NAU NORTHERN ARIZONA UNIVERSITY
Mechanical Engineering

Team #19F13

Biomechatronic Hip Exoskeleton Team

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Subject: Implementation Memo II

The Biomechatronic Hip Exoskeleton Team (BHET) is designing and manufacturing a robotic prosthetic for the NAU Biomechatronics lab. The goal of the device is to provide assistive torque to the wearer during a normal walking gait, assistance will aid with hip extension and flexion. The design has gone through many iterations, which is reflected in the revision number for each subsystem. The following memo outlines the team's final implementation plan for the last weeks of the project. This includes final design changes, applicable standards, codes and regulations, manufacturing status, and updates to the risk analysis.

1 Implementation – Weeks 7-11

The primary goals of Week 7-11 were to simplify the design that has been created so that manufacturing would not be difficult, and to finalize the ratio for the pulley diameter. Another goal was to machine/3D print other parts of the design.

1.1 Manufacturing

The following sections will breakdown the different aspects of manufacturing done for this project. This will primarily include the work conducted during March 2020.

1.1.1 Manufacturing Processes

There are two main manufacturing process used for this project, these being machining and forming. 3D printing was also used for non-critical components. Machining applies to most of the components included in the motor mount assembly. Forming applies to the hip belt and knee brace components of the design. Machining was done with both a manual vertical mill (Bridgeport mills in 98c) and a CNC vertical mill (Tormachs in 98c). The manual vertical mill was used for roughing the outer dimensions of the parts, as setup time on these machines was significantly shorter than the CNC mill. The below figure demonstrates a part being roughed on the manual mill.

Figure 1.1: Roughing a Part on a Manual Mill

The CNC mill was used to finish parts and to cut the more complicated features that could not be cut on the manual mill. The below figure shows this process.

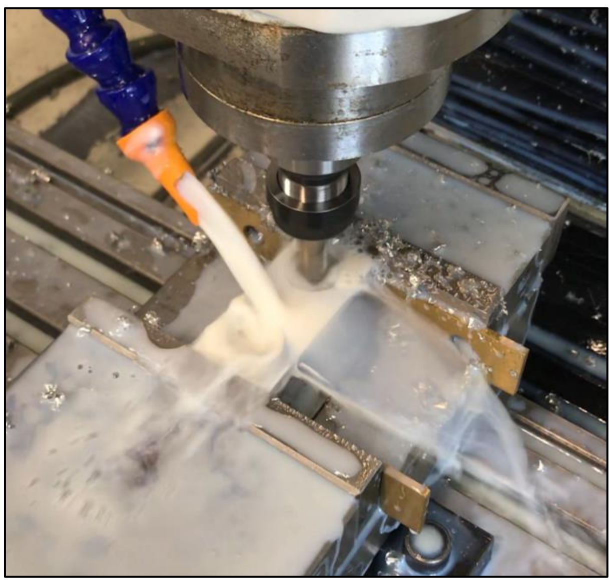

Figure 1.2: Finishing a Part on a CNC Mill

Both of these processes proved to be effective as a means of production for all of the aluminum parts required for this project.

Forming was required for all components made of Kydex, which includes the knee braces and the hip belt. When forming, the component was first cut from a flat sheet of Kydex using a stencil printed from CAD. After the Kydex was cut to shape, the component was then heated with a heat gun until it became flexible. At this point the component was molded over the user (who was wearing a towel to insulate from heat). The Kydex would set after 5-10 minutes and then the part was ready for hardware and finishing work.

3D printing was used for all non-critical components in the design. This included support pieces in the motor mount assembly that wouldn't experience any significant stress during the hip exoskeletons operation. 3D printing will also be used for prototyping and any additional non-critical components.

1.1.2 CAM (Computer Assisted Machining)

For all work done on the CNC mills, CAM was generated from SolidWorks parts to ensure that the parts were machined effectively. All CAM was generated in Autodesk Fusion 360. Shown below is a CAM program generated for this project.

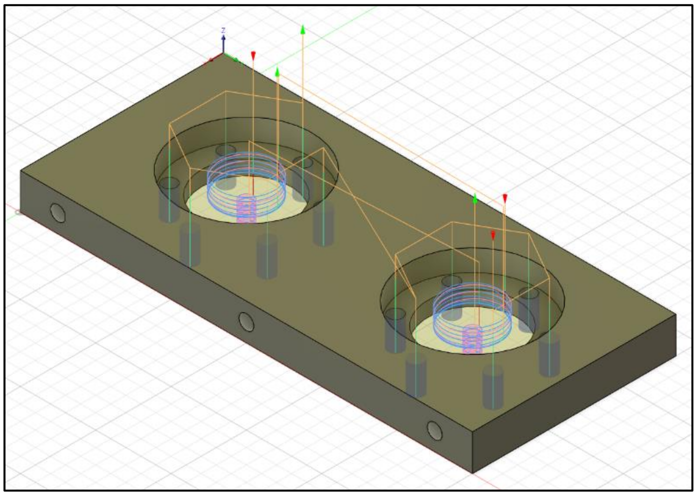

Figure 1.3: CAM generated in Fusion 360

The CAM program details all of the specific steps in the machining process required to cut a part. This was then used to export g-code (the programing language used by CNC mills) to load on a Tormach CNC mill. This program aided in calculating the required speeds and feeds for the CNC mill.

