NORTHERN ARIZONA UNIVERSITY
Mechanical Engineering

Team 19F13

Biomechatronic Hip Exoskeleton Team (BHET)

To: Dr. Sarah Oman & Ulises Fuentes

From: Sean Oviedo, Mohanad Fakkeh, Ruffa Inna Quiambao, and Keegan Ragan

Date: 02/28/2020

Subject: Implementation Memo

The goal of this capstone project is to design and build the mechanical portion of a biomechatronic hip exoskeleton. This hip exoskeleton will be used to reduce the metabolic cost of walking for children with cerebral palsy. The design this capstone team implements will ultimately be used by the Northern Arizona University Biomechatronics laboratory. The primary focus of this memo is to go over the current implementation for the project based on the manufacturing plan and the design changes for the project up to the time of this memo. In addition, this memo will provide plans for further manufacturing, a schedule breakdown and a budget breakdown.

1 Implementation

This section of the report will break down and describe the different manufacturing processes required to complete this project. Additionally, this section will cover the three main iterations the hip exoskeleton design has gone through. Iterations are broken down by subsystem to highlight the specific changes introduced in each iteration. The three iterations span from presentation 3 of the first semester to the time of this memo.

1.1 Manufacturing

The below sections describe the various manufacturing processes that will be used to construct the hip exoskeleton this semester.

1.1.1 Machining/Milling

All components made from aluminum will have to be machined in the NAU machine shop. All machining will be done by group members to reduce the time required to manufacture parts. All parts will be made out of 6061 T6 aluminum, which is both inexpensive and easy to machine. At the time of this memo, some parts have already been manufactured in the machine shop. The below figure shows a motor mount that was recently cut on a CNC mill.

Figure 1: Motor mount cut on a CNC mill

Machining has proven to be an effective way to produce parts that accurately reflect designs created in SolidWorks. Currently, group members are in the machine shop multiple times a week to manufacture parts. This will continue until the design is completed and ready for testing.

1.1.2 3D Printing

3D printing was used more during the Fall semester to manufacture the first prototypes (design iterations v1 and v2). The components manufactured using 3D printing include the motor mount, drive pulleys and Bowden tube clamps. These components will be milled from aluminum in the final version. 3D printing may also be used for some non-critical components to cut down on cost and machining time.

1.1.3 Heat Forming

The belt and knee brace are made of Kydex, a thermoplastic that is used to create form-fit coverings such as holsters. Overall, forming this thermoplastic is simple. First, we cut out the form of the belt and knee brace from the thermoplastic. The belt was cut into three sections for the left hip, right hip, and back. Then the thermoplastic was heated up with a heat gun, then we placed the heated and softened material on the user. For protection a towel was placed on the area being shaped, it is also thin enough protection so that the thermoplastic was efficiently formed. The knee brace has been cut, the shape was referenced from a template, and it will be formed in the next week. It follows the same process, the thermoplastic will be heated, and then it will be formed onto the user's knee. The user's knee will also be protected by a towel to avoid burns.

1.2 Design Changes

The following section will give an overview of the major design changes that the hip exoskeleton design has gone through. These design iterations go as far back to the beginning of the first semester to the time of this memo.

1.2.1 Design Iteration 1

The below figures show both the CAD model and prototype of the first design iteration. Aspects of the design are broken into subsystems in the below sections. This first iteration of the design was created around the time of presentation 3 in the first semester. This design acted as a strong starting point for the team but ultimately needed revisions to better fit the customer needs.

