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Structural Analysis Framework

2021 ALEX Team

Advanced Lower-Extremity Exoskeleton

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Exoskeleton Framework

Table of Contents

1 Introduction

This document demonstrates a methodology to evaluate the structural integrity of a lower-limb exoskeleton that is designed for assisting the person with paraplegia to walk. The inspiration of the evaluation method mainly comes from an international standard – ISO 22685, Prosthetics – Testing of ankle – foot devices and foot units – Requirements and test methods.

However, there are several differences between the ankle- foot devices/ foot units and the low- limb exoskeleton that this document has considered. Adjustments are made in the methodology. The differences include:

1. Due to the structural complexity that comes from the numerous components of an exoskeleton, comparing to the devices (without any rotational joints with actuators) tested in the prosthetics standard, further research has been conducted and additional assumptions are made.
2. As the exoskeletons are expensive, destructive testings are replaced by Finite Element Analysis (FEA).
3. The gait of using exoskeleton by a pilot with spinal injury is different from the gait of an amputee using prosthetic ankle-foot device owing to the involvement of the crutches and how the device supporting the user.

Finally, it must be noted that this document tackles the common structural design (more details in Scope section) of the lower- limb exoskeletons. Additional analysis may be required to ensure the structure integrity if the design of the exoskeleton varies from the common structural design.

In this document, Section 2 will provide background knowledges of the exoskeletons and some insights on the possible application of this framework.

Section 3 includes the literature review of the development team has done to support the development of this framework.

Section 4 and 5 are the methodology of calculating the forces the components of the exoskeleton are bearing.

Section 6 reveals the adjustments of the forces that should applied on FEA.

Section 7 provide some evaluations on the analysis performances of this framework and recommendations on the future development of the exoskeleton structural safety analysis beyond this framework.

Section 8 is the conclusion emphasising the goals of developing this framework and the approach that is used to accomplish them in this framework.

2 Scope

2.1 Classes of Exoskeleton and Generalization

This framework provides methodology for the analysis for an assistive bipedal exoskeleton that uses two crutches for stability. Usually, this type of exoskeletons can be classified as assistive and non-transparent. Assistive means that it will move the pilot; in comparation to rehabilitative to allow people to relearn walking after injury. While transparency dictates how much the pilot can move against the force applied by. Within a transparent exoskeleton a pilot can move the motors of the exoskeleton with the motion of their body, while within a non-transparent exoskeleton a pilot can move against the motion.

Though an assistive and non-transparent exoskeleton is designed primarily for people that are unable to move their legs only, such as people with spinal cord injury. However, the exoskeleton could be modified to become more transparent through system code editing and be able to rehabilitate patients such as who had a stroke before. The framework focusses on non-transparent mode of the exoskeleton, but the same analysis can be applied on a transparent mode exoskeleton to make sure its safety as well. Since the patient with spinal cord injury fully rely on the exoskeleton, the force acting on the exoskeleton is larger than the force acting on the exoskeleton by the patient used for rehabilitation.

This framework can be applied to exoskeletons with similar structure consisted of the following components:

1. The backpack that is attached to the back of the pilot.
2. L shape lengths that are extended from the backpack to sides of the body covering the hip of the pilot.
3. Lengths that are attached to the outside of the thighs.
4. Lengths that are attached to the outside of the calf.
5. Foot plates that are attached to the foot soles.
6. the exoskeleton is fastened onto the pilot’s legs, hips, and chest; while they hold two crutches that allow them to stabilise themselves.

The framework evaluates the structurally integrity of exoskeletons operating the following conditions:

- Step forward/backward.
- Step so feet are together.
- Go from sitting and standing positions.

The exoskeleton is not designed for high impact loading such as running and jumping.

2.2 Possible application of the framework

This framework fully focuses on the structural analysis of exoskeletons. The ultimate goal of applying this framework is determined by the users. Some of the possible goal examples are: 1. Redesigning components to eliminate redundant mechanical designs, 2. Ensuring the structural integrity before installing new designed parts for operation and 3. Assisting in development of a completely new exoskeleton during design phase

Some of the data gathered by following the instructions in this framework such as the force measurements can be transferred to other exoskeletons but there will be variations in properties based on other factors. The estimated forces could be transferable to other exoskeletons, with similar motion, as it is expected that the system will experience similar forces from the typical human pilot. These forces can be applied to other system specific CAD files and the stress concentrations will be calculated; based on its dimensions. The analysis will specify if failure occurs within the system. The areas of highest stress will be the main points of failure; either from yielding causing plastic deformation or the development of cracking from fatigue. Within these areas of high stress, there will need to be a focus on ensuring structural integrity for safety. If the safety factor can be considered too low, then the design will be modified such as increasing local thickness. This will allow to iterate on the design to make the system safe. Alternatively, the framework can find out the redundant mechanical design areas of the exoskeleton and redesigning them to minimise the weight of the exoskeleton and reduce the production cost.

2.3 Other Relevant Standard

2.3.1 Robots and robotic devices

The standards for exoskeletons are less developed compared to other similar fields such as prosthetics. The most relevant introductory standard for the purposes of this framework, ISO 13482 *Robots and robotic devices — Safety requirements for personal care robots* (International Organization for Standardization, 2014) gives some recommendations on various aspects of safety. While this includes factors such as durability, that will be useful for structural analysis, it also includes many other factors such as energy storage and posture of the pilot. The factors being considered for durability are the stresses, properties of materials, vibrations, environmental conditions (such as heat) and extreme cases for forces or misuse. However, this standard only provides the factors that need to be considered and does not provide a methodology for analysis. Therefore, this standard simply provides general concepts on the safety requirements of an exoskeleton and the initial direction of the framework development. This framework will develop methods to evaluate the effects of some of the factors mentioned in clause 5.11.1 of this standard. Specifically, it will include the mechanical stresses and material properties that will potentially introduce hazards due to insufficient durability.

2.3.2 Prosthetics

Compare this to ISO 22675 *Prosthetics — Testing of ankle-foot devices and foot units — Requirements and test methods* (International Organization for Standardization, 2016), that specifically give a three-step method for testing prosthetics. Initially, testing with a force for normal operations, and then, a higher force that simulates sudden or unexpected motions, and finally, a cyclic loading to simulate fatigue. This is done by testing specific samples of the prosthetics and checking if failure has occurred at any of these stages. The initial operation was done with a representative force of the system with a 1.75 safety factor. The second test was done similarly with a force 1.5-2 times larger than the initial static force. Finally, the fatigue test was done with the initial static force applied for cycles. These three tests cover all the possible types of stresses (static loading, impact loading and cyclic loading) that would potentially introduce mechanical failures in the exoskeletons. However, destructive tests can be costly, especially for robotic parts. Therefore, instead of conducting the destructive tests on a real exoskeleton, simulation software should be utilised to conduct these three analyses. So, this framework will build on this standard by adapting its proposed tests for use on exoskeletons.

3 Background

The goal of this project is to propose loading conditions for FEA analysis of exoskeletons. To do so, this literature review focuses on two categories in the literature. First, a model-based dynamic analysis of the loads undertaken during exoskeleton gait, including a description of the crutch-based gaits commonly employed in exoskeletons, as well as existing models in the literature. Secondly, this review analyses existing professional standards in the literature for similar technological-based medical devices.

3.1 Gait

Walking gait is a cycle of coordination movements controlled by continuous human lower limb joint rotations. To identify the critical point (the location most likely to introduce a defect) and find out the corresponding forces and torques under a worst-case scenario (a specific instant during the gait), the motions of every link must be investigated. It is because the design of exoskeletons for paraplegics always involves application of crutches for balancing purpose (two different crutch- based gait types will be introduced in the section 3.2), different forms of gait can be examined with each having a different impact load on the foot plate of the exoskeleton. Modified three-point crutch gait and four-point crutch gait are commonly used by different lower limb exoskeleton designs such as ReWalk (Zeilig, et al., 2012) and Ekso Bionics (The Engineer UK, 2011).

3.2 General gait cycle

To evaluate the static internal forces using the Newton-Euler equations, the free body diagram must be drawn, which requires the orientations of the exoskeleton's links to be defined. Because of the variety of the gait design of different exoskeletons, it is assumed that the postures of all exoskeletons follow what is known as the general gait cycle.

Although the individual gait pattern will be influenced by age, personality, mood, and sociocultural factors, eight phases (Physiopedia, 2021) can always be observed from the walking cycle of a healthy human which are illustrated in Figure 3 (Lineage Medical, Inc., 2021). 60% of the time of the gait cycle is in the standing phase which begins at the instant that the foot touches the ground, and the body is supported by both feet. The rest of the time belongs to the swing phase with single foot support. The motion of the gait is completed by rotating the ankle, the knee, and the hip simultaneously with the changes of angles in Table A. With the working rotation range of every joint mentioned in Table A, every possible angle combination that the exoskeleton will conduct during the walk can be extracted to find out the maximum loading acting on each specific link.

