.00092	1.479415659	0.000367649
38	-372.78	0.00095	1.440483679	0.000377586
39	-382.59	0.00097	1.403548189	0.000387522
40	-392.4	0.00100	1.368459508	0.000397459
41	-402.21	0.00102	1.335082431	0.000407395
42	-412.02	0.00105	1.303294771	0.000417332
43	-421.83	0.00107	1.27298556	0.000427268
44	-431.64	0.00110	1.244054085	0.000437205
45	-441.45	0.00112	1.216408445	0.000447141
46	-451.26	0.00115	1.189964781	0.000457078
47	-461.07	0.00117	1.164646398	0.000467014
48	-470.88	0.00120	1.140382921	0.00047695
49	-480.69	0.00122	1.117109831	0.000486887
50	-490.5	0.00125	1.094767588	0.000496823

6.4 Ankle Joint (1805565)

6.4.1 Overview

The ankle joint is a major component in the exoskeleton system. The purpose of the ankle joint is to transfer load from the lower exoskeleton leg to the foot clamp without hindering the ankle mobility of the wearer. The ankle joint must allow freedom of rotation around 3 axes to replicate the rotational freedom of the human ankle. A combination of off the shelf components as well as custom machined parts are used in the ankle joint design to maximise the capability of the joint while minimising the manufacturing cost of the exoskeleton.

6.4.2 Attachment to exoskeleton leg

Figure 26 displays a rendering of the complete ankle joint assembly. The ankle joint of the exoskeleton connects to the exoskeleton leg (coloured red in Figure 41) via two M5x8 Torx head screws. The two screws locate through through-holes in the exoskeleton leg and are tightened into threaded holes in the uppermost component of the ankle joint assembly to a torque of 12Nm. This bolt torque was chosen as it is large enough to prevent the screws from working lose while the exoskeleton us in use, without risking damaging the threads in the exoskeleton. The screws and threaded holes can be observed in Figure 42, labelled as “leg and bearing inner race attachment component”. This method of attachment of the ankle joint to the leg allows for easy maintenance of the exoskeleton as the ankle joint can be quickly removed by removing the two screws using only basic tools. 6061 aluminium was selected for this component as it exhibits high corrosion resistance, high strength compared to other aluminium alloys a low density compared to steel [14] [15] allowing the component to be considerably lighter than it would have been if steel had been used. The high corrosion resistance of the material will prevent the part from corroding if it is exposed to water or other contaminates.

Figure 41: Computer Rendering of the complete ankle joint assembly.

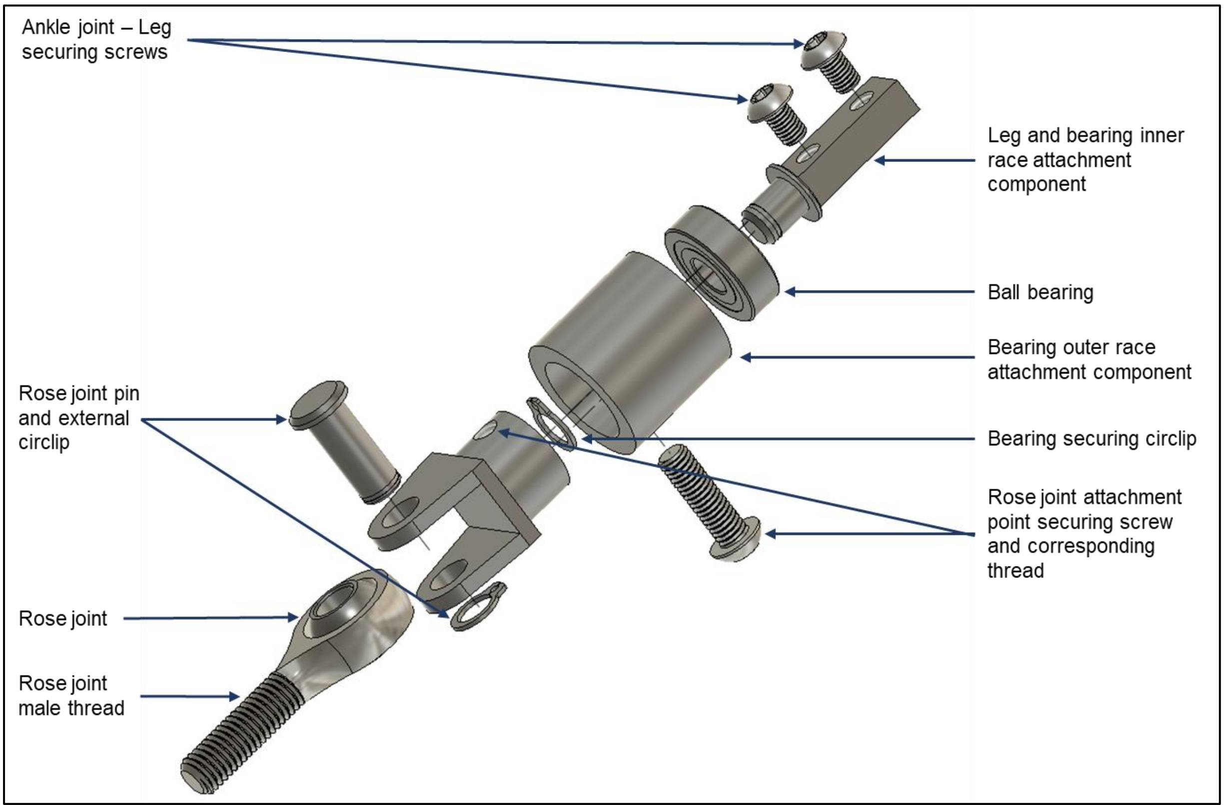

Figure 42: Exoskeleton ankle joint exploded view.