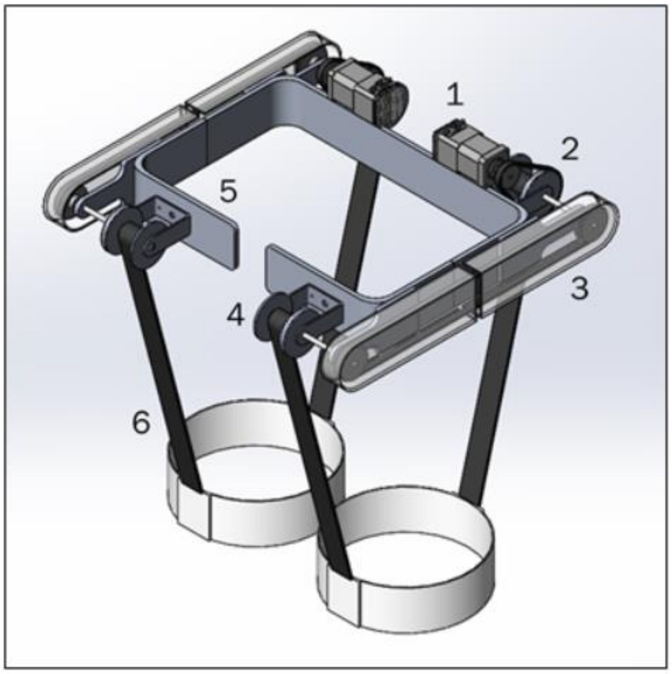

Figure 2: CAD model of design iteration 1 which employs a dual-pulley belt actuation system.

Figure 3: Low-Fidelity prototype for iteration 1 of the BHE

1.2.1.1 Actuation System

The actuation system for this iteration relied on two motors placed at the back of the rigid frame, which were connected to the two back pulleys. These back pulleys, and the two front pulleys, were connected to a belt system which would move the pulleys in the needed direction. The actuation was done by the force pulling on the soft belts which would have been attached to a knee brace.

1.2.1.2 Motor mount

The drive system for V1 transmits force through a belt drive system, which multiplies the output torque through reductions in the pulleys. Only two motors are used to reduce weight and cost, aligning with the customer's requirements. This design causes the footprint of the device to extend away from the wearer's hips, since the belt to transfer torque to the front pulley must be aligned with a rigid member.

1.2.1.3 Knee Brace

The initial design for the hip exoskeleton accounted for using an off-the-shelf soft knee brace as a connection point between the soft belts and the user's knees. At the time of this design iteration, using this type of knee brace was the most practical, as it was cheap, easy to obtain, and comfortable for the user. The use of an off-the-shelf knee brace also allowed the team to dedicate more time to designing the more complicated drive systems of the hip exoskeleton.

1.2.2 Design Iteration 2

After reviewing the first design iteration, the client identified the need to reduce the footprint of the design. The box-like frame could potentially interfere with the wearer's natural arm movement during the walking cycle. The client stressed the importance of maintaining the natural range of motion for arms and legs during the walking cycle. With this information, changes were made to the design, the primary change was the decision to use a Bowden cable system to transmit torque. This allowed for the components to be arranged in a more space-optimized configuration and eliminated the need to align drivetrain components. The following sections describe the changes made to the hip exoskeleton subsystems for design iteration 2.

Figure 4: Design iteration 2 initial CAD rendering

Figure 5: Prototype demonstrating the changes made for design iteration 2

1.2.2.1 Actuation System

The actuation between Iteration 1 and Iteration 2 changed a lot. Since there were concerns of fraying in the soft belts in Iteration 1 after extended use, this new design moved towards using high strength cord and Bowden tubes. The design still relies on two motors, though these motors now lay vertical on the back surface of the rigid frame, the pulleys are placed on the motors, and the cord is wrapped around it. The cord is threaded though the Bowden tubes which act as a protection. The tubes are placed in these clamps which the cord exits through and then attach to the front or back of the knee brace.

1.2.2.2 Motor Mount

The initial redesign maintained the horizontal motor orientation but was changed to vertical for the prototype, shown in Figure 6. This accommodates the implementation of the Bowden tube actuation, which was initially designed to route over the shoulders but was changed to reduce the total length of tubing and cord material. This version of the motor mount was designed as a single piece that encloses the motor and attaches to the frame with threaded fasteners.