1.2 Design Changes -Weeks 7-1

The below sections describe major design changes made in weeks 7-11. These changes were conducted to fix manufacturing issues, update the design to new engineering requirements, or to fit requirements found from individual analysis reports. The below sections are organized by specific components of the design. Any components not listed below have had no significant design changes in weeks 7-11.

1.2.1 Component 1: Motor Mount Design Iterations

The Motor Mount subsystem functions to affix the drive components to the harness worn by the user and maintain alignment of the belt drive and cable actuation systems. The previous revision (V3) of the Motor Mount is shown in Figure 1.4 below.

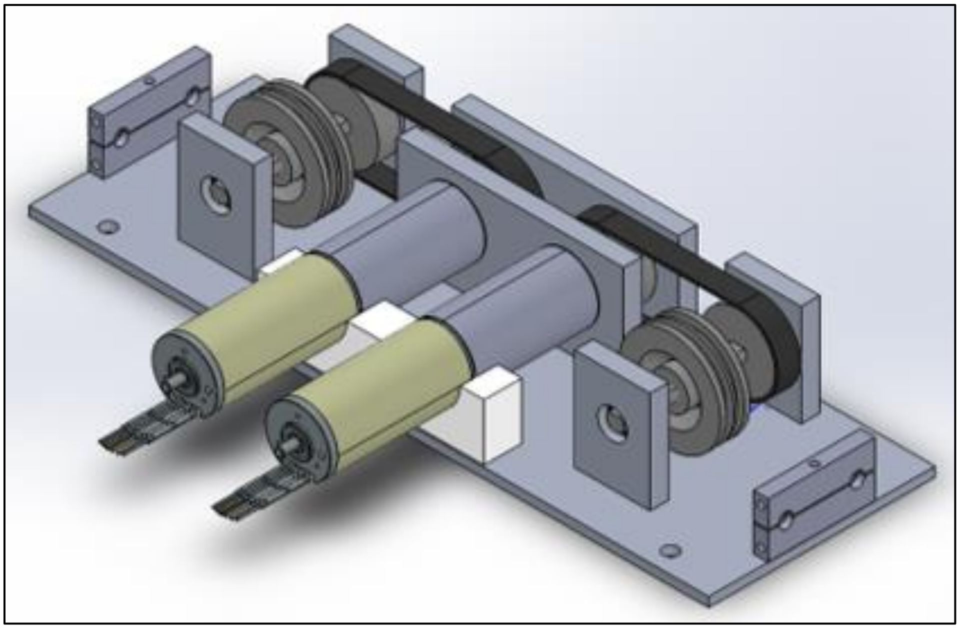

Figure 1.4 V3 Motor Mount subsystem

Changes to the Motor Mount design were required after the team performed a technical analysis on the cable pulley and belt drive. The results of the analysis required the cable pulley to be increased, such that the base plate and bearing blocks supporting the output shaft of the belt drive required modification. V4 of the Motor Mount assembly is shown below, in Figure 1.5. Additionally, the output shaft diameter was increased from 6mm to 8mm, after performing a stress analysis using the larger pulley diameter and applying distortion energy theory ($n = 1.5$), new bearings were selected to match the shaft.