Joints	Standing phase				Swinging phase			
	Heel Strike	Foot Flat	Mid stand	Heel off	Toe off	Acceleration	Mid-swing	Deceleration
Ankle	$0°$	$5°\ PF$	$10°\ DF$	$0°$	$20°\ PF$	$10°\ PF$	$0°$	$0°$
Knee:	$0°$	$15°$	$5°$	$0°$	$30°$	$60°$	$30°$	0
Hip:	$20° Flex$	$15°\ Flex$	$0°$	$15° Ext$	$20°\ Ext$	$20°\ Flex$	$20°\ Flex$	$30°\ Flex$

Table A. Change of joint positions during the walk

* PF: Plantarflexion, DF: Dorsiflexion, Flex: Flexion, Ext: Extension (joint movements)

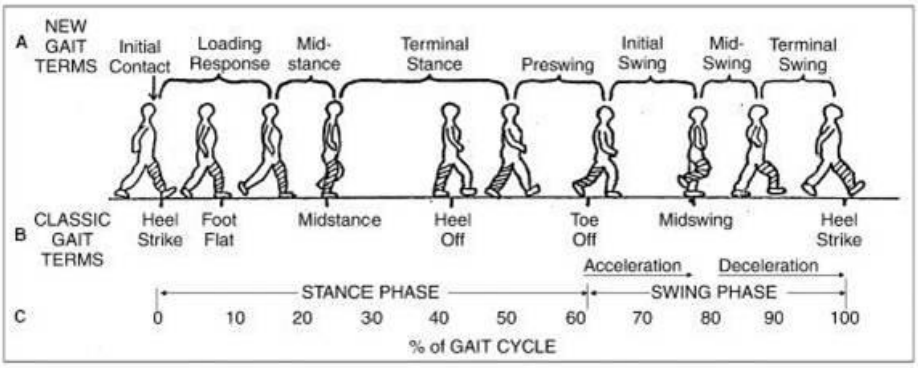


Figure 1. Graphical explanation of a gait cycle, (Lineage Medical, Inc., 2021)

3.3 Three-point crutch gait

In general, normal three-point crutch gait is used when one side of the lower extremities is unable to bear weight. The gait cycle proceeds as follows:

1. The gait begins under the tripod standing position with the crutches placed slightly outside the feet in front of the patient as in Figure 2 (Brookside Associates Medical Education Division, 2008)
2. The weak foot and the crutches are advanced at the same time while the strong foot supports the weight.
3. The patient leans on the crutches and moves the weak foot forward, slightly behind the crutches.
4. The strong foot is advanced parallel to the weak foot again.
5. Step 2 to 4 are then repeated for another gait cycle.

The postures of the patient when conducting the three-point crutch gait are visualised in Figure 3 (Walk Easy Inc, 2019). In contrast to normal three-point crutch gait, the exoskeleton pilot alternates the standing foot for every step. After conducting step 2 of the normal three-point crutch gait, the body weight support is shifted from the rear foot to the front foot. The crutches and the rear foot can move forward simultaneously to process another step.

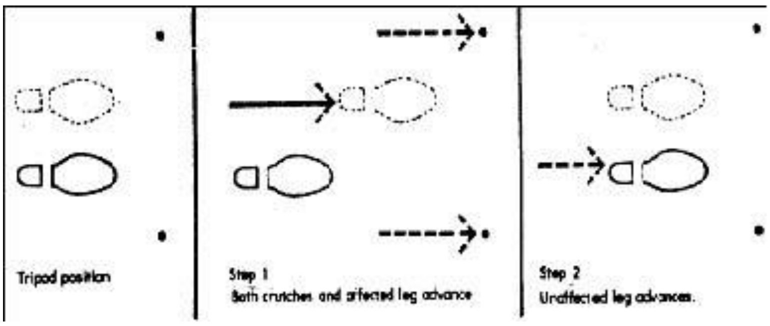


Figure 2. 3-point crutch walking gait, (Brookside Associates Medical Education Division, 2008)

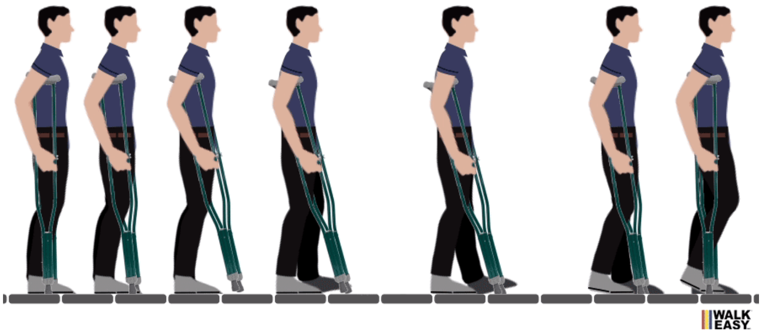


Figure 3. Side view of normal three-point crutch gait, (Walk Easy Inc, 2019)

3.4 Four-point crutch gait

Compared to three-point, the four-point crutch gait pattern is more stable and more suitable for patients with poor balance or coordination (Physiopedia, 2021). It is easier for the exoskeleton pilot to complete gait cycles because only one supporting point moves forwards at any time. The gait cycle proceeds as follows:

1. The crutches are placed slightly outside of the parallel standing feet in front of the patient.
2. One crutch is moved forwards.
3. The opposite foot is advanced and lands slightly behind the advanced crutch.
4. The other crutch is moved to somewhere slightly in front of the advanced crutch to complete one gait cycle.
5. Step 2 to 4 are then repeated for another gait cycle.

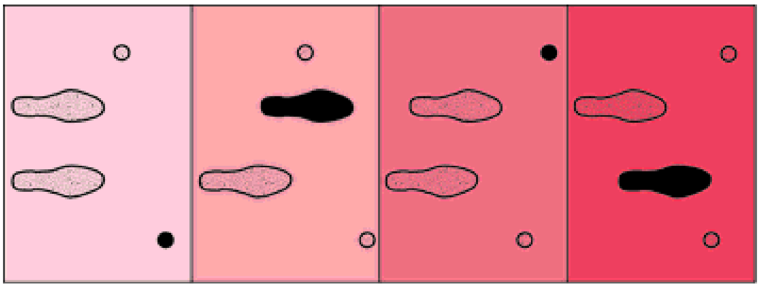


Figure 4. 4-point crutch walking gait, (Farlex, Inc., n.d.)

3.5 Equations of Motion

Equation of motion can be derived by using various approaches including Lagrangian, Newton Euler and joint space expressions. Lagrangian equation of motion (eq.1) expresses the movement of the systems in terms of potential and kinetic energy. The required forces and torques (τ) generated by the motors equal to the difference of the kinematic energy gain and the potential energy loss.

$$\tau = \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{Q}}\right) - \frac{\partial T}{\partial Q} + \frac{\partial V}{\partial Q} \quad \text{...(eq.1)}$$

$Where$:

$$T = Kinetic\ energy$$

$$V = Potential\ energy$$

$$Q = linear\ or\ angular\ displacement\ of\ the\ joint$$

$$\dot{Q} = linear\ or\ angular\ velocity\ of\ the\ joint$$

Newton Euler equation of motion (eq. 2&3) analyses the kinetics and kinematics of every individual link (rigid body) respectively. Although the analysis is more complex than other approaches, internal forces and moments are evaluated in the kinetic side of the equation and the load that every rigid body is bearing can therefore be revealed.

For every rigid body, a pair of resultant force and moment equations is formed,

$$\sum F = \dot{p} = \frac{d}{dt}(m\dot{r_G}) \text{.. (eq.2)}$$

$$\sum M^G = \dot{h}^G = \frac{d}{dt}(I^G \omega) \text{... (eq.3)}$$

$Where$:

$m = mass\ of\ the\ rigid\ body$

$\dot{r_G} = linear\ velocity\ of\ the\ rigid\ body$

$I^G = tensor\ of\ inertia\ about\ the\ center\ of\ mass\ of\ the\ rigid\ body$

$\omega\ =\ absolute\ angular\ velocity\ of\ the\ rigid\ body$

Under the Newton Euler approach, the equation of motion (eq.4) can be represented in the joint space expression which is commonly used in robot dynamics. The required joint torque (τ) is the summation of three individual terms, the inertia matrix, A, the Coriolis and centrifugal terms, $b(q, \dot{q})$. and the gravity term, $G(q)$. All these terms are expressed in joint space instead of the Euclidean space. This approach is employed for deriving the equation of motion of the robot because it is systematic and can be written as coding along with the robotic manipulation script.

$$\tau = A\ddot{q} + b(q, \dot{q}) + G(q) \text{ .... (eq.4)}$$

Eventually, Newton Euler approach in task-space expression is selected to be used for the analysis. The reasons would be elaborated in the Methodology section of this framework.

3.6 Centre of Mass of the pilot

During the gait cycle, the movement of the Centre of Mass (CoM) of the pilot can be modelled as an inverted pendulum (IP), which is widely used for biped robots (Chen, Cheng, Yue, Huang, & Guo, 2018). The body of the pilot is represented by a point mass with distance (r) from the point of contact of the standing foot with the ground. The calculations assume that the ankle joints are not actuated, as is the case for most exoskeletons. Therefore, the base of the pendulum can be considered as a point foot. Figure 5 illustrates this model. On the next step, the IP model is again used, but with the base position then being the other foot. The pilot applies external force (τ) to the CoM with crutches to prevent falling. The terms ($2r\dot{r}\dot{\theta}$) and ($r\dot{\theta}^2$) consider the Coriolis acceleration, which is ignorable in this case because its effect is small compared to other terms. The Equations of Motion (EoM) for the point mass are obtained as follows:

In the radial direction:

$$r^2\ddot{\theta} + 2r\dot{r}\dot{\theta} - grsin(\theta) = \frac{\tau}{M}$$

In the tangential direction:

$$r^2 - r\dot{\theta}^2 + gcos(\theta) = \frac{f}{M}$$

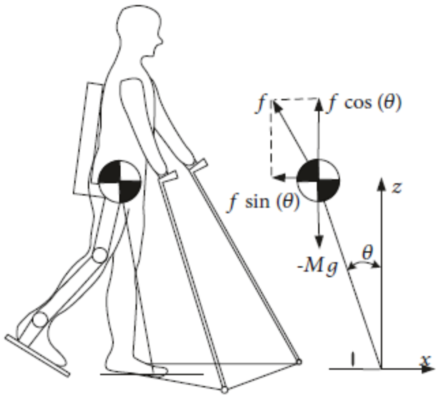


Figure 5. Model of exoskeleton and human based on IP model, (Chen, Cheng, Yue, Huang, & Guo, 2018)

By considering the equations above, the total force that acting on the crutches and the front foot plate can be calculated by using the kinematic data (i.e., $\theta, \dot{\theta}\ and\ \ddot{\theta}$). If the forces that are acting on the crutches are measured, the impact force can be retrieved by using free body diagram and the total force that is calculated previously without using the EoM. The impact force can then be used to assess whether any link will fail.

