NORTHERN ARIZONA UNIVERSITY
Mechanical Engineering

19F13

Biomechatronic Hip Exoskeleton Team

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Subject: Engineering Requirements and Testing Procedures Revamp

The primary focus of this memo is to go over Customer and Engineering Requirements and to describe any changes that have been made to them since last semester. The Engineering Requirements provide the target and tolerance values needed for the final product. Also, team will conduct test procedures based on these engineering requirements. The test procedures will provide a complete description of how the final exoskeleton design meets the established engineering requirements.

1 Customer Requirements (CRs)

The instructor of the course and sponsor for the project defined the customer requirements for the exoskeleton. The following table displays the customer requirements and their respective weights.

Table 1: Customer Requirements and Weights

Customer Requirements	Weights
Hip Actuation	5
Full Range of Motion	5
Sense Torque	5
Minimize Metabolic Cost	4
Safe to Operate	4
Untethered	4
Durable	3
Easy to don and doff	2
Comfortable	2
Reliable	2
Within Budget	1
Fit small to medium build	1

The main objective of our design is to actuate movement in the hip. The movement is assisted in extension/flexion but needs to be passive in all other directions. The team's design also needs to sense the torque applied within the system. These three requirements are a priority in the design which is why they are ranked the highest out of all the customer needs.

Another goal is to minimize the metabolic cost of the user's walking. This means that the design cannot be too heavy because then it would require more work to operate. Also, the design needs to be safe and able to be used untethered. The untethered aspect means that the design can be taken anywhere without needing to be plugged into a power source, and the team also must ensure that the device will not harm the user while activated. These requirements are of moderate priority.

The next requirements revolve more around how the exoskeleton interacts with the user. Durability is important in this design because the subject will most likely be using it in their daily lives. It is important, but it is not our priority to make it last for years at this point in the process. The next requirements revolve around it being comfortable, easy to take on and off, and reliable. Exoskeleton's are designed to be an extension of our bodies, so the team wants the final design to be as comfortable and reliable as possible for the user. Though if needed the team will sacrifice some aspects of comfortability to ensure the design works.

The last requirements are that the design needs to fit within budget and fit small to medium builds. They are ranked the lowest since we do not want budget to hinder our design choices. However, this does not mean that we will ignore the budget, we want to be as open as we can with our choices. Lastly, our design is meant for children, so we want the design to be adjustable. Though when designing we won't be testing on smaller frames, so it is not currently a priority.

After we have met with our client this semester regarding the Customer Requirements, the client approved all of them except the following: Sense Torque, Minimize Metabolic Cost, and Untethered. These are not relevant anymore and are now out of the scope of the current design.

2 Engineering Requirements (ERs)

To meet the customer requirements, they must be translated into quantitative technical specifications. This allows the team to quantify the customer's needs and measure the designs ability to meet those needs. The following section covers the individual engineering requirements for the Hip Exo project. Some of these engineering requirements have changed since last semester. If this is the case, it is noted in the section heading. All other engineering requirements have remained unchanged since last semester.

2.1 ER #1: Torque Applied

This ER quantifies the amount of torque assistance to the wearer. The device provides assistive torque during extension/flexion only. An important detail of this requirement states that the design must be able to deliver the specified torque at any point along the full extension/flexion range of motion (ER #10).

2.1.1 ER #1: Torque Applied Target = 12.5 N-m

The target value for applied torque was determined over several steps. The customer initially stated that the design should be able to apply 25% of the wearers natural torque, assuming the average patient has a natural hip joint torque of $1\frac{N\cdot m}{kg}$. This constitutes the peak torque the design must be capable of delivering, it is assumed that the PWM controlled motors will be capable of torque delivery from 0 to peak. Taking the maximum mass of a patient from the NAU Biomechatronic Lab records ($50\ kg$) and multiplying by the client-stated 25% gives $12.5\ N \cdot m$.

2.1.2 ER #1: Torque Applied Tolerance = ±3.5 N-m

This tolerance was specified by the client.

2.2 ER #2: Metabolic Cost of Walking (Now out of project scope)

The metabolic cost of walking measures how much energy is consumed by the user during a normal walking cycle. Knowing the metabolic cost of walking with and without the hip exoskeleton allows for an assessment of the hip exoskeleton's effectiveness. Determining the metabolic cost of walking is a difficult process that requires the hip exoskeleton to be fully tested and functioning. Because of this, determining the metabolic cost of walking with the hip exoskeleton is now out of the scope of this project.