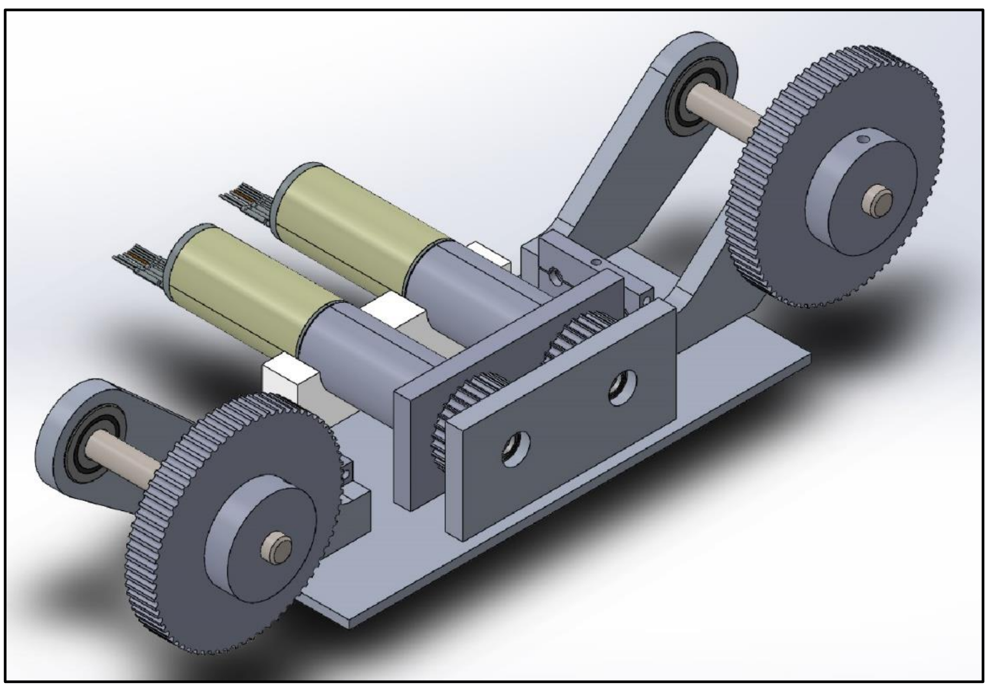

Figure 1.5 Motor Mount V4

The bearing block design had the most significant changes for the V4 Motor Mount. The previous design was a rectangular plate that located the bearing centered between the mounting bolts (Figure 1.6). The need for more clearance for the cable pulley and the timing belt pulley led to the design shown in Figure 1.7. The new part locates the shaft offset from the mounting point. The offset design provides the necessary clearance for the drive system mentioned above, without extending too far which would cause disruption to the wearers arm swing during walking.