6.4.3 Ball bearing and bearing attachment

Figure 43 displays a diagram of the three axes of rotation permitted by the ankle joint. These three axes allow the exoskeleton ankle joint to mimic the rotational freedom of the human ankle joint. To allow for freedom of rotation of the ankle joint in the 'B' axis, the design includes a SKF W 608-2Z sealed, permanently lubricated ball bearing. The location of the ball bearing in the ankle joint assembly can be observed in Figure 42. The leg attachment component of the ankle joint features a protruding 8mm diameter shaft with a notch close to the end of the shaft. This shaft has a clearance fit with the inner race of the bearing allowing the bearing to slide onto the protruding shaft. The bearing is secured in place by a circlip that fits onto the notch on the shaft to prevent the bearing from moving along the shaft. The shaft diameter at the notch was 7.4mm, the circlip chosen for the application was designed to fit an 8mm shaft with a 7.4mm notch. The bearing is secured in the other direction by a sudden widening in the diameter of the protruding shaft. This allows the face of the inner race to evenly contact the face of the sudden widening on the shaft.

The outer race of the ball bearing is secured to the bearing outer race attachment component via friction. This component was dimensioned to give an interference fit between the inner walls of the bearing outer race attachment component and the outer race of the bearing. This assembly can be seen in Figure 42. 6061 aluminium was also selected for this component due to the same material properties that made it suitable for the exoskeleton leg attachment component. A ball bearing was used to provide rotation about this axis as a it provides very little resistance to rotation, even when subject to the axial loads seen during the use of the exoskeleton. A sealed bearing was chosen to prevent the ingress of dust and other foreign material to the bearing while the exoskeleton is used in harsh environmental conditions. A permanently lubricated bearing was chosen to reduce the maintenance required on the exoskeleton, as it will not need to be lubricated periodically.

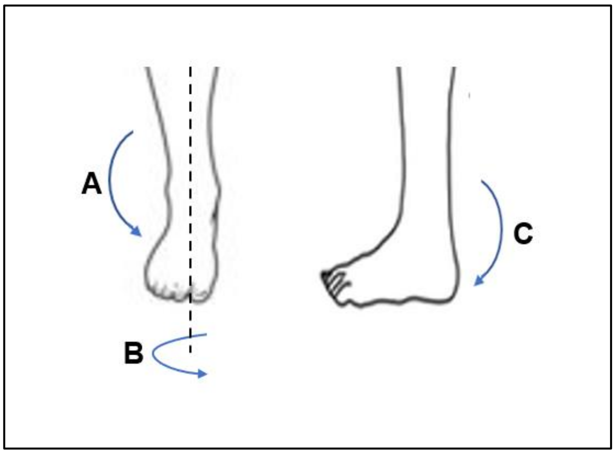

Figure 43: Diagram showing the three-axis of rotation allowed by the ankle joint. Adapted from [19]

6.4.4 Rose Joint attachment component

The rose joint attachment component (designed to be manufactured from 6061 aluminium) is rigidly fixed to the ball bearing outer race attachment component by a single M6x20mm Torx head screw. A through-hole is present in the bearing outer race attachment component while a threaded hole is present in the rose joint attachment component. A threaded screw is tightened into this thread after passing the through-hole in the bearing outer race attachment component. This screw is tightened to prevent movement between the two components. The design includes a torque of 16Nm for this screw as this torque will prevent the screw working lose while the exoskeleton is in use, without damaging the thread in the rose joint attachment component. The rose joint attachment component and the ball bearing outer race attachment component must be detachable from one another to allow for installation, or removal of the circlip that secures the ball bearing. The rose joint is secured to the rose joint attachment component via a shaft with a notch and external circlip. The nominal shaft diameter is 8mm, the shaft was given design tolerances to give an interference fit between the rose joint and shaft. A notch of diameter 7.6mm was used to secure the circlip in place. This assembly can be seen in Figure 42.

6.4.5 Rose Joint (Rod End)

A rose joint is a component that allows for limited rotation of components in two axes, while allowing unlimited rotation in the third axis. In the configuration used in the design, the rose joint allows for a large degree of rotation in the axis donated ‘C’ in Figure 43, and a small degree of rotation in the ‘A’ axis. The male shaft of the rose joint connects directly to the ‘Foot clamp’ component of the exoskeleton. The location of the rose joint in the ankle joint assembly can be observed in Figure 42. A steel off the shelf rose joint (rod end) was selected for the design to reduce manufacturing cost of the exoskeleton. The rose joint featured an 8mm ID bore, a length of 45mm and an external, standard pitch M6 thread.

6.4.6 Analysis

FEA analysis was conducted on the rose joint attachment component to simulate the equivalent stress and total deformation that would be experienced by the component while under load in the exoskeleton system. To make the results comparable to those obtained from FEA analysis of the hip joint, the part was tested under a load of 100kg to give a static loading safety factor of greater than 2.5. This safety factor counts for momentary higher stresses that may be observed on the exoskeleton during a trip or fall by the wearer of the exoskeleton. Figure 44 and Figure 45 display the FEA results for the equivalent (Von-Mises) stress and total deformation respectfully. The figures show that no region of the part experiences stress above the 6061 aluminium yield stress of 241MPa. As a result, it can be expected that no permanent deformation of the part will occur from normal loading of the exoskeleton system. Figure 29 shows that very little deformation of the part will occur under load with a maximum part deformation under the 100kg load of 1.66µm.