2.2.1 ER #2: Metabolic Cost of Walking Target = N/A

A target value was not specified by our client. The biomechatronics laboratory currently has no data on this engineering requirement.

2.2.2 ER #2: Metabolic Cost of Walking Tolerance = N/A

Similar to the target value described above, no tolerance value was specified by the client.

2.3 ER #3: Time to don/doff

The user must be able to put on and take off the hip exoskeleton within a reasonable amount of time. This makes the device more user-friendly.

2.3.1 ER #3: Time to don/doff Target = [1 minute]

After meetings with our client it was determined that it should take 1 minute to put the device on and 1 minute to remove the device. This value was chosen because it seemed like the most reasonable amount of time for this requirement.

2.3.2 ER #3: Time to don/doff Tolerance = [+/-10 Second]

Similar to the target value above, a tolerance of +/- 10 seconds was chosen because it seemed like a reasonable and achievable amount of time for this requirement.

2.4 ER #4: User Comfort Rating

The user comfort rating is a qualitative assessment of individual user's experience while using the hip exoskeleton. Multiple user's will be asked to rate the device's overall comfort on a scale of 1-10.

2.4.1 ER #4: User Comfort Rating Target = [9]

The goal of this capstone project is to produce a hip exoskeleton design that is as comfortable as possible. An average rating of 9/10 fits with this goal while accounting for the fact that a perfect average is not realistic.

2.4.2 ER #4: User Comfort Rating Tolerance = [+/-1]

This tolerance puts the expected user comfort rating average to be between an 8 and a 10. This intuitively seems like a reasonable goal to reach for overall user comfort.

2.5 ER #5: Weight

The hip exoskeleton must be as light as possible in order to reduce the user's metabolic cost of walking while wearing the device. A lighter exoskeleton yields a better user experience.

2.5.1 ER #5: Weight - Target = Minimize

The current hip exoskeleton does not have a target weight. The client will talk to us about it when we are manufacturing. Presently, we want to minimize the weight as much as possible with the present materials that have been acquired.

2.5.2 ER #5: Weight - Tolerance = not specified

Presently, there are no tolerances set for the weight. It is our priority to minimize it as much as possible.

2.6 ER #6: Operation time/cycle (Now out of project scope)

The hip exoskeleton must operate long enough to allow for a substantial amount of data to be collected from tests with users. Because the hip exoskeleton will now be using a control system from current exoskeletons, operation time is no longer under the control of this capstone team.

2.6.1 ER #6: Operation time/cycle Target = N/A

Original operation time was expected to be 2 hours. Now that the capstone team is no longer responsible for the exoskeleton's control systems, this engineering requirement is out of the scope of this project. The hip exoskeleton will now have an operation time/cycle similar to current exoskeletons at the biomechatronics laboratory. The run time of current exoskeletons is not currently known by the capstone team as it does not apply to this project.

2.6.2 ER #6: Operation time/cycle Tolerance = N/A

No longer applicable to this project.

2.7 ER #7: Power Required

This requirement specifies the input power to the device. How much power is needed to operate the motors and control module.

2.7.1 ER #7: Power Required Target = 185 Watts

The target value was determined based on the manufacturer ratings for each component, added together. The motors are rated at 90W each. The power draw for the control module was estimated using the peak power required for an Arduino microcontroller at 2.4W.

2.7.2 ER #7: Power Required Tolerance = ±1W

This number was estimated because the specific power required for the control module will not be known and is beyond the scope of this project.

2.8 ER #8: Cycles to Failure

The hip exoskeleton should be able to function for a given amount of cycles before maintenance is required or parts need to be replaced.

2.8.1 ER #8: Cycles to Failure Target = Not yet known

The client of this project was not able to provide a specific target value for cycles to failure. This was because they have not yet tested an exoskeleton of this type before. To compensate for this, fatigue testing will be conducted on the completed exoskeleton. The procedure for this fatigue testing will be described in a below section.

2.8.2 ER #8: Cycles to Failure Tolerance = Not yet known

As described above, tolerances for this engineering requirement are not yet known, but will determined during testing.