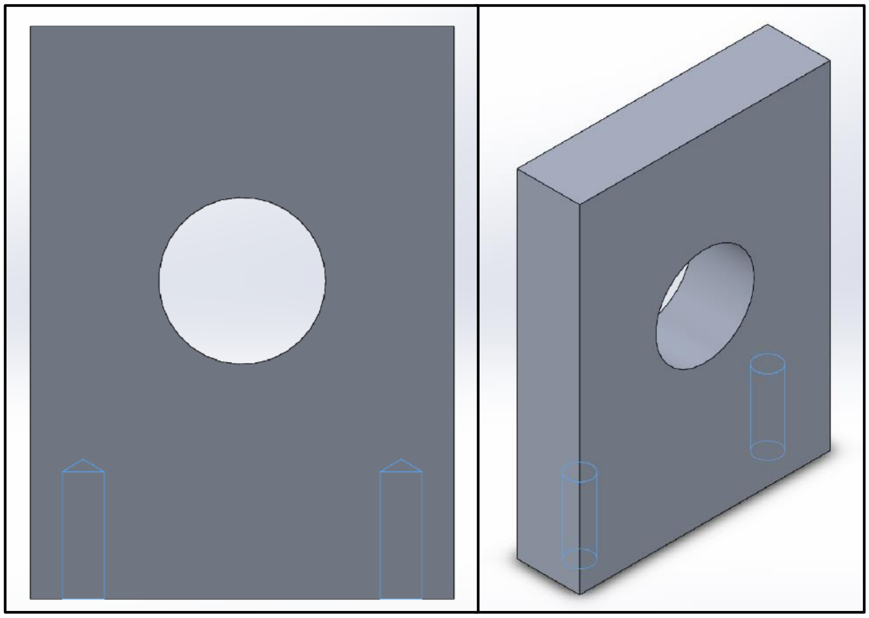

Figure 1.6 Previous Bearing Block design

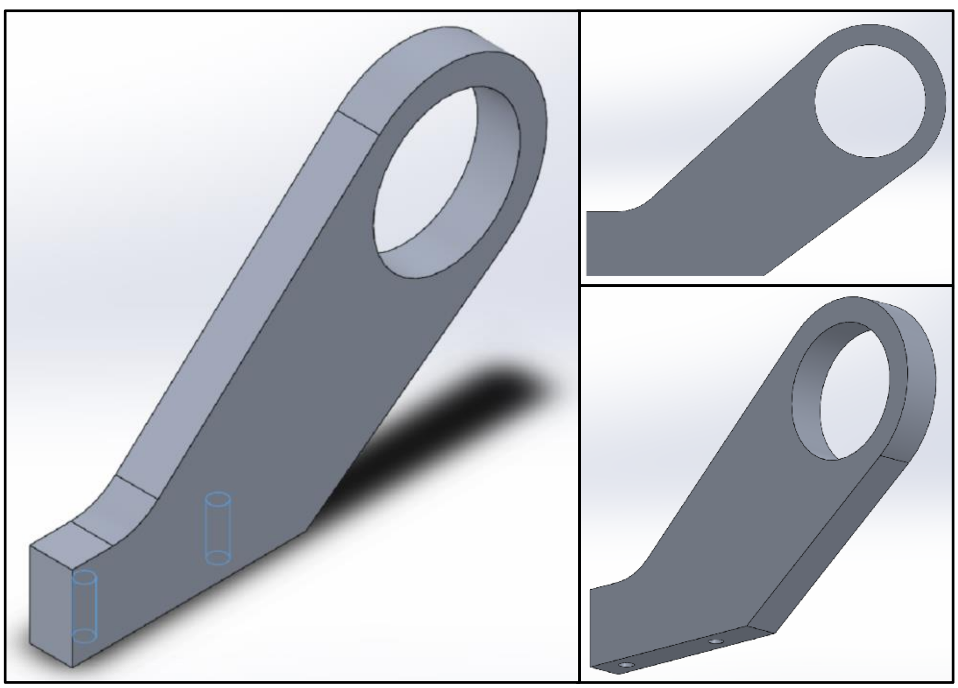

Figure 1.7 New Bearing Block design

The base plate of the Motor mount received minor changes to reduce the overall length and the location of mounting holes to facilitate the new configuration (Figure 1.8).

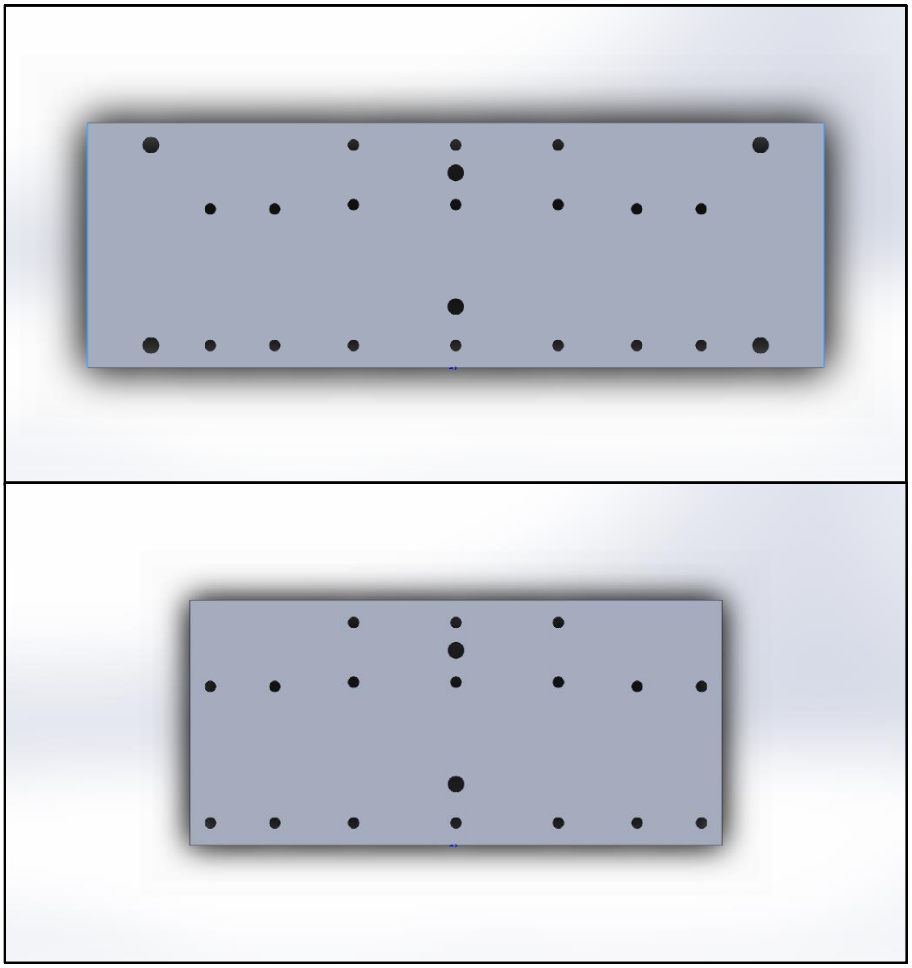

Figure 1.8 Base Plate, previous (top) vs new design (bottom)

1.2.2 Component 2: Pully Design Iterations

Though the pulley design has been relatively simple throughout each iteration of the system, the team needed to get a ratio for the pulley diameters. Our pully design is a dual pulley and each pulley will actuate movement in both the extension and flexion direction. In the original pulley design did not account for slack, so the radii of the pulleys were the same. This is shown below in Figure 1.9.