3.7 Impact Loading Approximation on heel

From previous research (Walsh, et al., 2006), it is revealed that more than 90% of the total weight of the pilot and the mass of the exoskeleton would transfer through the exoskeleton leg structure. From one of the figures in that article, an initial peak of the load which is corresponding to the heel strike is about 85% of the highest load that the heel would bear during the standing phase.

An impact load acting on the heel can be simulated by the following equation:

$$F_{impact} = (m_{pilot} + m_{exo}) \times 90\% \times 85\% = 0.765(m_{pilot} + m_{exo})$$

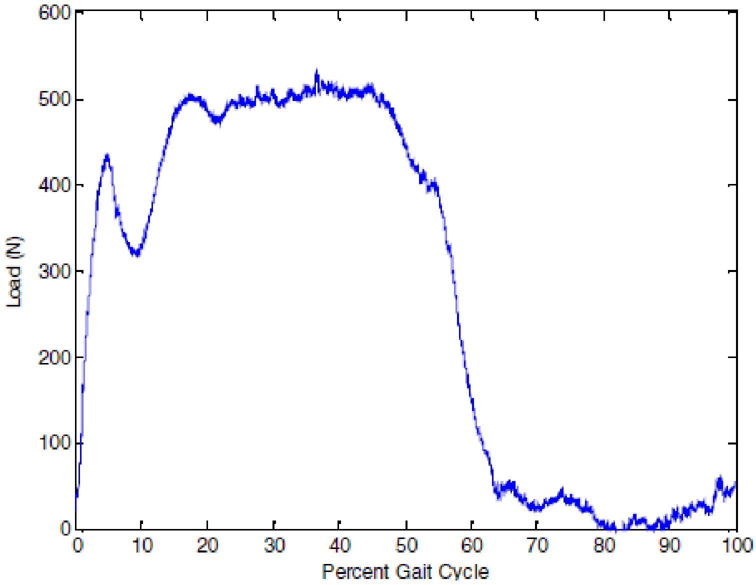


Fig 6. Variation of load in the exoskeleton transferred through the leg during the gait cycle, (Walsh, et al., 2006)

3.8 Existing Standard

The standards for exoskeletons are less developed compared to other similar fields such as prosthetics. The most relevant introductory standard for the purposes of this framework, ISO 13482 *Robots and robotic devices — Safety requirements for personal care robots* (International Organization for Standardization, 2014) gives some recommendations on various aspects of safety. While this includes factors such as durability, that will be useful for structural analysis, it also includes many other factors such as energy storage and posture of the pilot. The factors being considered for durability are the stresses, properties of materials, vibrations, environmental conditions (such as heat) and extreme cases for forces or misuse. However, this standard only provides the factors that need to be considered and does not provide a methodology for analysis. Therefore, this standard simply provides general concepts on the safety requirements of an exoskeleton and the initial direction of the framework development. This framework will develop methods to evaluate the effects of some of the factors mentioned in clause 5.11.1 of this standard. Specifically, it will include the mechanical stresses and material properties that will potentially introduce hazards due to insufficient durability.

3.9 Prosthetics

Compare this to ISO 22675 *Prosthetics — Testing of ankle-foot devices and foot units — Requirements and test methods* (International Organization for Standardization, 2016), that specifically give a three-step method for testing prosthetics. Initially, testing with a force for normal operations, and then, a higher force that simulates sudden or unexpected motions, and finally, a cyclic loading to simulate fatigue. This is done by testing specific samples of the prosthetics and checking if failure has occurred at any of these stages. The initial operation was done with a representative force of the system with a 1.75 safety factor. The second test was done similarly with a force 1.5-2 times larger than the initial static force. Finally, the fatigue test was done with the initial static force applied for cycles. These three tests cover all the possible types of stresses (static loading, impact loading and cyclic loading) that would potentially introduce mechanical failures in the exoskeletons. However, destructive tests can be costly, especially for robotic parts. Therefore, instead of conducting the destructive tests on a real exoskeleton, simulation software should be utilised to conduct these three analyses. So, this framework will build on this standard by adapting its proposed tests for use on exoskeletons.

4 Methodology - Design

4.1 Design considerations

Within the exoskeleton there are going to be variation in the stress that occurs depending on factors such as the material, shape, and force. To determine if there is failure, the highest areas of stress need to be found. Initially, the forces must be calculated. The maximum stresses can be found by considering the area that these forces are applied over. These values need to be cross referenced with the material properties to determine if failure will occur. As there are different materials present within the exoskeleton, several parts may need to be considered.

4.2 Safety factors

The same assumptions can be used as for prosthetics from the international standard. This means that the safety factor of 1.75 will be used for the maximum force that is allowable within the system which is mentioned in the Table 3 on page 9 in the standard ISO 22675-2016_2. These are the routine forces that the exoskeleton is expected to operate at, and this force will also be use in fatigue. However, the prosthetics standards also consider the situation where non-routine forces may also be applied. This includes situations such as unexpected motion, and a further safety factor of 2 is applied for this situation, which is mentioned in the same table, giving a total safety factor of 3.5 for the max stress.

4.3 Static Loading and Dynamics Loading

During every walking cycle, two different loadings, static loadings and dynamic loading are implied on each segment of the exoskeleton and the crutches. Static loadings are induced by the superposition of the weight of the pilot and the exoskeleton itself. Dynamic loadings are forces that occur because of motion, these can be more difficult to measure so static forces are calculated with safety factor. This method is still valid as prosthetics experience similar statics, and this was the same method that was used for testing prosthetics within International Standards.

4.4 Loading conditions

Initially, the forces need to be considered, these will form the basis of later analysis of the maximum stresses. Unlike prosthetics, there is a range of motions and positions that the exoskeleton will need to consider; due to ambiguity on where the maximum and minimum forces exist. There is some uncertainty within what position will have the greatest force acting within the system. There are a few different configurations that can be used to determine this:

4.4.1 Upright without crutches

Some exoskeletons will go from a sitting position to an upright position. To assist this motion then the pilot will need to rotate their crutches behind themselves and push up. However, after this is completed then the pilot will need to rotate their crutches in front of themselves, to get into a four-gait position. This means could mean that the pilot balances their weight only across the two legs of the exoskeleton, so the exoskeleton must be strong enough to withstand this force. This is the simplest force to determine as the centre of mass should be in line with the legs of the exoskeleton, only horizontal forces.

4.4.2 During gait cycle

During the walking cycle one of the legs will lift of the ground. This means that the gravitational forces will be exclusively going down one of the legs and the two crutches. The forces in this case will depend on three different things: (1) the angle the first leg makes with the floor, (2) the angles the first and second crutches make with the ground, (3) the mass and centre of masses of both the pilot and exoskeleton. As previously stated, the points of interest will be considered the moments that the mid swing of the leg and the heel strike, which is 85% of the reaction force.

4.5 Equation of Motion

The purpose of the integrity analysis is to evaluate if the exoskeleton lengths can withstand the forces generated under some reasonable circumstances. Task-based force expression is more appropriate to be used for this case than the joint- based force expression since it can reveal all the forces that every single length bears individually. In other words, every single length can be evaluated individually and explicitly. On the other hand, Newton Euler approach is more appropriate to be used than the Lagrangian approach. Since Newton Euler approach describes motions by forces which can be directly used for further analysis making it easier to derive force with kinematic chains. While they would both arrive at the same conclusion Newton Euler is used as that is easier to analysis. For the purposes of further analysis only the maximum and minimum forces are required. Therefore, the maximum/minimum forces of the different orientations will be used to calculate stress.

4.6 Required strength

The required strength will also be consistent with the system for prosthetics with the International Standards. Therefore, forces that is needed for the system will be 2x the initial static forces calculations. This is to deal with potential unexpected motions or possible misuse. These will likely occur but should not occur regularly.

4.7 Required fatigue strength

Required fatigue strength will also be consistent with the prosthetics international standards where the forces calculated in the initial calculations of the statics, these will be taken as the routine cyclic forces that the exoskeleton will experience. Due to being like the prosthetics we can also use the same number of cycles, which were given as 2×10^6. From this use fatigue equations, dimentions and material properties for calculations.

$$\sigma_{amplitude} = 0.5(\sigma_{max} - \sigma_{min})$$

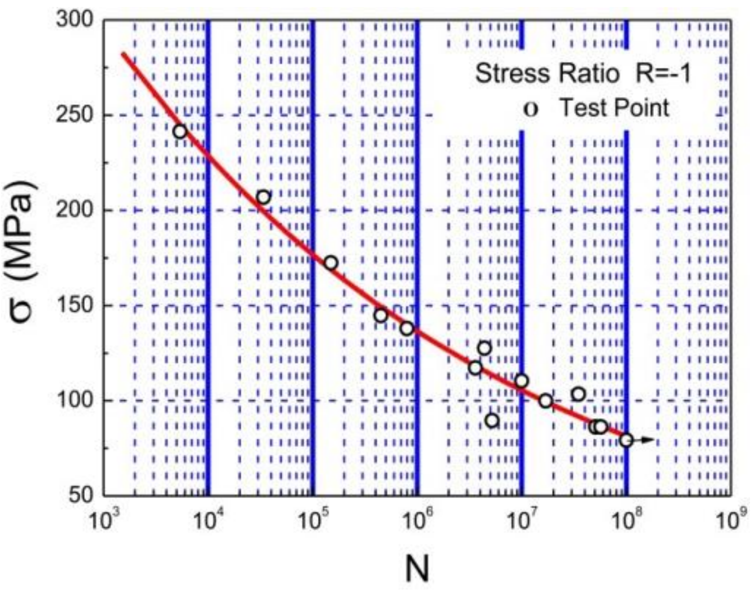


Figure 7: Fatigue curve for Aluminium 6061 (Bai, Li, Xie, Zhou & Ou, 2014).