2.9 ER #9: Cost to Manufacture

A requirement of this project was that hip exoskeleton stay within the allotted budget of $2250.

2.9.1 ER #9: Cost to Manufacture Target = [<$1900]

The total budget for this project is $2250, and it was already known that the motors would cost roughly $1600. This leaves roughly $300 for all other materials required to build the exoskeleton. The extra $350 is being set aside for testing and manufacturing costs. This value has not changed significantly since last semester.

2.9.2 ER #9: Cost to Manufacture Tolerance = [+/-$100]

A tolerance of +/-$100 was factored into the budget for this project. This is to account for any differences in material pricing, or if additional materials are required closer to the completion of the project.

2.10 ER #10: Extension/Flexion

This value describes the range in extension/flexion that the hip exoskeleton applies torque to the user's hips.

2.10.1 ER #10: Extension/ Flexion Target = [-30° Extension/45° Flexion]

The target value for this engineering requirement was provided to the team by Leah of the Biomechatronics Lab and from published material on similar devices [1, 2]. This target is important because the primary requirement of the hip exoskeleton is to actuate movement in extension and flexion.

2.10.2 ER #10: Extension/ Flexion Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

2.11 ER #11: Abduction/Adduction

This value describes the range in abduction/adduction that the user has full freedom of movement.

2.11.1 ER #11: Abduction/Adduction - Target = [40° Abduction/ 20° Adduction]

The target value for this requirement was taken from the Range of Joint Motion Evaluation Chart [3]. This value is important because our hip exoskeleton requires free range of motion in all other directions besides extension and flexion.

2.11.2 ER #11: Abduction/Adduction - Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

2.12 ER #12: Rotation

This value describes the range in rotation that the user has full freedom of movement.

2.12.1 ER #12: Rotation - Target = [45°]

This target value was taken from a report by Sanker et al [1]. This target value is important because, similar to abduction and adduction, the designed hip exoskeleton needs to have free range of rotation when it is powered.

2.12.2 ER #12: Rotation - Tolerance = [+/-5°]

These tolerances were taken to keep in mind that not everyone has the same range of motion.

2.13 ER #13: Noise (No longer relevant)

An important requirement of this project is that the hip exoskeleton produces as little noise as possible. Less noise generally results in a better and more comfortable user experience.

2.13.1 ER #13: Noise - Target = Minimize

Previously, the goal was to design a device that reduces noise as much as possible. However, this only applied when the team was weighing between a pneumatic or electric actuation system. Now that the project will utilize an electric actuation system noise is no longer a concern.

2.13.2 ER #13: Noise - Tolerance = Not Specified

No noise tolerances were ever required.

2.14 ER #14: Conformability/Compliance

Conformability/compliance measures the range of body types and sizes that the hip exoskeleton can fit.

2.14.1 ER #14: Conformability/ Compliance - Target = Various Sizes

One of the customer requirements for the hip exoskeleton is that it fits small to medium builds. So, it is our priority to make it as adjustable as possible. Since we are testing it on the team, we all have varying hip sizes, which can be translated into the small and medium sizes of the children.

2.14.2 ER #14: Conformability/ Compliance - Tolerance = not specified

There are no tolerances on how adjustable the hip exoskeleton needs to be. The team just wants it to fit various sizes.

3 Testing Procedures (TPs)

The engineering requirements quantitatively define the project, describing what the design must do through numeric values. When manufacturing is complete, the team needs to verify that the design meets those requirements. Accordingly, the team has developed a series of tests which will measure all the stated engineering requirements. The following section outlines the objectives, procedures, schedule, and required resources for the tests.

3.1 Testing Procedure 1: Torque/Power Output

This test will evaluate the output torque that is produced by the hip-exo. Performing the test allows the team to verify the torque applied and power delivery of the design.

3.1.1 Testing Procedure 1: Objective

The test will be performed using the motor mount assembly, attached to a test fixture. the motor mount will include the final speed reduction pulley and actuation cables, which will be secured to statically mounted load cells. An Arduino microcontroller will be programed to record the output of the load cells and instruct the motor speed controllers. The motors will be powered on for two second intervals, tensioning the cables. Different power levels will be tested to run the motors, to develop an expected range of torque the hip exo is capable of. Each level will be run three times and the results will be averaged.