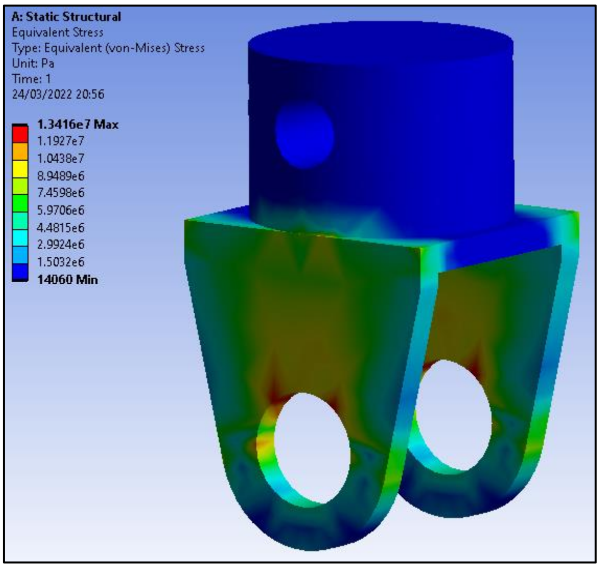

Figure 44: FEA results of equivalent stress of the rose joint attachment component

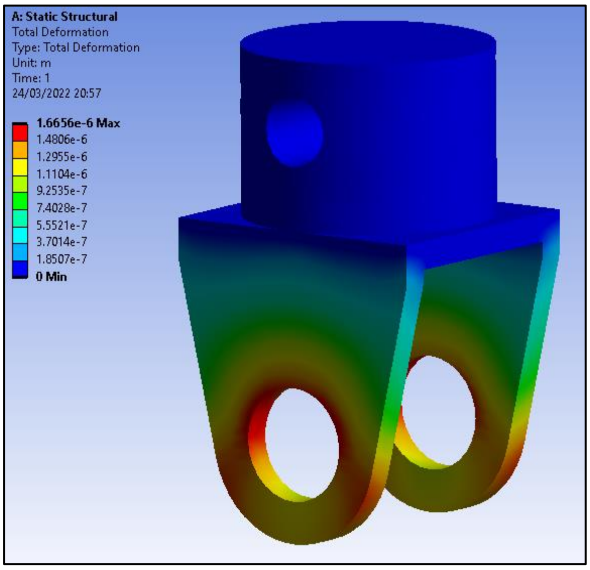

Figure 45: FEA results of total deformation of the rose joint attachment component

Under normal use, the load supported by the exoskeleton will be transferred to the ground through the exoskeleton. As a result, when the exoskeleton is supporting the maximum load of 40kg, a load of 392N (40kg x 9.91m/s^2) will be transferred axially through the ball bearing located in the ankle joint. The SKF bearing chosen for the application was rated a maximum static axial load of 780N [16]. Using equation 1, it was calculated that the bearing has a safety factor of 1.99 (780N / 392N = 1.99) in this application.

The same maximum load of 392N will also be transferred through the rose joint. The RS pro rose joint chosen for the application has a maximum rated static load of 4800N [17]. Again using equation 1, it was calculated that the rose joint has a safety factor of 12.2 (4800N / 392N = 12.2). As a result, it can be confidently stated that neither the ball bearing or rose joint will fail under normal use of the exoskeleton.

$$Safety\ Factor = \frac{Maximum\ Allowable\ Load}{Design\ Load} \qquad (1)$$

6.5 Foot Clamp (1906405)

The foot clamp clamps around the rear of the user's shoe, and therefore thick-soled shoes such as walking boots are required. If the user does not wear thick-soled shoes the clamp is unlikely to grip the user's shoe and it will be uncomfortable. This will result in the exoskeleton not moving with the user and therefore will be ineffective. The main body of the foot clamp will be 3D printed from PLA and this will make the foot clamp lightweight and cheap to produce while maintaining the required strength.

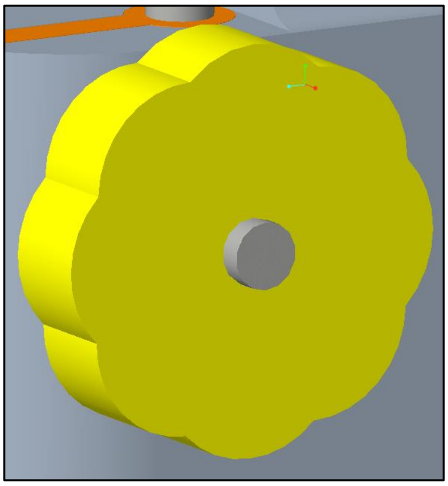

Figure 46: Shows the adjustment wheel

The foot clamp can be adjusted using the wheel shown in Figure 46. The wheel is made from 3D printed PLA, and it is grooved to make it easier to grip and turn. While the wheel was designed to be large enough for a human hand to twist it may still be too small for some people, however, its size was limited by the height of the foot clamp. The wheel is connected to the rod via a screw, which sits flush with the surface of the wheel to avoid injuring the user.

The wheel rotates a rod (made from nylon) that is supported by a bearing - which will be a bought part. The rod is given clearance within the foot clamp to stop friction. A bearing was

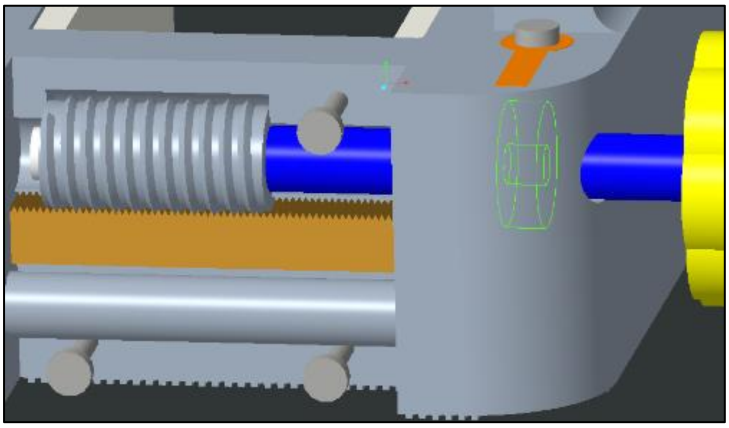

Figure 48: Shows the worm gear, rod (in blue), bearing (highlighted in green) and rack (in orange) – all with the back panel removed.