$\sigma_{amplitude}$ will dictate the point that the material will fail. Given the fatigue cycles as 2×10^6 each specific material will have a $\sigma_{amplitude}$ that is acceptable. For example, for Aluminium 6061 it is 125 MPa.

4.8 Using FEA

Finally, FEA will be used to verify the results. This is done through simulating the forces of gravity that were found while adding constraints to simulate the ground. These should give us a visual representation of the stresses within the system. From this it can be verified that the results gathered are valid. Additionally, there could also be insight into other stress concentrations that originate from the design of the exoskeleton that could be used to inform redesigns.

The main area that needs to be verified is the stress concentrations that occur within the exoskeleton. For example, if there are sharp edges then stress concentrations could occur at those point and cause fatigue cracking.

5 Methodology – Calculations

Code done for calculations available for download at:
https://github.com/capstonealex/Hardware2021

5.1 Forming the free body diagrams

The Exoskeleton components are divided into six different components:

- Backplate
- Hip
- Upper Thigh
- Lower Thigh
- Upper Shank
- Lower Shank
- Foot

These may have some variation with different exoskeletons with some pieces being combined or split into multiple components.

Within these components there are five regions of rotation

- Hip modules that allow the legs to be spread (location: hip)
- Region between hip extension and upper thigh (location: hip)
- Region between lower thigh and upper shank (location: knee)
- Region between lower shank and food (location: ankle)
- Within the foot plate (location: toes)

There are three different cases that will be considered

Case I – free standing: The initial free-standing case will be considered the baseline.

Case II – Heel strike: When the leg is swinging there will be an impact force that the leg experiences when it makes contact will the ground this will, force will be 90%*85% of reaction as described in literature review.

Case III – mid-swing: During the mid-swing of a leg, where the reaction force will be equal to the mass of the exoskeleton.

This calculation will follow the exoskeleton through a step and assume the following follow:

- Mass of the pilot's leg will be rigidly attached to the exoskeleton
- The force wholly contained within the exoskeleton components
- The angles of the exoskeleton will be the same as a standing phase walking gait
- The crutches are station at a 45° angle
- There will always be a foot that flat against the ground

Using this the upright stance and a step can be analysed. Diagram will attach the right footplate to the floor and analyse a step from heel strike to swinging leg. Using symmetry the forces and moment can analyse throughout entire cycle.

Link	Components
1 & 9	Footplate
2 & 8	Upper Shank Lower Shank
3 & 7	Upper Thigh Lower Thigh
4 & 6	Hip module
5	Backplate

Table B: Links of the exoskeleton

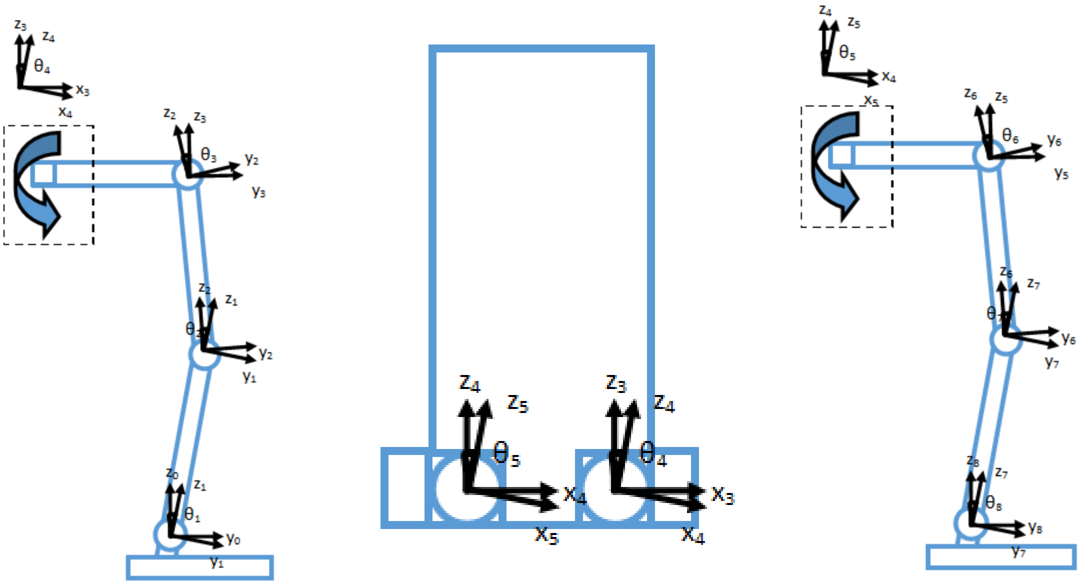


Figure 8: Diagram cross section of the exoskeleton

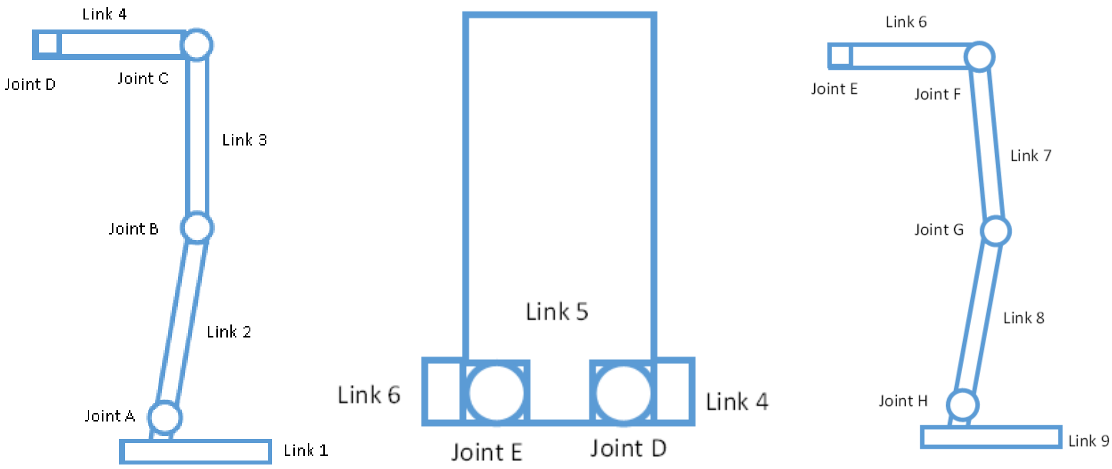


Figure 9: Labels and Joints of cross section

5.2 Rotations

The rotation matrices for these are:

$$
{}^0_1R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_1 & sin\theta_1 \\ 0 & -sin\theta_1 & cos\theta_1 \end{bmatrix}
$$

$$
{}^1_2R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_2 & -sin\theta_2 \\ 0 & sin\theta_2 & cos\theta_2 \end{bmatrix}
$$

$$
{}^2_3R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_3 & sin\theta_3 \\ 0 & -sin\theta_3 & cos\theta_3 \end{bmatrix}
$$

$$
{}^3_4R = \begin{bmatrix} cos\theta_4 & 0 & sin\theta_4 \\ 0 & 1 & 0 \\ -sin\theta_4 & 0 & cos\theta_4 \end{bmatrix}
$$

$$ {}^{4}_{5}R = \begin{bmatrix} cos\theta_5 & 0 & sin\theta_5 \\ 0 & 1 & 0 \\ -sin\theta_5 & 0 & cos\theta_5 \end{bmatrix} $$

$$ {}^{5}_{6}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_6 & sin\theta_6 \\ 0 & -sin\theta_6 & cos\theta_6 \end{bmatrix} $$

$$ {}^{6}_{7}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_7 & sin\theta_7 \\ 0 & -sin\theta_7 & cos\theta_7 \end{bmatrix} $$

$$ {}^{7}_{8}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_8 & sin\theta_8 \\ 0 & -sin\theta_8 & cos\theta_8 \end{bmatrix} $$

5.3 Angles

5.3.1 Case I – Free standing

The angles within the initial state will all be taken as 0° as this is the neutral position or baseline.

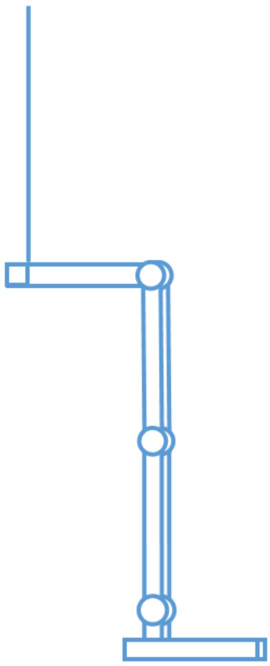


Figure 10: Exoskeleton in case 1

5.3.2 Case II – Heel Strike

The angles are taken from general gait cycle within the literature review. Specifically, first leg is in the standing heel strike phase, while the second leg is in the swinging toe off phase. When this occurs, there is a force within the heel transferred to the whole exoskeleton. This would be expected to cause a reaction force within the crutches and the other leg. For the analysis the force is wholly contained within the crutches, represented as a force from the pilot approximately 140 mm up from the hip modules (where the pilot is strapped) on the backplate. This will result in a conservative estimate of the force in the other leg as the upwards force will cause the force to decrease.