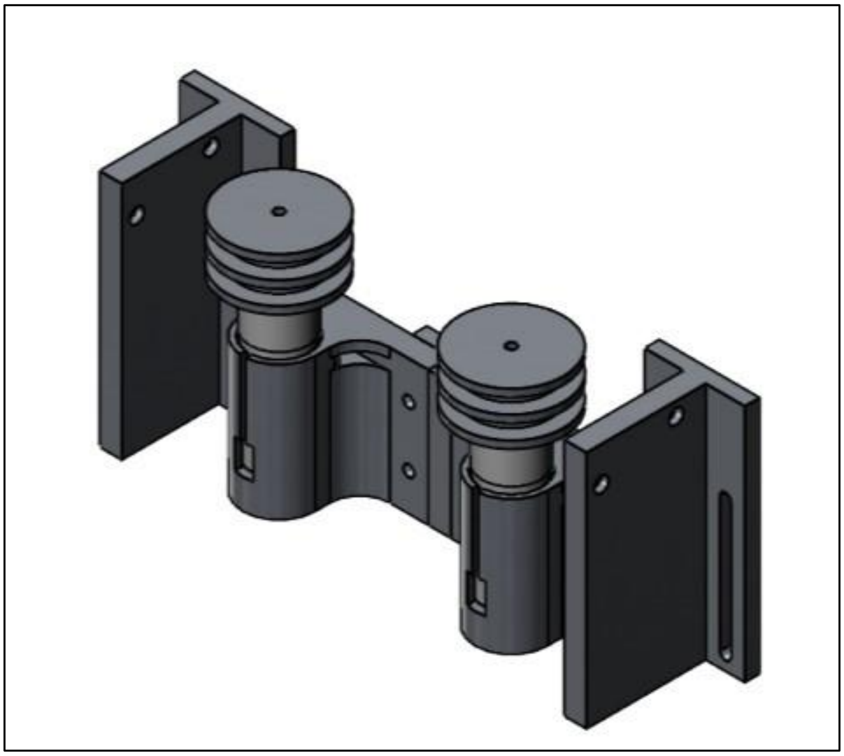

Figure 6: Motor mount for design iteration 2

1.2.2.3 Knee Brace

As shown in Figure 5, the off-the-shelf soft knee brace was carried over from the first iteration. However, in this second iteration some issues with this type of knee brace were established. Namely, the soft knee brace was not a stable enough platform to connect the Bowden cables. What this meant for the user was that when the Bowden cables were attached it would cause the knee brace to ride up the user's leg. This resulted in discomfort for the user and inefficiencies in the torque applied to the user's hips. To address this issue, the team looked to designing a fully rigid knee brace for the next iteration.

1.2.3 Design Iteration 3

The primary changes made for iteration 3 include creating a rigid, hinged knee brace, revising the motor mount components, integrating the soft harness and rigid frame into a molded thermoplastic hip belt with subsystem components attached.