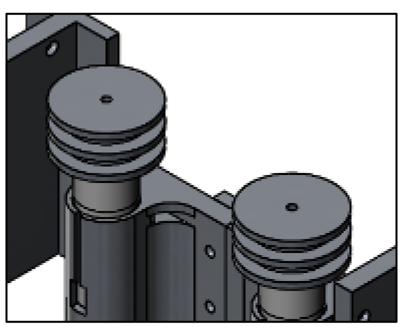

Figure 1.9 Initial Pulley design

This semester the team did tests on how much slack occurred in a length of cord when moving in extension and in flexion, and then Inna was able to derive a ratio from this test. The ratio can be referenced below.

$$1.44r_{back} = r_{front} \tag{1.1}$$

The first iteration of a pulley design using this ratio is also shown below.

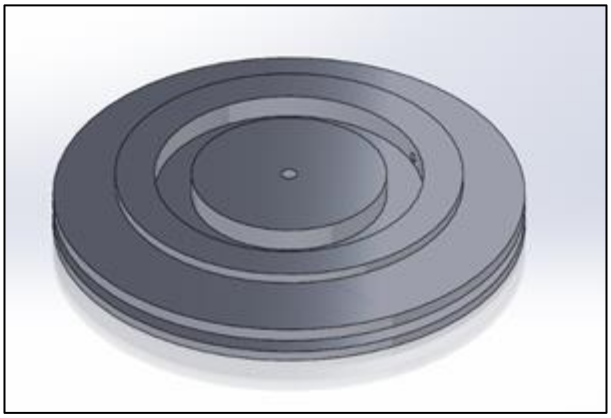

Figure 1.10

Figure 1.11

1.2.3 Component 3: Cable Clamp Design Iterations

The hip exoskeleton transmits torque from the electric motors via tension cables. The cables are routed through a Bowden tube, which terminates at a location coplanar with extension/flexion motion of the user's thigh. It is critical that the termination point of the Bowden tube be maintained at a known position deviation can cause fluctuation in the torque being applied to the user. Design of this component has been changed to favor simple manufacturing. The previous design was a single piece block which secures the tube using set screws. The client was concerned that this design might cause excessive mechanical wear to the cables, as they will rub against the black prior to exiting. The redesigned clamp will hold the outer sheath of the Bowden cable. The inner sheath will extend beyond the clamp, ensuring the cord only directly contact the inner sheathe before exiting the tube. The new design is two pieces that achieve clamping pressure by being bolted together. This design simplifies the manufacturing process, allowing for numerous parts to be made quickly and easily, ensuring an iterative process may occur to refine the design.

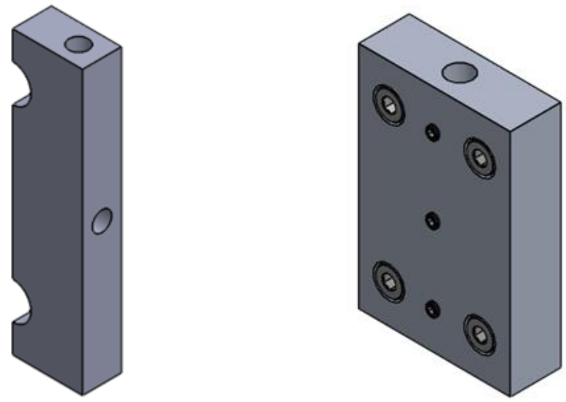

Figure 1.12: Cable clamp design revisions: new (left) vs old (right)

1.2.4 Component 4: Hip Belt Iterations

Shown below is a CAD model of the current state of the hip belt design.

Figure 1.13: Current State of Hip Belt Design

The simplicity of the molded rectangular pieces of Kydex in this design has proven to be effective. However, manufacturing this design has identified some issues with mounting the hinges. Originally the hinges were mounted to the kydex with epoxy, but this proved to not be strong enough. To fix this issue, future iterations of the hip belt design will bolt the hinges to the hip belt, increasing the strength of this part of the design.

1.2.5 Component 5: Knee Brace Iterations

Shown below is the current state of the knee brace design.

Figure 1.14: Current State of Knee Brace Design

This iteration of the knee brace design proved to be very easy to manufacture, however some possible improvements for the manufacturing process were identified. One issue with manufacturing this design was cutting the knee braces by hand. While this was easy to do, it left the part very rough around the edges. Ideally, finalized parts for this component will be cut on a CNC router prior to molding. This will allow for parts to have a better fit and finish. Additionally, the hinge is currently held together with a flush mounted bolt and a nylon lock-nut. While this proved to effective and inexpensive, it could be improved with better hardware.