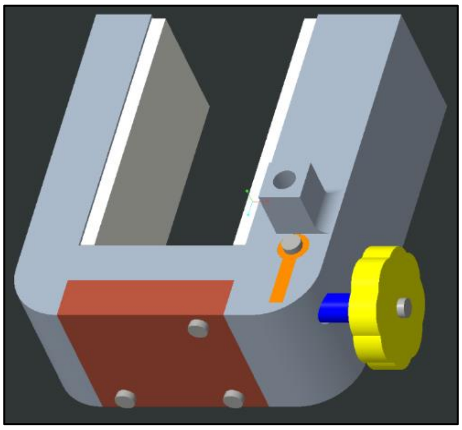

Figure 47: Shows the entire foot clamp while it is at its minimum width

chosen to allow the rod to rotate freely and reduce friction. The bearing will increase the weight of the foot clamp, but the ease of rotation is worth the drawback

The orange rack shown in Figure 48 screws into the top of the foot clamp to allow the bearing to be accessed for cleaning and replacement. This is important because the environment in which the exoskeleton will be used is likely to involve mud and water which can cause additional wear on the bearing.

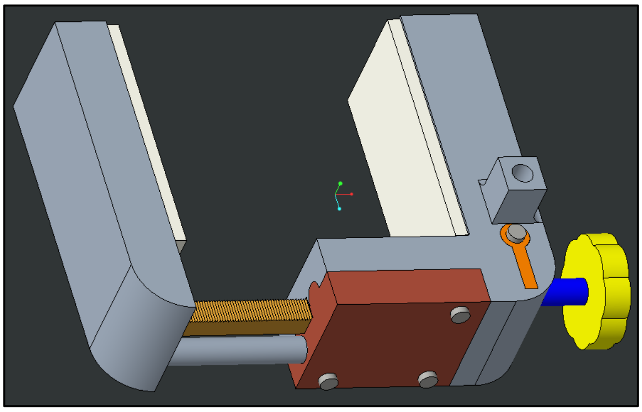

Figure 49: Shows the entire foot clamp while it is at its maximum width.

The rod is connected to a worm gear that moves a rack, and this will be purchased. The worm gear was chosen to give a mechanical advantage to the user to allow the user to tighten the clamp against their foot more effectively, improving the connection. In addition to this, the worm gear prevents the rack from driving the motion and therefore keeps the foot clamp tight during use. Using the worm gear was an expensive choice, but the benefits outlined outweigh the cost. The worm gear is made from steel. This is because it is likely to be a wear point and using steel will help reduce this. In addition, the worm wheel, while possible to replace, will be difficult and therefore the worm wheel must have a long-life expectancy. The range of adjustment is shown in Figure 47 and Figure 49.

The rack (which will be bought as a part, made from plastic) is connected to the left side of the foot clamp (using a screw) and as the wheel is rotated the left side of the foot clamp is moved either away or towards the right side of the foot clamp. This allows wider shoes to be inserted into the clamp and subsequently tightened. While the width of the foot clamp was designed with as many people as possible in mind due to limitations of space and parts that could be bought, the range of the width of the clamp will not encompass all people. The range of widths that the foot clamp provides is from 60mm to 120mm (this does not include the thickness of the neoprene grips, as it is assumed that these will be compressed against the shoe and are therefore negligible).

The bottom of the clamp is lined with small lumps to increase the surface area of the clamp and therefore improve grip. This is important as the exoskeleton is likely to be used in off-road applications. The lumps on the

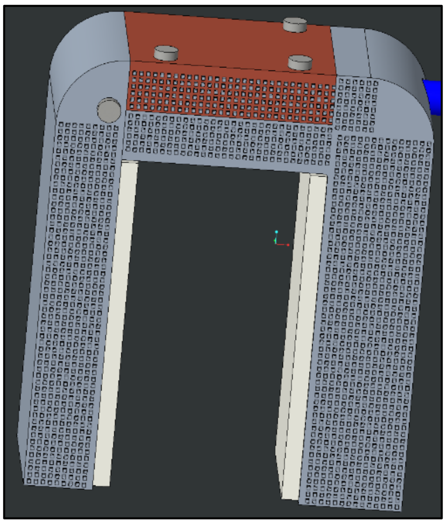

Figure 50: Shows the bottom of the foot clamp with the small lumps and large surface area. The neoprene rubber can also be seen in white.

bottom will also help to distribute the weight of the loaded exoskeleton to the ground.

The foot clamp was designed with a large bottom surface area in mind to help spread the weight of the load. This is important because the environment in which the exoskeleton will be used is likely to involve mud and unfavourable terrain which will require additional grip.

The inside sides of the clamp are lined with neoprene rubber to increase the friction between the shoe and foot clamp. This will also help the clamp mould to the user's shoe and therefore increase the grip through the increased surface area. This will prevent the clamp from coming loose from the user's shoe and therefore improve the usability of the exoskeleton.

The clamp mechanism is designed with easy cleaning in mind, as the exoskeleton will often be in wet and muddy conditions. As a result, the clamp mechanism may get dirty and full of water - requiring a clean. The panel on the back can be easily unscrewed to allow the user to flush out the mechanism with water (if required) and re-apply lubricant (if required) this will increase the life span of the clamp mechanism and prevent the mechanism from seizing.

The rack can also be unscrewed and replaced if it snaps or wears out. However, to combat the rack breaking, two guide rods (3D printed as part of the left part of the foot clamp) have been implemented to prevent the rack from solely preventing all the rotation between the left and right sides of the clamp. This is a cheap alternative to buying a metal rack, as it increases the strength of the mechanism. This is also a lighter alternative and therefore the more effective option.