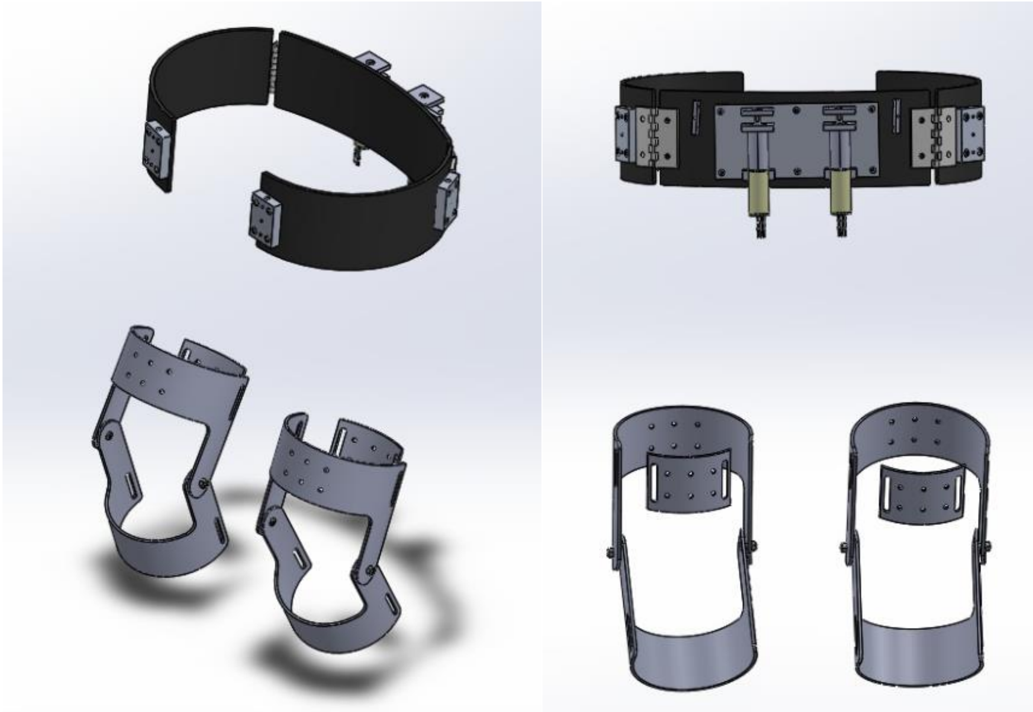

Figure 7: Design iteration 3 full assembly

1.2.3.1 Frame/Harness

In the first and second iterations, the hip belt rigid frame and harness were separate components. After discussions with our client at the end of last semester, we decided to design the rigid frame and harness together as one component. The result is more simplicity in the manufacturing and design process. The frame in this iteration will be primarily constructed from molded Kydex, and will utilize hinges to allow the user to easily take the exoskeleton on and off.

1.2.3.2 Actuation System

The actuation between Iteration 2 and Iteration 3 did not change a lot. The idea is the same, the movement will be actuated by a cord which is attached to the rigid knee braces. The motors are still placed vertically, though there are changes to the type of pulley that is used in this iteration. Also, the use of timing belts is going to be explored in this iteration. The specific motor in this design has a short shaft to place the pulleys on. This issue will be explored in our testing procedures.

1.2.3.3 Motor Mount

This version of the motor mount maintains the vertical motor orientation. The design was changed from a single piece enclosing the motor to smaller discrete components which support the motor at different locations. These changes were implemented to reduce the manufacturing complexity and to eliminate unnecessary material, reducing the overall weight of the design. Figure 8 shows a CAD drawing of the motor mount design.

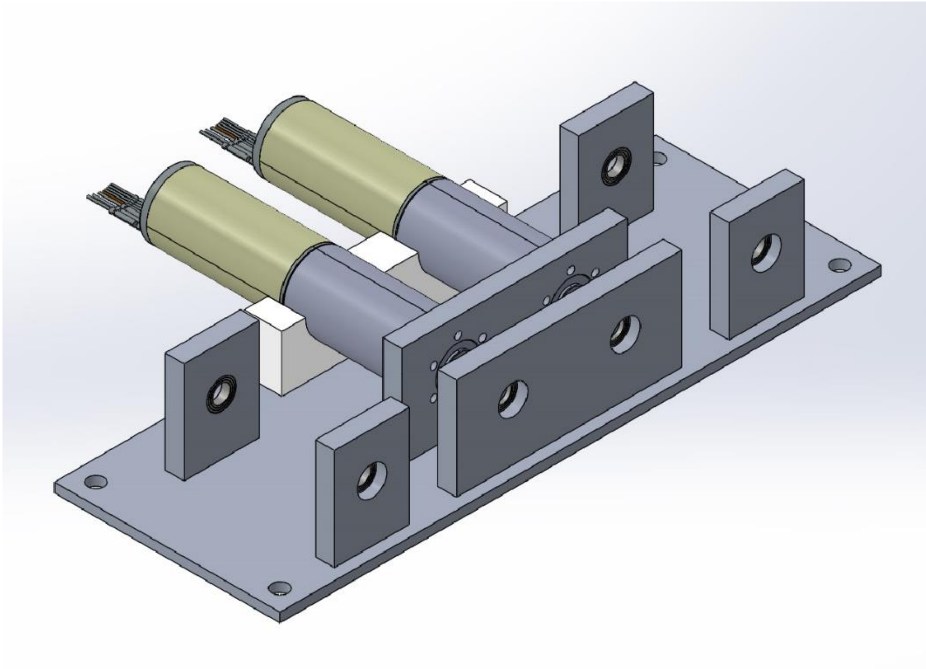

Figure 8: Current revision of the motor mount assembly

All of the grey components in the above figure (excluding the motors) will be machined out of 6061 T6 aluminum. The motor support (shown in white in the above figure) will be 3D printed. This is because it keeps the motors in place but at the same time doesn't experience enough stress to justify it being made out of aluminum. 3D printing this component will also reduce weight.