2 Standards, Codes, and Regulations

Engineers have an ethical responsibility to ensure a design is safe for the stakeholders. It can be difficult to know when designing a new product exactly how to measure the inherent safety of a design. Industry standards and legal requirements exist to ensure a design is safe before it reaches the end user. The team is obligated to identify relevant documentation and ensure compliance of the Hip Exoskeleton design. The following section is included to summarize the standards, codes, and regulations that apply to their project.

2.1 Standards applied to project

Table 2.1 Applicable standards

Ref. #	Standard Identifying Code	Title of Standard	How it applied to Project
1	ASNI/AAMI HE 74:2001	Human Factors Design Process for Medical Devices	Helps in the design of how the device with interface with the user in a safe manner.
2	HFDS – ch.14	Human Factors Design Standard – Anthropometry and biomechanics	Provides aggregated statistical data for body measurements; Offers standard practices when designing for human ergonomics
3	ASTM F3323	Standard Terminology for Exoskeletons and Exosuits	Provides a reference for common applicable terms that will be used in the final documentation of the project.
4	ASTM F3392	Standard Practice for Exoskeleton Wearing, Care, and Maintenance Instructions	Specifies minimum information to be conveyed in user documentation.
5	ASTM F3427	Standard Practice for Recording Environmental Conditions for Utilization with Exoskeleton Test Methods	Establishes what environmental conditions to consider need to be specified and potential performance impacts.

Committee F48 was established by ASTM International to develop a collection of standards specific to the exoskeleton and exosuit industry. As of the date of this memo, the committee has published three standards (Table 2.1, Ref # 3,4,5), though they have numerous proposed new standards still in development. Future work on the Hip Exoskeleton will be affected by the implementation of the proposed standards.

3 Risk Analysis and Mitigation

The Risk Analysis and Mitigation have not been changed from last semester even though we did some changes on the design for more simplicity for the user and the manufactory progress but still all subsystems and components same from last semester. The below sections discuss the FMEA of this current design. This includes the top ten projected critical failures of the design and a discussion on risks and trade-offs analysis.

3.1 Potential Failures Identified Fall Semester

Critical Failures

The following sections will cover the top ten critical failures that could result from our current design. To categorize the failures, we split the system into four subsystems: the soft harness, rigid frame, actuation system, and control systems. These failures were recorded and ranked in the FMEA sheet which was done by the team. It can be referenced in Appendix A.

3.1.1 Potential Critical Failure 1: Creep in the Chassis

This failure relates to creep deformation on the chassis, which is the main metal bar in the rigid frame. The failure can be caused by the rigid frame material being too thin, which makes it more susceptible to deformation when is being used. When this happens, the rigid frame will no longer fit close to the user's body. To mitigate the failure the material of the metal can be switched out to something with a higher cycle life.

3.1.2 Potential Critical Failure 2: High Cycle Fatigue in the Spool Holder

High cycle fatigue in the spool holder is caused by the stresses from the spool moving. The reason it is high cycle is because the spool will be moving a lot while the system is active. This failure can be caused by the material of the spool holder not being robust enough. When this happens, fracture can occur which makes the spools unable to operate. This results in the system not working. The failure can be mitigated by using a stronger material and using FEA analysis to understand where the spool holders are experiencing the most stress.

3.1.3 Potential Critical Failure 3: Creep in the Spool Holder

Creep is deformation in the spool holder and is also caused by the stress from the moving spool. This failure can also be caused by the material not being robust enough. When this happens, there may be space in the mount between the spools and bracket. This failure is like the high cycle fatigue failure, and it can also be mitigated by using a stronger material and using FEA analysis to understand the forces.

3.1.4 Potential Critical Failure 4: Combined Creep and Fatigue in Motor Mount

Combined creep and fatigue in the motor mount is a result from the stresses on the component as the motor is running. This can result in deformation or fracture. The failure can be caused by the brackets in the mount being too thin. If this failure happens, motor mount failure will occur which would be a serious failure in the system. It can be mitigated by using a stronger episode in the bracket and using FEA analysis to see the forces acting on the brackets.

3.1.5 Potential Critical Failure 5: High Cycle Fatigue in the Motors

High Cycle Fatigue in the Motors is happening by overstressing and overheating the motor parts. Also, the high vibration can result many issues with motor. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is motor will be Unable to operate. Thus, the Recommended Action to this failure to be mitigated is to provide Preventative maintenance checks and services (FMEA) to avid this failure.