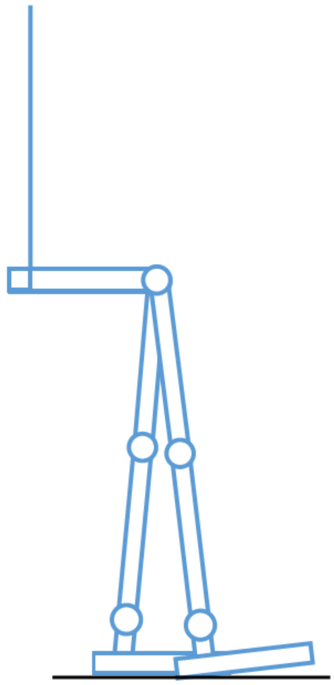


Figure 11: Exoskeleton in case 2

5.3.3 Case III – Mid-step

The angles are taken from general gait cycle within the literature review. Specifically, first leg is in the standing mid stand phase, while the second leg is in the swinging mid swing phase. For the analysis the force is wholly contained within the crutches, represented as a force from the pilot approximately 140 mm up from the hip modules (where the pilot is strapped) on the backplate.

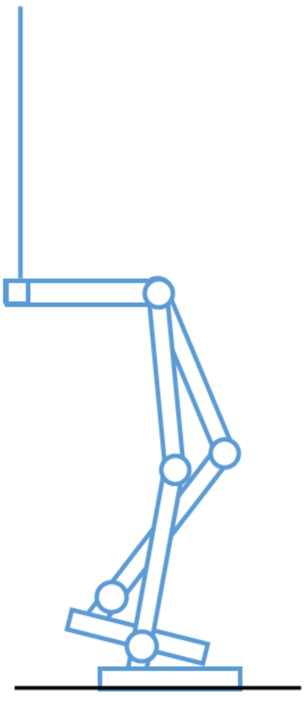


Figure 12: Exoskeleton in case 3

5.3.4 Angle Numerical Summary

	Case I	Case II	Case III
θ_1	$0°$	$0°$	$10°$
θ_2	$0°$	$0°$	$5°$
θ_3	$0°$	$20°$	$0°$
θ_4	$0°$	$0°$	$0°$
θ_5	$0°$	$0°$	$0°$
θ_6	$0°$	$-20°$	$20°$
θ_7	$0°$	$0°$	$30°$
θ_8	$0°$	$0°$	$0°$

5.4 Newton Euler Calculations

F	Force
${}^{f}F$	Force in frame f
F_j	Force at Joint j
G	Representation of mass acting at centre of gravity
F_{Gl}	Force from mass at link l
m	Mass
el	Exoskeleton at link l
pl	pilot at link l
m_{el}	mass of exoskeleton at link l
m_{pl}	mass of exoskeleton at link l
r_{SE}	Length from starting point S to end point

5.4.1 Constants required

This implementation requires two of the three external forces on the exoskeleton. The two reaction forces on the ground and the equivalent force from the body due to the crunches. The latter is difficult to measure so the reaction forces on the ground will be used. To do this the frames are attacked to the limbs of the exoskeleton and the backplate force will be solved for. It should be noted this analysis requires the assumption that the right foot is flat on the floor.

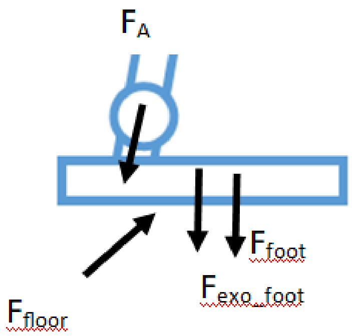
- Masses of pilot and exoskeleton for each link (link 1-9)
  - $m_{e1} \rightarrow m_{e9}$
  - $m_{p1} \rightarrow m_{p9}$
- Initial conditions (will change with different loading conditions)
  - ${}^{0}F_{floor}$ on link 1
  - ${}^{7}F_{floor}$ on link 9
- Length from joints to other joint and from joints to centres of gravity
  - Joint A (between ankle and shank)
    - rAO
    - rAB
    - rAGe1
    - rAGp1
    - rAGe2
    - rAGp2
  - Joint B (between shank and thigh)
    - rBA
    - rBC
    - rBGe2

        - rBGp2
        - rBGe3
        - rBGp3
    - Joint C (between thigh and hip module)
        - rCB
        - rCD
        - rCGe3
        - rCGe4
        - rCGp3
    - Joint D (between hip module and back plate)
        - rDC
        - rDE
        - rDcru
        - rDGe4
        - rDGp5
        - rDGe5
    - Through symmetry this will give the rest

Many of these will need to be taken through direct measurement or through CAD file measurements.

5.4.2 Link 1 – Footplate (right)

The footplate has three different force to consider: (1) the reaction force that would be expected within the connecting joint (Joint A), (2) the gravitational forces (from the mass of the footplate and the pilot's foot), and (3) the reaction force within the floor. For no acceleration then the forces must sum to zero. Similar calculations occur in the other free body diagrams. Code solving for values available at https://github.com/capstonealex/Hardware2021



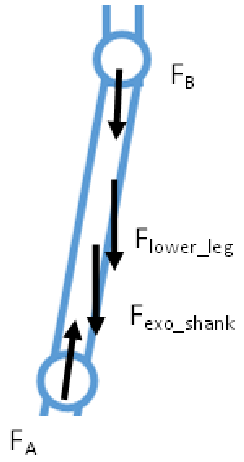
$$^{0}\sum F_{link1} = {}^{0}F_{A} + {}^{0}F_{G1} + {}^{0}F_{floor} = 0$$

$$^{0}\sum F_{link1} = {}^{0}F_{A} + \begin{bmatrix} 0 \\ -(m_{e1} + m_{p1})g \\ 0 \end{bmatrix} + {}^{0}F_{floor} = 0$$

$$^{0}F_{A} = -\begin{bmatrix} 0 \\ -(m_{e1} + m_{p1})g \\ 0 \end{bmatrix} - {}^{0}F_{floor}$$

5.4.3 Link 2 – Shank (right)

The second link the lower leg where the forces are from Upper and Lower joint and the mass.



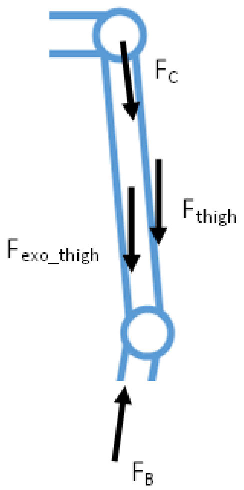
$$^{1}\sum F_{link2} = -{}^{1}F_A + {}^{1}F_{G2} + {}^{1}F_B = 0$$

$$^{1}\sum F_{link2} = -{}^{1}_{0}R\,{}^{0}F_A + {}^{1}_{0}R\begin{bmatrix} 0 \\ -(m_{e2} + m_{p2})g \\ 0 \end{bmatrix} + {}^{1}F_B = 0$$

$${}^{1}F_B = {}^{1}_{0}R\,{}^{0}F_A - {}^{1}_{0}R\begin{bmatrix} 0 \\ -(m_{e2} + m_{p2})g \\ 0 \end{bmatrix}$$

5.4.4 Link 3 – Thigh (right)

The force balance is like link 3.



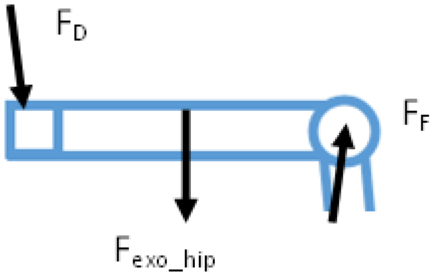
$$^{2}\sum F_{link3} = -{}^{2}F_B + {}^{2}F_{G3} + {}^{2}F_C = 0$$

$$^{2}\sum F_{link3} = -{}^{2}_{1}R\,{}^{1}F_B + {}^{2}_{0}R\begin{bmatrix} 0 \\ -(m_{e3} + m_{p3})g \\ 0 \end{bmatrix} + {}^{2}F_C = 0$$

$$^{2}F_C = {}^{2}_{1}R\,{}^{1}F_B - {}^{2}_{0}R\begin{bmatrix}0\\-(m_{e3}+m_{p3})g\\0\end{bmatrix}$$

5.4.5 Link 4 – Hip module (right)

This portion of the exoskeleton does not strap to the pilot's body so the mass can be taken as being applied to the backplate. This means that the force of the pilot will be applied at joint D.



$$^{3}\sum F_{link4} = -{}^{3}F_C + {}^{3}F_{p3} + {}^{3}F_D = 0$$

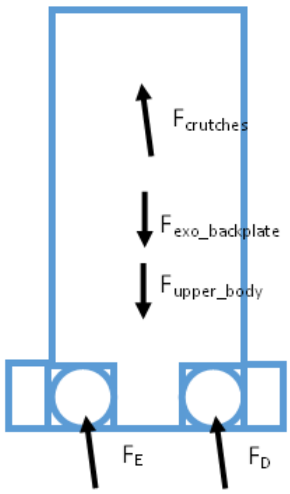
$$^{3}\sum F_{link4} = -{}^{3}_{2}R\,{}^{2}F_C + {}^{3}_{0}R\begin{bmatrix}0\\-(m_{e4})g\\0\end{bmatrix} + {}^{3}F_D = 0$$

$$^{3}F_D = +{}^{3}_{2}R\,{}^{2}F_C - {}^{3}_{0}R\begin{bmatrix}0\\-(m_{e4})g\\0\end{bmatrix}$$

This portion of the exoskeleton does not strap to the pilot's body so the mass can be taken as being applied to the backplate. This means that the force of the pilot will be applied at joint D.