7 Bill of Materials

Waist			
Part Name	Qty	Cost/unit	Total cost
Deep Groove Bearing, 16mm Diam	8	£1.550	£12.40
M6 x 16 Bolt	8	£0.040	£0.32
M6 x 10 Bolt	8	£0.030	£0.24
M8 x 35 Bolt	2	£0.110	£0.22
M8 x 65 Bolt	2	£0.150	£0.30
M6 Weld Nut	16	£0.030	£0.48
M8 Lock Nut	4	£0.040	£0.16
M6 Washer	16	£0.005	£0.08
M8 Washer	6	£0.040	£0.24
M8 Rose Joint	2	£1.920	£3.84
18mm Steel Bar, 60mm Length	1	£1.620	£1.62
70000mm^2 Steel Sheet, 3mm Thick	1	£10.000	£10.00
Condor belt	1	£35.950	£35.95
			£65.85

Ankle Joint			
Part Name	Quantity	Per Unit	Total Price Per Part
M5 X 8mm T25 Torx Button Screws (ISO 7380) - Stainless Steel (A2)	2	£0.48	£0.96
M6 X 20mm T30 Torx Button Screws (ISO 7380) - Stainless Steel (A2)	1	£0.63	£0.63
SKF Deep Groove Ball Bearing - Plain Race Type, 8mm I.D, 22mm O.D	1	£15.68	£15.68
RS Pro M6 x 1 Male Steel Rod End, 6mm Bore Size,	1	£12.89	£12.89
Steel External Circlip, 8mm Shaft Diameter, 7.6mm Groove Diameter	2	£0.06	£0.11
RS PRO Aluminium Square Bar, 20mm W, 20mm H	1	£22.01	£22.01
			£52.28

Foot Clamp			
Part Name	Quantity	Cost/unit (INC VAT) (£)	Cost (INC VAT) (£)
Gear Rack, 250mm Long, 9mm Width	2	£9.42	£18.84
Worm Gear, 18mm Diam	2	£4.70	£9.40
Steel Pan Head Self Tapping Screw, 25mm Length	12	£0.05	£0.56
Deep Groove Bearing, 19mm Diam	2	£4.25	£8.50
Nylon Rod, 10mm Diam, 1m Length	2	£2.00	£3.99
Self Tapping Screw, 51mm Length	2	£6.87	£13.74
Neoprene Grippers	2	£0.11	£13.74
			£68.77

Part Name (3D printed)	Quantity	Mass per part (kg)	Cost (INC VAT) (£)
Foot holder right	2	0.304	£14.53
Foot holder left	2	0.196	£9.38
Rear cover	2	0.0396	£1.89
Twist handle	2	0.0162	£0.78
Bearing cover	2	0.000758	£0.04
			£26.62

Knee			
Part Name	Quantity	Per Unit	Total Price Per Part
5mm Linear Shaft x 45mm	1	£1.07	£1.07
Ball Bearing	2	£1.99	£3.98
Circlips	2	£0.06	£0.12
M3 Hex Socket Screw	1	£0.34	£0.34
M5 Hex Bolt	3	£0.18	£0.54
M5 Hex Nut	3	£0.09	£0.27
5mm Aluminium Sheet Metal (100mm x 50mm)	1	£6.73	£6.73
10mm Square Aluminium Bar x 30mm	1	£0.17	£0.17
			£13.22

Backpack Interface						
Manufacturing Cost						
Parts	Volume (mm^3)	Material	Rate (per 105 mm3)	Cost	Quantity	Total Cost
I bracket Attachment	192895	Steel	£13.40	£25.85	1	£25.85
Ajustable Plate	290802	Aluminum	£4.81	£13.99	1	£13.99
Pin	1936.18	Aluminum	£4.81	£0.09	1	£0.09
Rotational Clips (20 mm)	368.57	Aluminum	£4.81	£0.02	2	£0.04
Rotational Clips (17.5 mm)	326.521	Aluminum	£4.81	£0.02	4	£0.06
Cuboidal Plate	58007.8	Carbon Fibre	£24.75	£11.70	4	£46.78
						£86.81

Parts	Rate (per unit)	Quantity	Total Cost
Spring	£0.12	1	£0.12
Straps	£0.59	1	£0.59
			£0.71

Grand total
£314.26

8 Conclusion

Having performed a literature review and reviewed the concepts designs, the design that has been chosen has managed to meet all the design requirements outlined in the brief and specification. Since the final design has met all these requirements, it is ready for manufacture.