1.2.3.4 Knee Brace

The design for the knee brace in this iteration can be seen in Figure 7. This new knee brace design is fully rigid and made from 2 pieces of molded Kydex connected by hinges. This new design should improve upon the brace used in iterations 1 and 2 by acting as a more solid mounting point for the Bowden cables. The hope is that this design will not shift up the users leg and therefore allow for a more efficient application of torque to the user's hips.

2 Future Implementation

This section will discuss the remaining manufacturing required for this project, a schedule breakdown showing the remaining deliverables, and budget breakdown.

2.1 Further Manufacturing and Design

At the time of this memo, the remaining manufacturing is primarily machining all of the components in the motor mount assembly (shown in Figure 8). This is by far the most time-consuming part of the manufacturing process, so it is the current focus of the team. There is still some Kydex molding that must be completed, but this will only take a few hours which is minor compared to machining components out of aluminum. After these processes are done, the hip exoskeleton will be fully assembled and prepared for testing.

There are no anticipated design changes at this point in the project. There are possible modifications though. For example, if the motor mount assembly is too heavy when fully assembled, individual components will be taken to the machine shop and drilled out to reduce weight.

2.2 Schedule Breakdown

The following figure and table represent our schedule until the Hardware Review 2. Overall, the schedule has been going smoothly, and we have not run into any major issues regarding manufacturing.

Table 1 Current Gantt chart

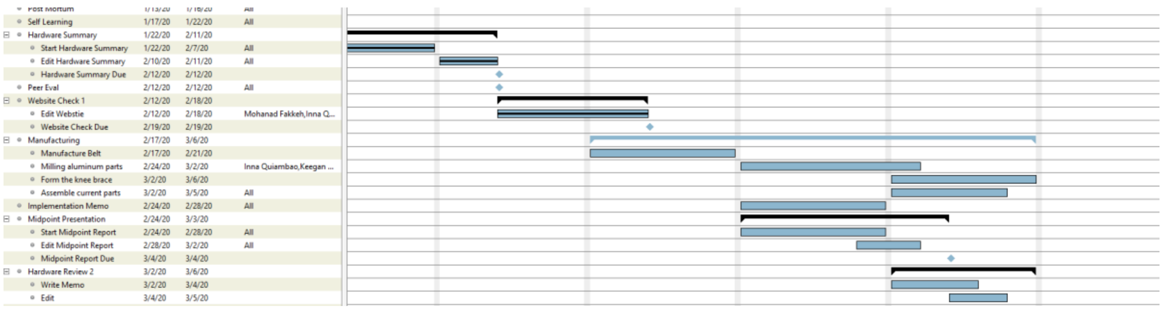

Table 2 Task list

Website Check 1	2/12/20	2/18/20	
Edit Webstie	2/12/20	2/18/20	Mohanad Fakkeh,Inna Q...
Website Check Due	2/19/20	2/19/20	
Manufacturing	2/17/20	3/6/20	
Manufacture Belt	2/17/20	2/21/20	
Milling aluminum parts	2/24/20	3/2/20	Inna Quiambao,Keegan ...
Form the knee brace	3/2/20	3/6/20	
Assemble current parts	3/2/20	3/4/20	All
Implementation Memo	2/24/20	2/28/20	All
Midpoint Presentation	2/24/20	3/3/20	
Start Midpoint Report	2/24/20	2/28/20	All
Edit Midpoint Report	2/28/20	3/2/20	All
Midpoint Report Due	3/4/20	3/4/20	
Hardware Review 2	3/2/20	3/6/20	
Write Memo	3/2/20	3/4/20	
Edit	3/4/20	3/5/20	
Submit	3/5/20	3/6/20	

By Monday, March 2nd, we want to be done milling the major components. Then, we will form the knee brace that week, ideally before the presentations on March 4th. March 3rd the team wants to assemble the current parts we have manufactured so that they can be used for material in the presentation. Overall, our focus is mostly on completing the belt including the base plate, motor mounts, etc. Forming the knee brace does not take a lot of time so that is not a major priority.

Keegan and Inna have been in charge of manufacturing at 98C. They've been manufacturing the motor mounts and base plate. The whole team works on forming the thermoplastic, since people are needed to cut the thermoplastic while others are forming it to Keegan. Sean and Mohanad have been making design changes where needed and have also focused on getting their safety training done so that they can go into the machine shop to assist with any further manufacturing.