5.4.6 Link 5 – Backplate

Need to consider the force from the mass of the pilot's upper body, the exoskeleton and the forces produced on the crutches. Need ${}^{4}F_E$ or $F_{crutches}$ to solve.



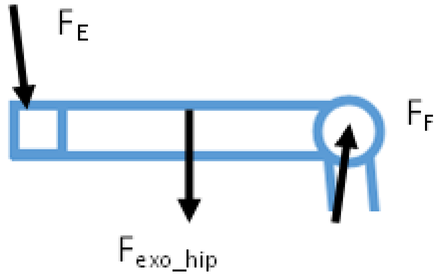
$$^{4}\sum F_{link5} = -{}^{4}F_D + {}^{4}F_{p4} + {}^{4}F_{G5} - {}^{4}F_E + F_{crutches} = 0$$

$$ {}^{4}\sum F_{link5} = -{}^{4}_{3}R\,{}^{3}F_D + {}^{4}_{0}R \begin{bmatrix} 0 \\ -(m_{p5} + m_{e5})g \\ 0 \end{bmatrix} - {}^{4}F_E + F_{crutches} = 0 $$

$$ {}^{4}F_E = -{}^{4}_{3}R\,{}^{3}F_D + {}^{4}_{0}R \begin{bmatrix} 0 \\ -(m_{p5} + m_{e5})g \\ 0 \end{bmatrix} + F_{crutches} $$

5.4.7 Link 6 – Hip module (left)

Similar to link 4



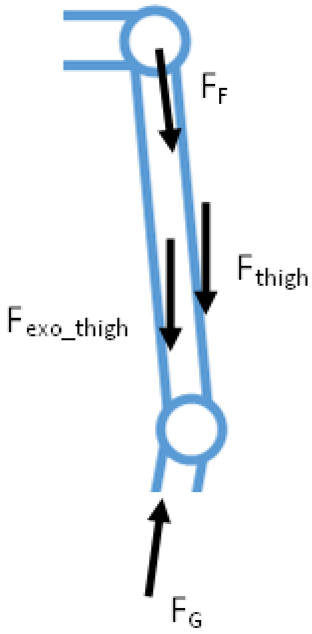
$$ {}^{5}\sum F_{link6} = {}^{5}F_E + {}^{5}F_{p6} - {}^{3}F_F = 0 $$

$$ {}^{5}\sum F_{link6} = {}^{5}_{4}R\,{}^{4}F_E + {}^{5}_{0}R \begin{bmatrix} 0 \\ -(m_{e6})g \\ 0 \end{bmatrix} - {}^{5}F_D = 0 $$

$$ {}^{5}F_F = -{}^{5}_{4}R\,{}^{4}F_E + {}^{3}_{0}R \begin{bmatrix} 0 \\ -(m_{e6})g \\ 0 \end{bmatrix} $$

5.4.8 Link 7 – Thigh (left)

Similar to link 3



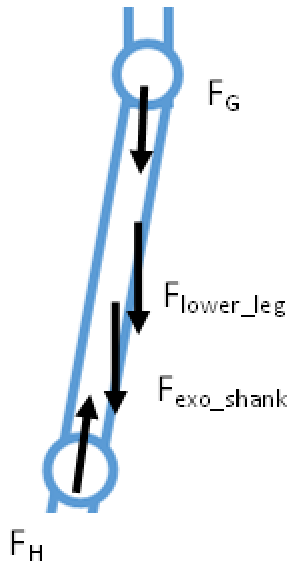
$$ {}^{6}\sum F_{link7} = +{}^{6}F_F + {}^{6}F_{G7} - {}^{6}F_G = 0 $$

$$ {}^{6}\sum F_{link7} = {}^{6}_{5}R\,{}^{5}F_F + {}^{6}_{0}R\begin{bmatrix} 0 \\ -(m_{e3} + m_{p7})g \\ 0 \end{bmatrix} - {}^{6}F_G = 0 $$

$$ {}^{6}F_G = -{}^{6}_{5}R\,{}^{5}F_F + {}^{6}_{0}R\begin{bmatrix} 0 \\ -(m_{e3} + m_{p7})g \\ 0 \end{bmatrix} $$

5.4.9 Link 8 – Shank (left)

Similar to link 2



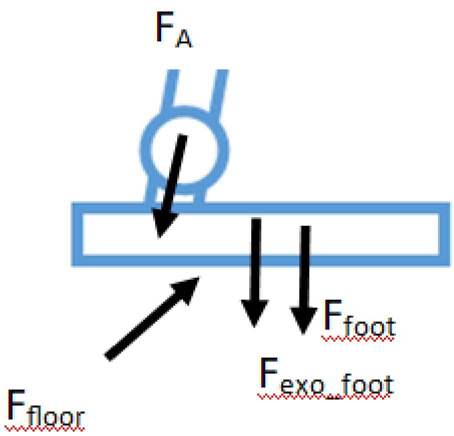
$$ {}^{7}\sum F_{link8} = {}^{7}F_{G} + {}^{7}F_{G7} - {}^{7}F_{H} = 0 $$

$$ {}^{7}\sum F_{link8} = {}^{7}_{6}R\,{}^{6}F_{G} + {}^{7}_{0}R\begin{bmatrix} 0 \\ -(m_{e8}+m_{p8})g \\ 0 \end{bmatrix} - {}^{7}F_{H} = 0 $$

$$ {}^{7}F_{H} = -{}^{7}_{6}R\,{}^{6}F_{G} + {}^{7}_{0}R\begin{bmatrix} 0 \\ -(m_{e8}+m_{p8})g \\ 0 \end{bmatrix} $$

5.4.10 Link 9

Similar to link 1



$$ {}^{8}\sum F_{link7} = {}^{8}F_{H} + {}^{8}F_{G9} + {}^{8}F_{reaction} = 0 $$

$$
{}^{8}\sum F_{link7} = {}^{8}_{7}R\,{}^{7}F_{H} + {}^{8}_{0}R \begin{bmatrix} 0 \\ -(m_{e9} + m_{p9})g \\ 0 \end{bmatrix} + {}^{8}F_{reaction} = 0
$$

$$
{}^{8}F_{reaction} = -{}^{8}_{7}R\,{}^{7}F_{H} - {}^{8}_{0}R \begin{bmatrix} 0 \\ -(m_{e9} + m_{p9})g \\ 0 \end{bmatrix}
$$

To solve MATLAB code was written to calculate to link 5, then from link 9 to link 5 (using given reaction force) so the equivalent force from the crutches could be found to calculate the moment.

5.5 Moment

Moments within the system will be of two types: actuated motor and joint moment. The actuated motors will be a moment from the motors resisting motion, while the joint moment is a reaction force from a joint due to moment imbalance. Moments are taken at the joints. They are the cross product of the forces and their distances for the system to have zero angular acceleration then the sum must be equal to zero.

5.5.1 Joint A – Between ankle and shank (right)

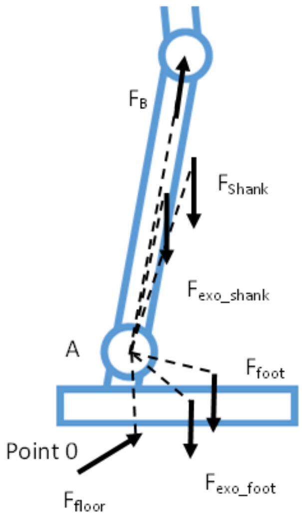


Figure 22: Free body diagram of the moment at Joint A

$$
{}^{0}\sum M_{A} = -{}^{0}M_{A} + {}^{0}r_{AO} \times {}^{0}F_{floor} + {}^{0}r_{AB} \times {}^{0}F_{B} + {}^{0}r_{AGe1} \times {}^{0}F_{Ge1} + {}^{0}r_{AGp1} \times {}^{0}F_{Gp1} + {}^{0}r_{AGe2} \times {}^{0}F_{Ge2} + {}^{0}r_{AGp2} \times {}^{0}F_{Gp2} = 0
$$

5.5.2 Joint B – Between Shank and thigh (right)

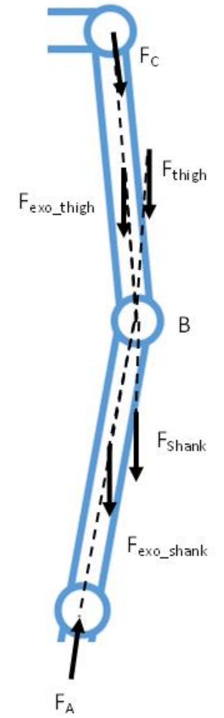


Figure 23: Free body diagram of the moment at Joint A

$$ {}^{1}\sum M_{B} = -{}^{1}M_B + {}^{1}r_{BA} \times -{}^{1}F_A + {}^{1}r_{BC} \times {}^{1}F_C + {}^{1}r_{BGe2} \times {}^{1}F_{Ge2} + {}^{1}r_{BGp2} \times {}^{1}F_{Gp2} + {}^{1}r_{BGe3} \times {}^{1}F_{Ge3} + {}^{1}r_{BGp3} \times {}^{1}F_{Gp3} = 0 $$