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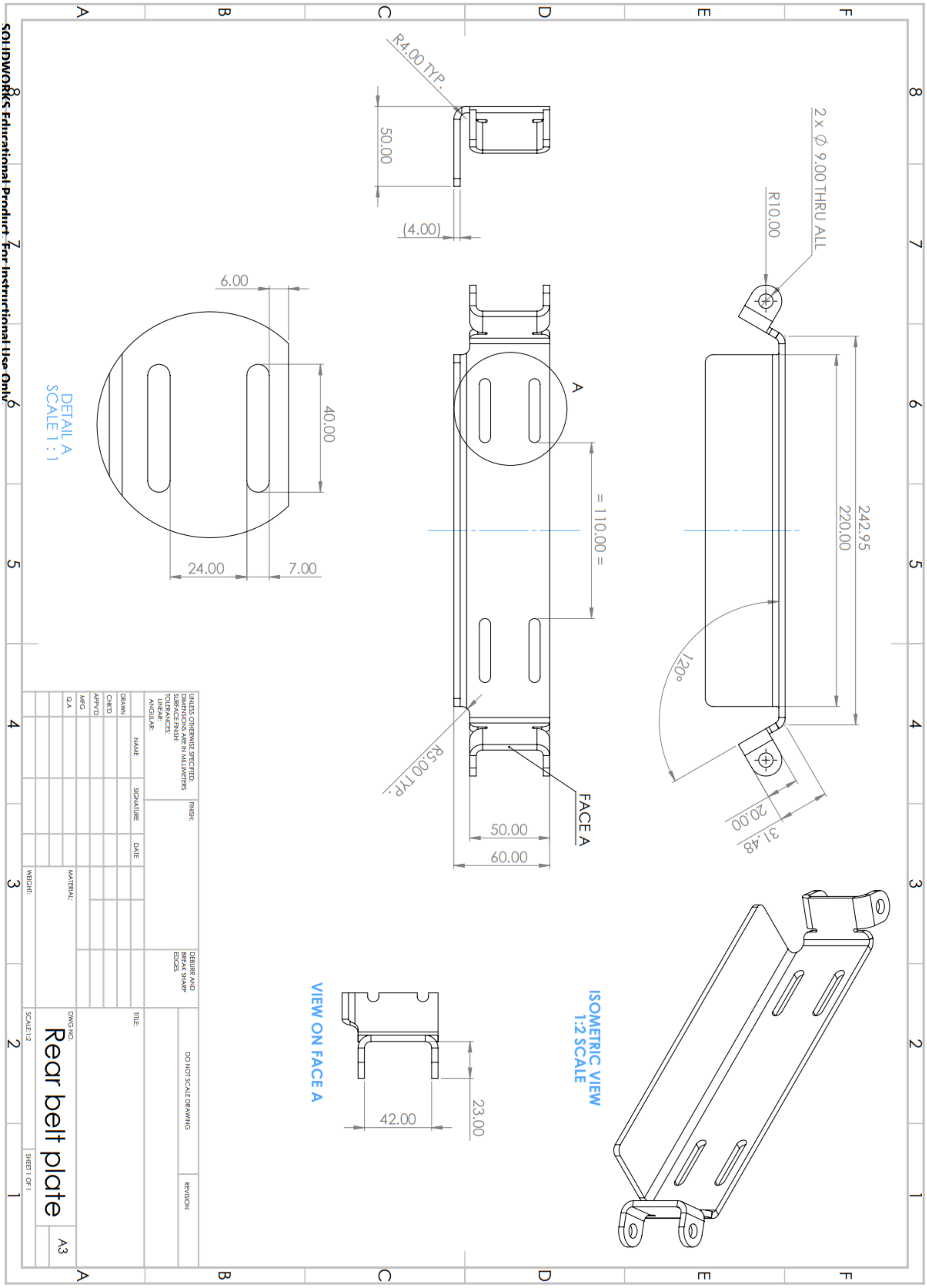
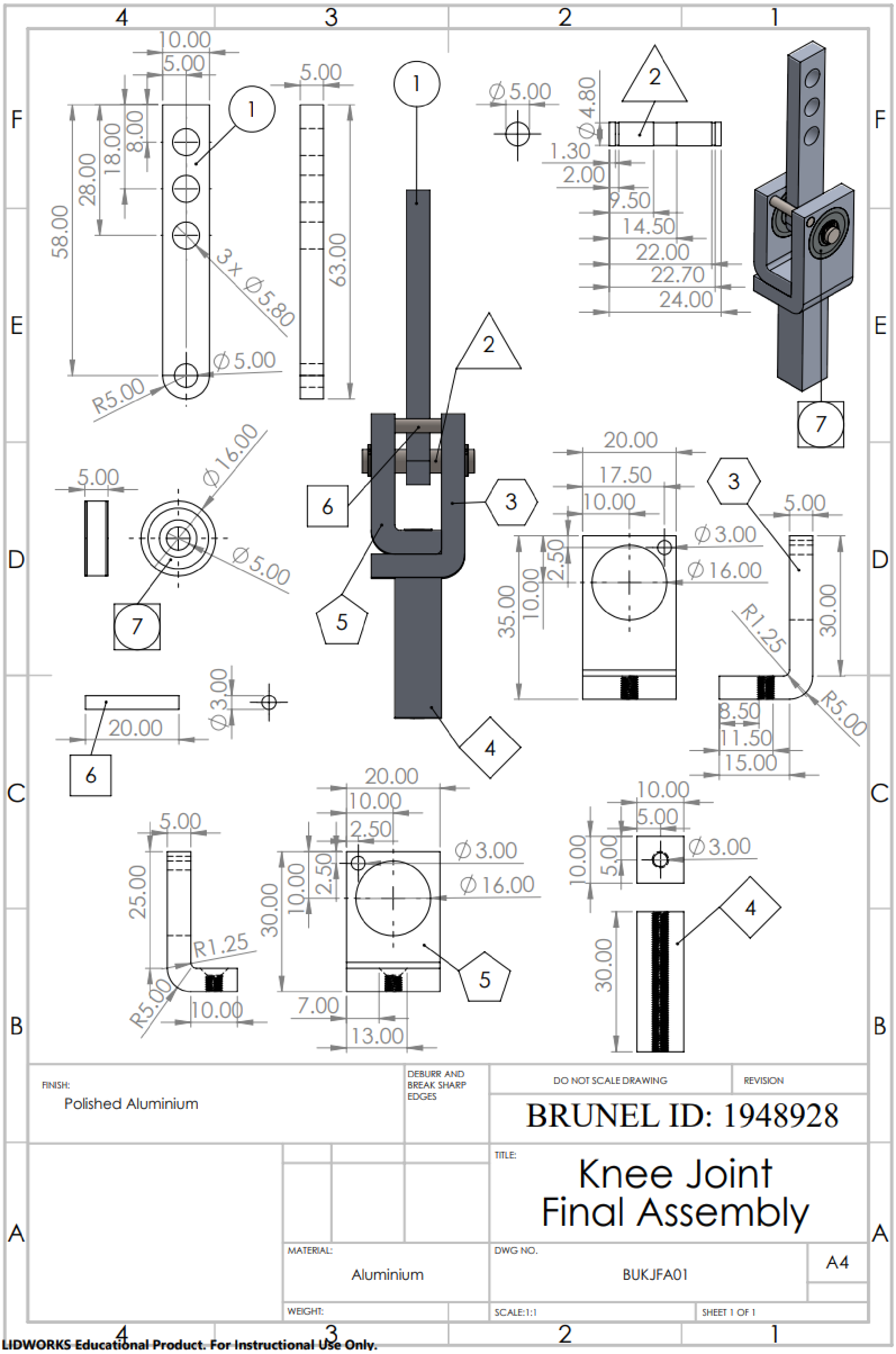
10 Appendix A – Technical Drawings