Power delivery will be evaluated utilizing the motor mount and test fixture, with the load cells replaced by pulleys. Weights will be attached to the cable ends. The test assembly will be placed at the edge of a table, with the cables routed through the pulleys. The motors will be programed to run, lifting the weights. Recording the time taken to move the weight allows the power delivered to be calculated.

3.1.2 Testing Procedure 1: Resources Required

The equipment and resources needed for this test are listed below with a brief description of their use and sources.

Test fixture – simple frame designed to constrain the motor mount and load cells such that they are aligned, and displacement of the load cell occurs colinear with the cord. The test fixture will also be used for fatigue testing. The fixture is currently being designed by the team and will be manufactured by 2/28/2020 using off the shelf materials and tools, already owned by one of the team members. Figure 1 shows the test fixture assembly.

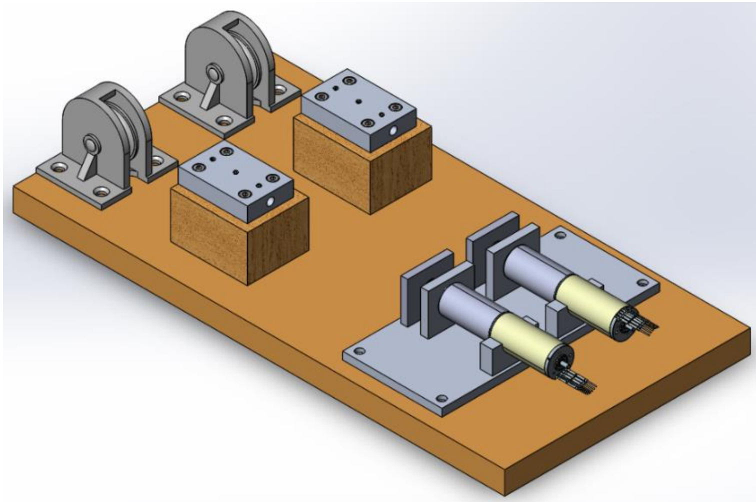

Figure 1 Test fixture CAD rendering, shown in pulley configuration for power test

Motor mount assembly – Including motors, cables, hardware and power source. The individual components will be manufactured by the team in the NAU Machine Shop, building 98C, using raw materials purchased from OnlineMetals.

Load cells (2) – Wheatstone bridge affixed to an aluminum member, sold with a 24-bit analog-to-digital converter. These were purchased by a team member for a previous project.

Arduino microcontroller – Open-source programable microcontroller to interpret and record load cell output. Already owned by a team member. Code will need to be written for the Arduino, which will be done in MATLAB.

Computer – Communicates with Arduino to store the measured data and will be used to process the test results.

3.1.3 Testing Procedure 1: Schedule

This test will require a lot of preparation before it can be run. Manufacture and assembly of the motor mount and test fixture are the team's current priority. Further time is needed to write the Arduino script. Additionally, the team is still waiting for the motors themselves, which are estimated to arrive on 03/27/2020. The milestone dates planned in preparation for this test are summarized in Table 3.1.

Table 3.1 Schedule of tasks for torque/power output test

Task	Date
Complete manufacturing of the motor mount	2/28/2020
Final test fixture design	2/21/2020
Test fixture manufacturing	2/26/2020
Arduino code finished and tested	3/12/2020
Final test equipment assembly	3/19/2020
Run torque test	3/26/2020

3.2 Testing Procedure 2: User Comfort Rating/Survey

3.2.1 Testing Procedure 2: Objective

The primary objective of this test is to get feedback about the new hip exoskeleton design from variety of people and check if there are any minor changes that need to be done to help get a more universal fit. The questions that will be asked to the user are based on customer requirements.

3.2.2 Testing Procedure 2: Resources Required

This test will be conducted at the NAU Biomechatronics Lab. The goal is to get 10 random people to try the new hip exoskeleton design and answer survey questions and comment on their experience. The questions will be provided to the user from an excel sheet that will be run by one of the team members. Table 1 shows the survey questions that will be asked during the test.