5.5.3 Joint C – Between thigh and hip module (right)

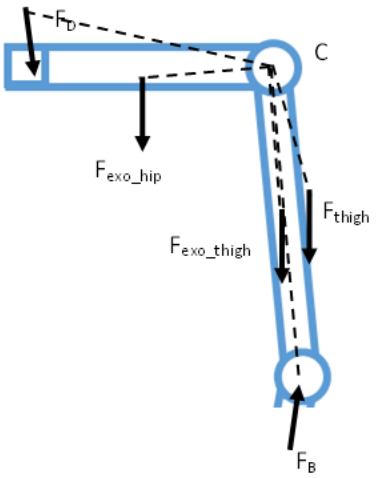


Figure 24: Free body diagram of the moment at Joint B

$$ {}^{2}\sum M_{C} = -{}^{2}M_C + {}^{2}r_{CB} \times -{}^{2}F_B + {}^{2}r_{CD} \times {}^{2}F_D + {}^{2}r_{CGe3} \times {}^{2}F_{Ge3} + {}^{2}r_{CGe4} \times {}^{2}F_{Ge4} + {}^{2}r_{CGp3} \times {}^{2}F_{Gp3} = 0 $$

5.5.4 Joint D – Between hip module and backplate (right)

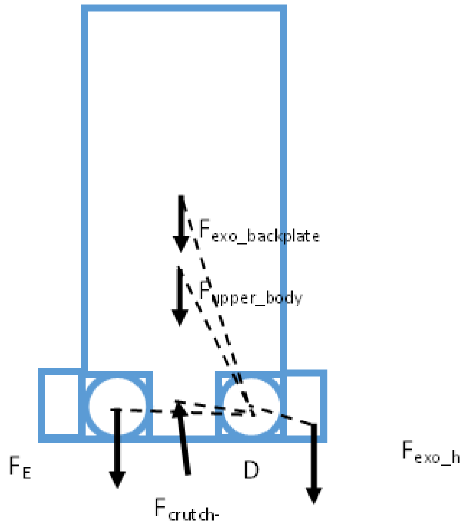


Figure 25: Free body diagram of the moment at Joint D

$$^{3}\sum M_{D} = -{}^{3}M_D + {}^{3}r_{DC} \times -{}^{3}F_C + {}^{3}r_{DE} \times {}^{3}F_E + {}^{3}r_{DGe4} \times {}^{3}F_{Ge4} + {}^{3}r_{DGp5} \times {}^{3}F_{Gp5} + {}^{3}r_{DGe5} \times {}^{3}F_{Ge5} + {}^{3}r_{Dcru} \times {}^{3}F_{cru} = 0$$

5.5.5 Joint E – between hip module and backplate (left)

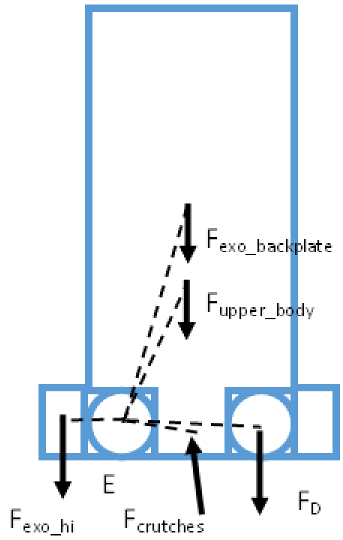


Figure 26: Free body diagram of the moment at Joint E

$$^{4}\sum M_{E} = -{}^{4}M_E + {}^{4}r_{EF} \times {}^{4}F_F + {}^{4}r_{FD} \times -{}^{4}F_D + {}^{4}r_{Ecru} \times {}^{4}F_{cru} + {}^{4}r_{EGe6} \times {}^{4}F_{Ge6} + {}^{4}r_{EGp5} \times {}^{4}F_{Gp5} + {}^{4}r_{EGe5} \times {}^{4}F_{Ge5} = 0$$

5.5.6 Joint F – Between hip module and thigh (left)

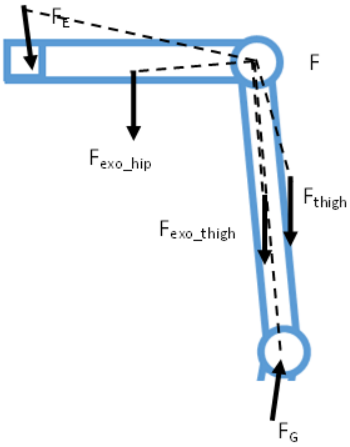


Figure 27: Free body diagram of the moment at Joint F

$$^{5}\sum M_{F} = {}^{5}M_F + {}^{5}r_{FE} \times -{}^{5}F_E + {}^{5}r_{FG} \times {}^{5}F_G + {}^{5}r_{FGe6} \times {}^{5}F_{Ge6} + {}^{5}r_{FGe7} \times {}^{5}F_{Ge7} + {}^{5}r_{FGp7} \times {}^{5}F_{Gp7} = 0$$

5.5.7 Joint G – Between thigh and shank (left)

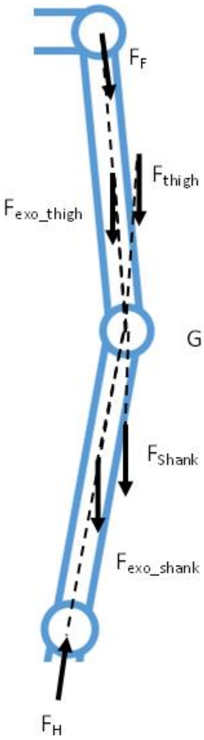


Figure 28: Free body diagram of the moment at Joint G

$$^{6}\sum M_{G} = -{}^{6}M_G + {}^{6}r_{GH} \times -{}^{6}F_H + {}^{6}r_{GF} \times {}^{6}F_F + {}^{6}r_{GGe7} \times {}^{6}F_{Ge7} + {}^{6}r_{GGp7} \times {}^{6}F_{Gp7} + {}^{6}r_{GGe8} \times {}^{6}F_{Ge8} + {}^{6}r_{GGp8} \times {}^{6}F_{Gp8} = 0$$

5.5.8 Joint H – Between shank and ankle (left)

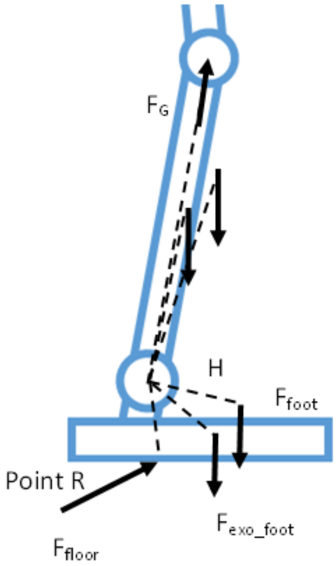


Figure 29: Free body diagram of the moment at Joint H

$$
{}^{7}\sum_{H} M = -{}^{7}M_{H} + {}^{7}r_{Hfloor} \times {}^{7}F_{floor} + {}^{7}r_{HG} \times {}^{7}F_{G} + {}^{7}r_{HGe8} \times {}^{7}F_{Ge8} + {}^{7}r_{HGp8} \times {}^{7}F_{Gp8} + {}^{7}r_{HGe9} \times {}^{7}F_{Ge9} + {}^{7}r_{HGp9} \times {}^{7}F_{Gp9} = 0
$$

5.6 Calculating Constants

5.6.1 Masses

$$
90\%\ percentile\ for\ male\ adult = 111.5\ kg
$$

(McDowell, Fryar, Ogden, & Flegal, 2008).

Link	Exoskeleton Part(s)	Body Weight (% of total Mass) (single limb where applicable)	Body weight (kg)
Link 1 & 9	Foot	1.43	1.594
Link 2 & 8	Upper Shank + Lower Shank	4.75	5.296
Link 3 & 7	Upper Thigh + Lower Thigh	10.5	11.708
Link 4 & 6	Hip module	N/A	N/A
Link 5	Backplate	66.64	74.304

Table C: Data retrieved from (Plagenhoef, Evans & Abdelnour, 1983)

5.6.2 Reaction Forces

During cycles with crutches the crutches were assumed to be Partial Weight Bearing (PWB) with a value of 50% (medium). This is due to Li, Armstrong, & Cipriani (2001) finding that a PWB of 50% being easier to preform compared to more extreme weight distributions. However, force data that is measured using force plate, could be used for more reliable measurements where possible.

5.6.2.1 Reaction force – Case I

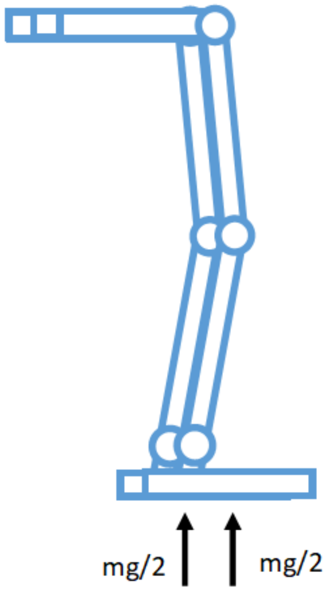


Figure 30: Free body diagram showing reaction force in case 1

Assumptions for calculating force.