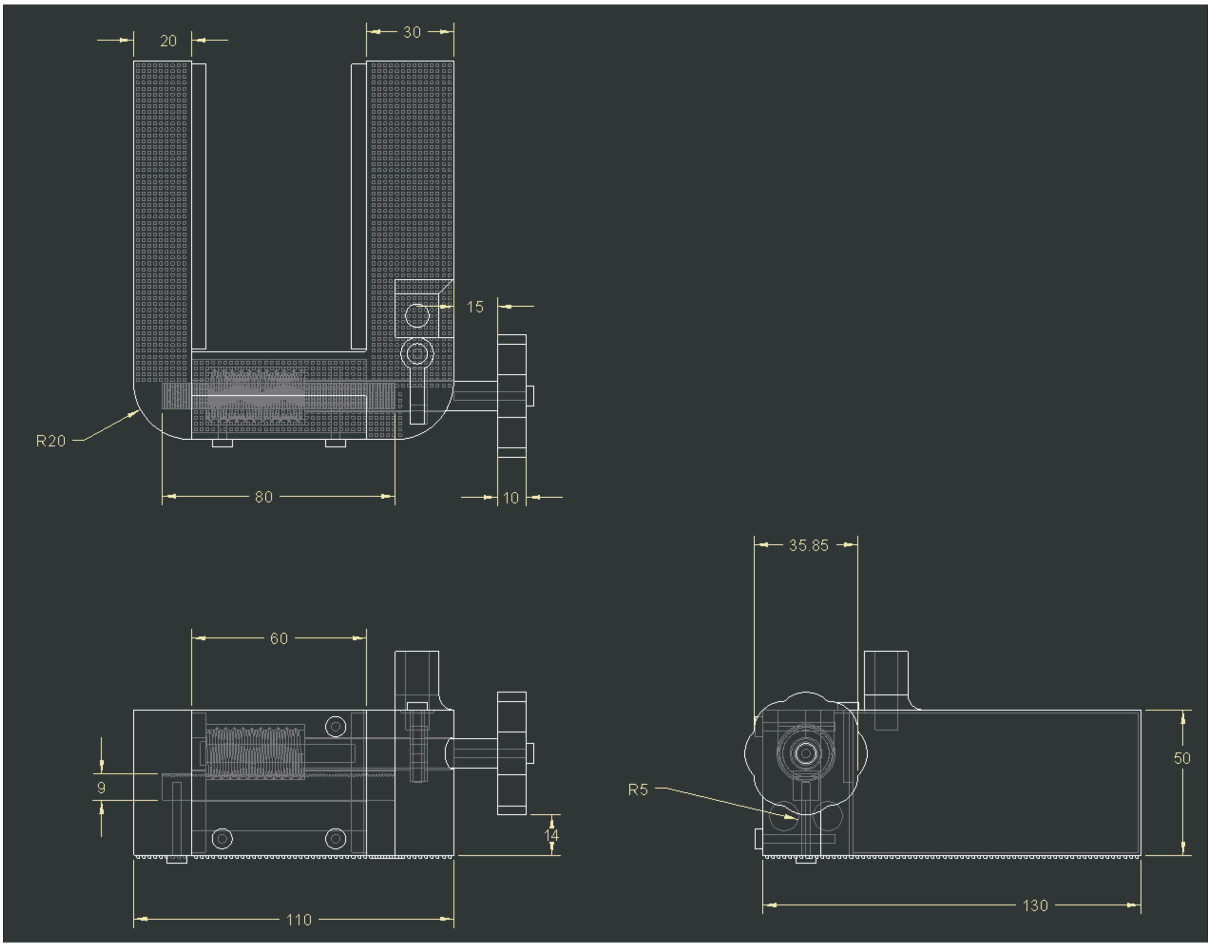
10.1 Waist rear plate (1820772)



10.2 Knee joint (1948928)



10.3 Foot clamp (1906405)



11 Appendix B – Weekly review sheets

BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN			
ME3623 GROUP DESIGN PROJECT			
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT			
Group: Q13		**Date: 18/01/22**	
Students Present:		**Signatures:**	
1	Jack Pledger		
2	Jayvratsinh Jadeja		
3	Aaron Blanco		
4	Rory Henderson		
5	Sam Gray		
6	Lamim Ruhid		
Students Absent:			
1		3	
2		4	

Report on Progress During the Previous Week

Objectives/Activities	Student
Research/concept knee joint	Jack Pledger
Research/concept hip joint	Jayvratsinh Jadeja
Research/concept foot/ground contact	Lamim Ruhid
Research/concept frame/materials	Rory Henderson
Research/concept backpack/load interface	Sam Gray
Research/concept body connection/adjustment	Aaron Blanco

Please turn over

Problems Encountered		
N/A		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Literature review on current passive exoskeleton designs, prepare ideas for brainstorming next week	All

Supervisor's Signature	Group	Date
SIGNED COPIES TO BE APPENDED TO FINAL REPORT		

BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN			
ME3623 GROUP DESIGN PROJECT			
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT			
Group: Q13		**Date: 25/01/22**	
Students Present:		**Signatures:**	
1	Jack Pledger		
2	Jayvratsinh Jadeja		
3	Lamim Ruhid		
4	Rory Henderson		
5	Aaron Blanco		
6	Sam Gray		
Students Absent:			
1		3	
2		4	

Report on Progress During the Previous Week	
Objectives/Activities	Student
Literature review on current passive exoskeleton designs, prepare ideas for brainstorming next week	All
Please turn over	

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments: Aaron was not able to attend Tuesday but shared research		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Research/concept knee joint	Jack Pledger
Research/concept hip joint	Jayvratsinh Jadeja
Research/concept foot/ground contact	Lamim Ruhid
Research/concept frame/materials	Rory Henderson
Research/concept backpack/load interface	Sam Gray
Research/concept body connection/adjustment	Aaron Blanco

Supervisor's Signature	Group	Date
SIGNED COPIES TO BE APPENDED TO FINAL REPORT		

BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN

ME3623 GROUP DESIGN PROJECT

OBJECTIVE REVIEW SHEET
SIGNED COPIES TO BE APPENDED TO FINAL REPORT

Group: Q13		**Date: 01/02/22**
Students Present:		**Signatures:**
1	Jack Pledger	
2	Jayvratsinh Jadeja	
3	Aaron Blanco	
4	Rory Henderson	
5	Sam Gray	
6	Lamim Ruhid	