3.1.6 Potential Critical Failure 6: Abrasive Failure in the Spools

Abrasive Failure in the Spools can be caused by Poor Maintenance and Assembly error to the spools. Also, overstressing in the spools can result Abrasive Failure in the Spools. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is erratic operation in the system will happen. Addition to that, the spools might run into noise and heat that will cause effects to other parts in the system. Thus, the Recommended Action to this failure to not happen is to provide Preventative maintenance checks and services (FMEA) to avoid this failure.

Potential Critical Failure 7: Abrasive Wear in Timing Belts

The main issue that will cause the failure of Abrasive Wear in Timing Belts can be caused by Poor Maintenance and Assembly error to the Timing Belts. Another thing causes this failure is overload into the motor will lead high fraction (Abrasive Wear) in the timing belts and that will lead to back it in certain time. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is noise in the system will happen. Addition to that, the Timing Belts might run into noise and heat that will cause effects to other parts in the system. Thus, the Recommended Action to this failure to not happen is to provide Preventative maintenance checks and services (FMEA) to avoid this failure.

3.1.7 Potential Critical Failure 8: Abrasive Wear in Pulleys

Abrasive Wear in Pulleys is can be caused by Poor Maintenance and Assembly error to the pulleys. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is noise in the system. Addition to that, as the abrasive wear in pulleys increase this will lead to the system to be more lose and not safe to use. Thus, the Recommended Action to this failure to be mitigated is to provide a stronger material and Preventative maintenance checks and services (FMEA) to avid this failure.

3.1.8 Potential Critical Failure 9: Fatigue Failure in Shafts

The primary issue that will cause the Fatigue Failure in Shafts is result from Assembly error to the shafts. Also, choosing the low-quality shafts with short cycle life during the assembly of the system another reason of this failure. If this failure occurs, then most likely the first sign of Potential Effect(s) of this Failure is breaking the shafts in the system. Thus, the Recommended Action to this failure to be mitigated is to provide Preventative maintenance checks and services (FMEA) to avid this failure.

3.1.9 Potential Critical Failure 10: Corrosion Wear in Wiring

Corrosion wear in the wiring is when the metal in the wiring will start to corrode due to its chemical reaction with its environment. Though, this failure would most likely be cause by assembly error. Once the material corrodes, it would result in a bad electrical connection which would hinder how the system transfers electricity. Overall, to mitigate this error, checks would need to be made during assembly to make sure there is not exposed wiring. Also, maintenance checks to see if all the wiring are up to our standard.

3.2 Risk Mitigation

Originally the systems with the highest risk of failure were the actuation system and the rigid frame. For the rigid frame there was specifically a risk of there being creep in the chassis. Though this failure isn't present in the final design since the rigid bar chassis has been removed. The main rigid member of the design is the mounting plate which is on the back of the belt. The belt and knee brace are made of thermoplastic which is susceptible to wear. Especially the knee brace since the cords will be attached to it and it will be subject to consistent movement.

There are no longer any spools in the final design, but we are implementing timing belts to the actuation system along with the pulleys and motors. This means that there is still risk for abrasive wear for both the timing belts and the pulleys.

Overall, the ways we can mitigate the risks in our design is to change the material the systems are made of. Also, depending the wear on the pulleys can be mitigates by possible changing the thickness of the overall pulley.