- Reaction force will be equal to the weight
- Distributed equally within both legs
- Reaction force assumed in the centre of the foot plate
- Reaction force assumed in the centre of the foot plate for standing leg and on the back of the foot for the impacting foot
- Assume no vertical force from crutches in leg

% Weight not in lower body = 66.64%

% Weight in single leg = 16.68%

$$Total\ weight\ of\ exoskeleton\ and\ pilot = M = \sum_{n=1}^{9} m_{en} + m_{pn}$$

$$Reaction\ force\ in\ each\ leg = \begin{bmatrix} 0 \\ 0 \\ \frac{Mg}{2} \end{bmatrix}$$

5.6.2.2 Reaction force – Case II

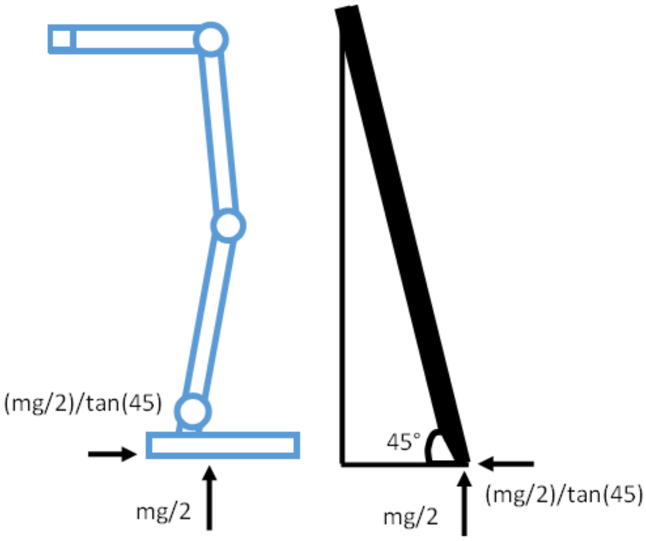


Figure 31: Free body diagram showing reaction force in case 2

Assumptions for calculating force.

- The crutches are used at an angle of 45°
- Just before the heel impact the reaction force is equal to the weight force
- The crutches take weight equal to the leg
- Assume no vertical force from crutches in leg
- Footplate will be parallel to floor

$$Reaction\ force\ in\ standing\ leg = \begin{bmatrix} 0 \\ \dfrac{\frac{Mg}{2}}{\tan(45)} \\ \dfrac{Mg}{2} \end{bmatrix}$$

$$Reaction\ force\ in\ leg\ on\ impact = \begin{bmatrix} 0 \\ 0.765 * \dfrac{\frac{Mg}{2}}{\tan(45)} \\ 0.765 * \dfrac{Mg}{2} \end{bmatrix}$$

5.6.2.3 Reaction force – Case III

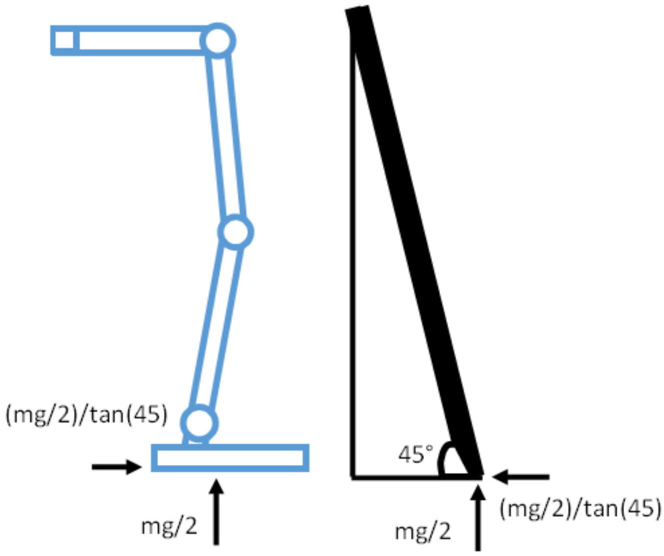


Figure 32: Free body diagram showing reaction force in case 3

Assumptions

- The crutches are used at an angle of 45°
- The crutches take weight equal to the leg
- Reaction force assumed in the centre of the foot plate
- No vertical force from crutches in leg
- Footplate will be parallel to floor

$$Reaction\ force\ in\ standing\ leg = \begin{bmatrix} 0 \\ \dfrac{\frac{Mg}{2}}{\tan(45)} \\ \dfrac{Mg}{2} \end{bmatrix}$$

5.7 Centre of Gravity Data

5.7.1 General CoG for exoskeleton

In general: Preliminary analysis done on the exoskeleton point to the CoG for each link to be approximately at the mid-point and based on these, the CoG will be approximated here for long components. For example, CoG for Link 1 will be $\frac{1}{2} \times Length\ of\ Link\ 1$. Exception: The CoG on the foot plate in the z direction appears at the top of the foot plate. These values are subject to change depending on exoskeleton design but can often be used as an approximation.

Shown in detail at https://github.com/capstonealex/Hardware2021.

5.7.2 Legs of pilot

For the legs CoG down the length will be taken from Plagenhoef, Evans & Abdelnour, 1983. While the thigh circumference will 46.5 (90% percentile) (McDowell, Fryar, Ogden, & Flegal, 2008) giving a radius of 7.4 cm. As all the CoG are going to be considered aligned within the z direction all CoG within the x direction will be considered 7.4 cm away from the joints.

Down the length of the link the CoG will be determined through data, from tables the CoG as a percentage of the length will be gathered.

From this $r = \%CoG * L$ down the limb and $r = (1 - \%CoG) * L$ up the link.The exception is the chest, the length of the chest was considered 30% of total body height.

Link	Exoskeleton Part(s)	Body CoG (% of total length)
Link 1	Foot	50
Link 2	Upper Shank + Lower Shank	43.4
Link 3	Upper Thigh + Lower Thigh	43.3
Link 4	Hip module	N/A
Link 5	Backplate	46

Table D: Data retrieved from (Plagenhoef, Evans & Abdelnour, 1983).

Using a standing height of 186cm (90% percentile) from McDowell et al., (2008) this can give as a distance from the CoG of the chest as $30\% * Length\ of\ chest * (1 - CoG_{chest}) = 30.132cm.$

5.8 Stress and Fatigue

For each specific material there is a specific stress oscillation that can safely occur before failure is expected. For the specific materials that we are using

Material	Steel SUS304
Yield Strength	410 MPa
Fatigue Strength	280 MPa
Material	Aluminium 6061
Yield Strength	410 MPa
Fatigue Strength	125 MPa

Table E: Data given values and Interlloy (2021), Zhang, Pyoun, Cao, Wu & Murakami (2012) & Madhukar†, Reddy, Kumar†, & Naik† (2018).

6 FEA calculations

6.1 Calculations

Based on the maximum force data received earlier. The force on the joints was found. Through this the forces can be simulated on CAD such as SOLIDWORKS and ANSYS to verify that the stresses within the system are within an acceptable range. Due to the symmetry of the system the maximum and minimum values of joints, such as Joint A and Joint H, can be used where applicable. As stated in literature review there will be a safety factor of 1.75 applied to get the force for typical operation, this will be used for fatigue calculations. A further safety factor of 2 will be applied to the forces when calculating the ultimate tensile stress, to control for sudden or unexpected forces.

$$Max\ \mathrm{Force} = F_d * Max\ Force$$

$$Max\ Force = 2 * 1.75 * Max\ Force$$

$$Max\ Fatigue = F_d * (Max\ Force - Min\ Force)$$

$$Max\ Fatigue = 1.75 * (Max\ Force - Min\ Force)$$

7 Discussion

7.1 Moment at the motors

The results will give the expect torque that is expected to be experienced at each of the joints. Due to this the exoskeleton will need locking motors to prevent the exoskeleton joints moving due to force from the standing weight of the exoskeleton.

This will also give an idea of how powerful the motors should be to function independently, if motors are not strong enough, then they will stall, this may cause the exoskeleton to stop functioning. If the system is given the angles of other positions such as sitting down, then other motions such as standing up could also be analysed through the Newton Euler equations. These motions will expert stronger moment on the motors. However, these can be alleviated to a certain extent by other means such as crutches. If crutches are used to stand up, then the exoskeleton could stand up from the pilot exserting enough force to prevent the motors from stalling.

If current motors do not provide enough moment, then they will need to be replaced. Though the weight factor should be considered when purchasing new motors. Stronger motors are going to be heavier and create a larger moment. Therefore, calculations should be performed prior to ensure specifications are met.

7.2 General Consideration of Stress

$$\sigma = \frac{F}{A}$$

Stress within a system is due to the force that acts within an area. To decrease the amount of stress that is occurring within a system either the force must be decreased, or the area must be increased. Within the exoskeleton system the force is largely predetermined by the weight of the pilot. This means that if there is too much stress the area, rather than the force, is the main area of change.

However, the stress in not uniformly distributed within the parts, the shape of the components can sometimes lead to stress concentration. Sharp corners causing the force to concentrate on a small area; thereby causing a regional high stress. When designing the exoskeleton parts these points of stress concentration should be avoided wherever possible. This is done by curving the structure of the exoskeleton where necessary. Even when this is the case there could still be parts that are under too much stress; therefore, they need to be made thicker.

Although, the amount of stress that a system can endure is down to the material that it is made from. This should be approached cautiously as the material of the parts will also affect the mass of the exoskeleton. Though, the calculations showing the mass of the pilot and the backplate being much larger than most induvial parts. Within exoskeletons that also have this feature then specific parts material changing would only moderately change the weight and could be changed so the stress could be withstood by the new material.

7.3 Assumptions affecting application

This is a generalised application of the framework, the Newton Euler equations were taken as zero, i.e., no acceleration or angular velocity. This acknowledged by using a safety factor. However, in situations where there is a large amount of acceleration then this framework will need to be modified to account for that situation. Additionally, in cases where the exoskeleton is running or jumping the angle between the foot and the ground will also need to be considered as this will affect the orientation of the gravitational forces.

8 Conclusion

In conclusion, after reviewing the literature of the analysis of exoskeletons and similar devices, a framework specifically tailored to the analysis of exoskeletons was developed. This builds upon the current literature and repurposes it for a different system. The Newton Euler equations were formed from the free body diagrams of the different parts of the exoskeleton. Using the analysis, the forces on the parts of the exoskeleton and the moments that will be experienced throughout the walking cycle can be determined through code available on GitHub; providing exoskeleton dimensions and masses. With this the design decisions can be informed such as part shapes and motor strength required. This will ultimately ensure that specifications are met and that the system is safe.

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