Table 3.2 User Comfort Rating/Survey

B	C	D	E	F	G	H	I	J	K	L	M
Survey Qusetion	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9	User 10	Total
User comfort(Hip Belt)											
User comfort(Knee Brace)											
Time to don/doff											

3.2.3 Testing Procedure 2: Schedule

The plan is to do this test when the final design is completed. This is planned to be the week following spring break, between March 23 and March 29 at the NAU Biomechatronics Lab.

3.3 Testing Procedure 3: Fitment Tests

3.3.1 Testing Procedure 3: Objective

This test will be run by the BHET team and it will be conducted on each team member. These tests will test the 'fit' of the device. Specifically, it is testing weight, conformability, and the range of motion. These factors are being tested because conformability is important to this project, since one of the objectives is that there is free range of motion in all other directions besides extension and flexion. Also, since it is a priority to make a soft exoskeleton, the team wants it to be as lightweight as possible.

3.3.2 Testing Procedure 3: Resources Required

The resources needed for this test are a testing space, a scale, measuring tape, and a goniometer. The testing space just needs to be open for the subject to move around in and test their motion. The goniometer will be used to measure how far each subject will be able to move their legs in the specific direction. The measuring tape will be used to measure the maximum and minimum hip size the belt can fit on. The scale will be used to weigh the hip exoskeleton belt.

3.3.3 Testing Procedure 3: Schedule

Fitment tests will be conducted the week of March 23rd (the week following spring break).

3.4 Testing Procedure 4: Fatigue Failure Modes

The hip exoskeleton will be used frequently by the biomechatronics lab for testing purposes. This frequent use will put significant fatigue on the device. Understanding the cause of failures due to this fatigue will be critical in ensuring that the hip exoskeleton can receive preventative maintenance. Appropriate maintenance will ultimately prevent catastrophic failures during device operation.

3.4.1 Testing Procedure 4: Objective

The objective of this test is to identify the most likely points of failure in the completed design. These points of failure will be taken from risk analysis and mitigation conducted last semester. The top two modes of failure determined from this analysis was creep deformation in components interfacing with the motors, and high cycle fatigue in the spools and Bowden cable/housing. The objective of this test procedure is to gain an understanding of these types of failures. The exoskeleton will be mounted to the test fixture shown in Figure 1 and will be run in a manner similar to when it's assisting a user's walking cycle. The test will run until an appreciable amount of wear is apparent on either the Bowden cable or motor mounts. When wear is present, the amount of cycles will be recorded. The amount of cycles till failure will be implemented into the maintenance plan for the hip exoskeleton.

3.4.2 Testing Procedure 4: Resources Required

One resource required for the completion of this test is an appropriate area for testing. This will likely be the biomechatronics lab. The test will also require the construction of the test bench shown in Figure 1 and the completed hip exoskeleton. Finally, a test program will have to be written to run the exoskeleton and record data for the number of cycles till failure. Creating an effective test program will be the most important resource for this test.

3.4.3 Testing Procedure 4: Schedule

The fatigue failure modes tests will be conducted the week of March 30th along with the Torque/Power output tests. Refer to Table 3.1 for a more detailed breakdown of the schedule.

4 Conclusion

The above report describes the work done by the Biomechatronic Hip Exoskeleton Team to interpret the client's stated needs into technical engineering requirements. These requirements are essential to understanding the project and there must be a plan for measuring how successfully the design meets those requirements. This will be accomplished through the testing methods described above. The scope of the project has changed since it began, and the engineering requirements were updated to reflect those changes.

5 References

[1] W. N. Sanker, C. T. Laird and K. D. Baldwin, "Hip range of motion in children: what is the norm?," *Journal of Pediatric Orthopaedics,* pp. 399-405, 2012.

[2] K. Kanjanapas and M. Tomizuka, "7 Degrees of Freedom Passive Exoskseleton for Human Gait Analysis: Human Joint Motion Sensing and Torque Estimation during Walking," in *IFAC Symposium on Mechatronic Systems*, Hangzhou, 2013.

[3] Department of Social and Health Services, *Range of Joint Motion Evaluation Chart,* 2014.

[4] K. Seo, J. Lee, Y. Lee, T. Ha and Y. Shim, "Fully Autonomous Hip Exoskeleton Saves Metabolic Cost of Walking," in *IEEE International Conference on Robotics and Automation*, Stockholm, 2016.