4 APPENDICES

4.1 *Appendix A: Failure Mode and Effect Analysis (Full FMEA sheet)*

Table 4.1 FMEA of each Subsystem, highlighted are top 10 FMEA of each Subsystem

Subsystem	Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Soft Harness	Belt	Abrassive Failure	Poor appearance	2	Overstressing(Contact with subject/frame)	5	Displacement	1	10	Stronger material, larger surface area
		Fretting Wear	Fabric could distress	3	Overstressing	7	Displacement	1	21	Stronger material
	Padding	Abrassive Failure	Poor appearance	1	Poor Quality	5	Displacement	1	5	Stronger material
		Surface Fatigue	Poor appearance	1	Contact with subject	5	Displacement	1	5	Stronger material
	Attachment Point	Fatigue Failure	Breaking, debris	7	Overweight	5	Displacement	1	35	Stronger material, minimize weight on points
		Brittle Fracture	Breaking, debris	7	Overweight	5	Displacement	1	35	Minmize weight
	Knee Brace	Abrassive Failure	Poor appearance	2	Overstressing(Contact with subject)	5	Displacement	1	10	Stronger material
		Fretting Wear	Fabric could distress	3	Overstressing	4	Displacement	1	12	Stronger material
	Buckle	Brittle Fracture	Debris, system can't be worn	7	Overweight, poor quality	3	Displacement	1	21	Minimize weight, high quality material
		Low Cycle Fatigue	Fracture	7	Stress	3	Displacement	1	21	Stronger material
	Adjustments	Abrassive Failure	Ripping	5	Roughly used	2	Displacement	1	10	Stronger material
		Low Cycle Fatigue	Distress in material, stretching	5	Stress	2	Displacement	1	10	Minimize elasticisity
Rigid Frame	Chassis	Creep	Ridid frame no longer fits close to body	5	Rigid frame material too thin	2	Displacement	9	90	Material with higher cycle life
		Deformation Wear	Ridig frame failure	8	Material not hard enough	2	Displacement	2	32	Material with higher cycle life
		High Cycle Fatigue	Ridig frame failure	8	Material not rigid enough	2	Displacement	2	32	Material with higher cycle life
	Spool Holder	High Cycle Fatigue	Fracture, spools unable to operate	8	Material not robust enough	6	Displacement	2	96	Stronger material, FEA analysis
		Creep	Play in mount between spools and brack	5	Material not robust enough	3	Displacement	9	135	Stronger material, FEA analysis
	Coupler	Low Cycle Fatigue	Deformation of braket, no longer fits	5	Coupler experiences unintended stresses	2	User Comfort	3	30	Stronger material, FEA analysis
		Combined Creep and Fatigue	Braket failure, frame detaches from harn	4	Coupler experiences unintended stresses	1	User Comfort	7	28	Stronger material, FEA analysis
	Motor Mount	High Cycle Fatigue	Motor comes free of rigid frame	9	Braket is too thin	4	Displacement	1	36	Stronger material, FEA analysis
		Combined Creep and Fatigue	Motor mount failure	8	Braket is too thin	4	Displacement	9	288	Stronger material, FEA analysis
	Drive Sys Covers	Impact Fatigue	Failure, covers no longer protect user	8	System is dropped	1	User Comfort	1	8	Impact testing
Acuation System	Motors	High Cycle Fatigue	Unable to operate	8	Overstressing	6	Extension/Flexsion	1	48	PMCS
		Thermal Fatigue	Odor, heat,	6	Over Voltage/Current	6	Extension/Flexsion	1	36	PMCS
	Gearbox	High Cycle Fatigue	Noise, erratic operation	5	Overstressing	3	Extension/Flexsion	1	15	PMCS
		THermal Fatigue	Heat	6	Poor Maintenance, Overstressing	3	Extension/Flexsion	1	18	PMCS
		Galling and Seisure	Noise	5	Poor Maintenance, Tolerance stack-up	3	Extension/Flexsion	1	15	PMCS
	Spools	Abrassive Failure	erratic operation, noise, heat	5	Poor Maintenance	4	Displacement	3	60	PMCS
		Stress Rupture	debris, unable to operate	9	Overstressing	1	Extension/Flexsion	1	9	PMCS
	Timing Belts	Abrasive Wear	Noise	7	Poor maintenance	5	Extension/Flexsion	7	245	PMCS
	Pulleys	Abrasive Wear	Noise	7	Assembly error	2	Displacemnet	7	98	PMCS
	Shafts	Fatigue Failure	Breaking	7	Assembly error	2	Extension/Flexsion	3	42	PMCS
	Webbing	Fretting Wear	Distress in material, stretching	5	Overstressing	5	User Comfort	1	25	PMCS
Control Systems	Battery	Corision Fatigue	bad connection, no power	9	Assembly error	1	Displacement	1	9	PMCS
		Thermal Fatigue	loss power, chemical may exposed	9	Overstressing	2	Extension/Flexsion	1	18	PMCS
	Wiring	Corision Wear	bad electrical connection	7	Assembly error	1	Extension/Flexsion	6	42	PMCS
		Abrasive Wear	heat	6	Overstressing	3	Extension/Flexsion	2	36	PMCS
	Sensors	Deformation Wear	unaccurate read, erratic operation	7	Assembly error	1	Extension/Flexsion	2	14	Calibration schedule
		Abrassive Wear	Noise, erratic operation	6	Fracture	2	Extension/Flexsion	2	24	PMCS
	Control Module	Corision Wear	Heat	6	Overstressing	1	Extension/Flexsion	6	36	Stronger material, FEA analysis
		Thermal Fatigue	heat	6	Overstressing	3	Extension/Flexsion	2	36	Stronger material, FEA analysis
	Switches	Low Cycle Fatigue	no connection, no power	7	Assembly error,Overstressing,Fracture	1	Displacement	1	7	Stronger material, FEA analysis
		Impact Fatigue	bad quality,noise	5	Assembly error	1	Displacement	1	5	Stronger material, FEA analysis