Students Absent:

1		3	
2		4	

Report on Progress During the Previous Week

Objectives/Activities	Student
Research/concept knee joint	Jack Pledger
Research/concept hip joint	Jayvratsinh Jadeja
Research/concept foot/ground contact	Lamim Ruhid
Research/concept frame/materials	Rory Henderson
Research/concept backpack/load interface	Sam Gray
Research/concept body connection/adjustment	Aaron Blanco

Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week
(To be achieved/completed before the next weekly meeting)

Activity	Student(s)
Specifications, project requirements	Lamim
Compiling literature review	Rory, Aaron
Compiling concept generation and selection	Sam
Concept CAD design	Jack, Rory
Further ankle joint research	Jack, Jay

Supervisor's Signature	Group	Date
SIGNED COPIES TO BE APPENDED TO FINAL REPORT		

BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN			
ME3623 GROUP DESIGN PROJECT			
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT			
Group: Q13		**Date: 08/02/22**	
Students Present:		**Signatures:**	
1	Jack Pledger		
2	Jayvratsinh Jadeja		
3	Aaron Blanco		
4	Rory Henderson		
5	Sam Gray		
6	Lamim Ruhid		
Students Absent:			
1		3	
2		4	

Report on Progress During the Previous Week

Objectives/Activities	Student
Specifications, project requirements	Lamim
Compiling literature review	Rory, Aaron
Compiling concept generation and selection	Sam
Concept CAD design	Jack, Rory
Further ankle joint research	Jack, Jay

Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments: Aaron was not able to attend Tuesday		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Specifications, project requirements	Lamim
Compiling literature review	Rory, Aaron
Compiling concept generation and selection	Sam
Concept CAD design	Jack, Rory
Further ankle joint research	Jack, Jay

Supervisor's Signature	Group	Date
SIGNED COPIES TO BE APPENDED TO FINAL REPORT		

BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN
ME3623 GROUP DESIGN PROJECT
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT

Group: Q13		**Date: 15/02/22**
Students Present:		**Signatures:**
1	Jack Pledger	
2	Jayvratsinh Jadeja	
3	Aaron Blanco	
4	Rory Henderson	
5	Sam Gray	
6	Lamim Ruhid	

Students Absent:

1		3	
2		4	

Report on Progress During the Previous Week

Objectives/Activities	Student
Specifications, project requirements	Lamim
Compiling literature review	Rory, Aaron
Compiling concept generation and selection	Sam
Concept CAD design	Jack, Rory
Further ankle joint research	Jack, Jay

Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Waist and hip joints CAD	Jack
Knee CAD, Design spec	Lamim
FEA Writeup	Rory
Ankle joint CAD	Sam
Literature review	Aaron
Backpack interface and length adjustment CAD	Jay

Supervisor's Signature	Group	Date
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BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN
ME3623 GROUP DESIGN PROJECT
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT

Group: Q13		**Date: 22/02/22**
Students Present:		**Signatures:**
1	Jack Pledger	
2	Jayvratsinh Jadeja	
3	Aaron Blanco	
4	Rory Henderson	
5	Sam Gray	
6	Lamim Ruhid	

Students Absent:

1		3	
2		4	

Report on Progress During the Previous Week

Objectives/Activities	Student
Waist and hip joints CAD	Jack
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FEA Writeup	Rory
Ankle joint CAD	Sam
Literature review	Aaron
Backpack interface and length adjustment CAD	Jay

Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Waist and hip joints CAD	Jack
Knee CAD	Lamim
Foot clamp CAD	Rory
Ankle joint CAD	Sam
Literature review	Aaron
Backpack interface and length adjustment CAD	Jay

Supervisor's Signature	Group	Date
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ME3623 GROUP DESIGN PROJECT			
OBJECTIVE REVIEW SHEET SIGNED COPIES TO BE APPENDED TO FINAL REPORT			
Group: Q13		**Date: 01/03/22**	
Students Present:		**Signatures:**	
1	Jack Pledger		
2	Jayvratsinh Jadeja		
3	Aaron Blanco		
4	Rory Henderson		
5	Sam Gray		
6	Lamim Ruhid		
Students Absent:			
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Report on Progress During the Previous Week	
Objectives/Activities	Student
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Knee CAD	Lamim
Foot clamp CAD	Rory
Ankle joint CAD	Sam
Literature review	Aaron
Backpack interface and length adjustment CAD	Jay
Please turn over	

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
Waist and hip joints CAD, Technical writeup	Jack
Knee CAD, Technical writeup	Lamim
Foot clamp CAD	Rory
Ankle joint CAD, Technical writeup	Sam
Literature review	Aaron
Backpack interface CAD	Jay

Supervisor's Signature	Group	Date
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BRUNEL UNIVERSITY LONDON – MECHANICAL ENGINEERING ME3623 ENGINEERING SYSTEMS DESIGN			
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Group: Q13		**Date: 08/03/22**	
Students Present:		**Signatures:**	
1	Jack Pledger		
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Ankle joint CAD, Technical writeup	Sam
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Backpack interface CAD	Jay
Please turn over	

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
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ME3623 GROUP DESIGN PROJECT

OBJECTIVE REVIEW SHEET

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Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	**~~No~~**
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
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Technical writeup	Lamim
Technical writeup	Rory
Technical writeup	Sam
Literature review	Aaron
Technical writeup	Jay

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3	Aaron Blanco		
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Report on Progress During the Previous Week

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Technical writeup	Lamim
Technical writeup	Rory
Technical writeup	Sam
Literature review	Aaron
Technical writeup	Jay

Please turn over

Problems Encountered		
Progress as Planned?	**Yes**	~~**No**~~
Comments:		

Objectives/Activities for next week (To be achieved/completed before the next weekly meeting)	
Activity	**Student(s)**
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Technical writeup	Lamim
Technical writeup	Rory
Technical writeup	Sam
Literature review	Aaron
Technical writeup	Jay

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