2.3 Budget breakdown

As shown in the below table, the bill of materials was constructed for the most recent design iteration. The new biomechatronic hip exoskeleton design will be made of aluminum (6061 T6) and Kydex. We have determined to use Aluminum (6061 T6) based on its low cost, low weight, and appropriate strength. Also, our client agrees with using this type of aluminum snice the current exoskeletons in the biomechatronics lab use 6061 T6 with no issues. The aluminum has been purchased in the form of rectangular bar stock so it can be machined into the appropriate components in the machine shop (98C). Kydex was selected for the hip belt and knee brace for its low weight, low cost, and it comes in flat sheets that can be easily cut and molded to the shape of the user's body. Our client provided us with the Kydex so we did not have to purchase it for ourselves (this is why it is highlighted yellow in the BOM).

Table 3 Bill of Materials for Hardware Review Final Design

PART (SOLIDWORKS PART NAME)	MATERIAL	DIMENSIONS (in.)	SUPPLIER	QTY.	COST/UNIT	COST
Base_Plate_V1	6061 T6 AL	0.25 x 3 x 12	OnlineMetals	1	$6.30	$6.30
Bearing_Block_V1	6061 T6 AL	0.25 x 1.5 x 48	OnlineMetals	1	$10.05	$10.05
Housing Clamps (At motor assembly)						
Housing Clamps (At cable termination)						
Face_Plate_V2						
Mounting_Bracket_V5	6061 T6 AL	0.5 x 1.5 x 24	OnlineMetals	1	$12.06	$12.06
KneeBraceTop_V2	Kydex	0.125 x 12 x 12	McMaster-Carr	2	$10.16	$20.32
KneeBraceTop-Back_V2						
KneeBraceBottom_V2						
Motors	N/A	N/A	Maxxon	2	$815.73	$1,631.46
					Total	$1,680.19
HARDWARE	**MATERIAL**	**DIMENSIONS (in.)**	**SUPPLIER**	**QTY.**	**COST/UNIT**	**COST**
M4 x 20mm (100 pack)	SS A2-70	N/A	Copper State	1	$8.76	$8.76
M4 x 10mm (100 pack)	SS A2-70	N/A	Copper State	1	$6.20	$6.20
M3 x 10mm (100 pack)	SS A2-70	N/A	Copper State	1	$4.09	$4.09
M3 x 20mm (100 pack)	SS A2-70	N/A	Copper State	1	$5.77	$5.77
Shoulder screw	316 SS	0.25 Shoulder, 10-32	McMaster-Carr	2	$5.32	$10.64
Nylon Insert Locknut (50 Pack)	316 SS	10-32 Thread Size	McMaster-Carr	1	$4.71	$4.71
Bearings for Bearing_Block_V1	Steel	3mm W, ID 6mm, OD 10mm	McMaster-Carr	2	$12.06	$24.12
					Total	$64.29
Alternative Part Materials	**MATERIAL**	**DIMENSIONS (in.)**	**SUPPLIER**	**QTY.**	**COST/UNIT**	**COST**
Bearing_Block_V1	7075 T6	0.25 x 1.5 x 48	OnlineMetals	1	$40.24	$40.24
Housing Clamps (At motor assembly)						
Housing Clamps (At cable termination)						
Face_Plate_V2						
					Total	$40.24
Legend			Shipping - Online Metals			$21.92
Already Purchased			Amount Purchased			$1,681.79
Aquired w/out Purchase			Amount to Purchase			$64.29
No longer needed			Budget			$2,250.00
			Funds Available			$568.21

The total budget that was provided to the Biomechatronic Hip Exoskeleton Team (BHET) for this new design is $2250. Total cost of the hip exoskeleton at the time of this memo is roughly $1681.79. This leaves roughly $568.21 to cover shipping, manufacturing, testing, and any additional materials. Items that still need to be purchased by the team is hardware (nuts and bolts) and Bowden cables. Hardware is projected to cost roughly $65 or less, and the Bowden cable system is projected to cost roughly $60. This would still leave roughly $450 remaining after those items are purchased. Manufacturing costs should be relatively low since the exoskeleton will be produced by the capstone team. At this point the project is well below the allotted budget.