Below-the-Knee Exoskeleton

Finalized Testing Plan

Ryan Oppel: Budget Lead

Alexandra Schell: Team Lead

Nick Watkins: Design Lead

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NORTHERN ARIZONA UNIVERSITY

Project Sponsor: W.L. Gore

Faculty Advisor: Prof. Zachary Lerner

Instructor: David Willy

DISCLAIMER

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1 Design Requirements

1.1 Customer Requirements (CRs)

The first customer requirement is durability (CR1). This will be important as the device will eventually be used in a customer's everyday life, and when walking outdoors, it is likely that eventually they may either kick or walk to close to an object and contact the device. Eventually we will design a protective cover, but along with this, the components need to be stable and close to the leg to avoid damage. A high range of motion (CR2) is important as the device is designed to be assistive rather than simply an ankle brace. This means that the user will be able to use the motion of their ankle freely, and the device should be able to accommodate to that full range of motion. Once again, the device will eventually be used for everyday life such as hiking and recreational walking. Because of this, the system will likely be used for an entire day at a time, thus both comfort (CR3) and long battery life (CR4), both of which can sustain the user for a full day are relevant to the product. Both adjustability (CR5) and affordability (CR7) are important as the device is intended to be accessible to a wide range of individuals who need assistance. Because the device is intended for those with cerebral palsy and other muscular deficiencies, it is crucial that the device is lightweight (CR6) and can be easily attached to the user's feet for as long as they need while still allowing them to walk normally. The customer requirements can be listed out at follows:

- CR1: Durable
- CR2: High range of motion
- CR3: Comfortable
- CR4: High battery life
- CR5: Adjustable
- CR6: Lightweight
- CR7: Affordability

1.2 Engineering Requirements (ERs)

A lightweight design is our most important design requirement, and based on other similar products, 3kg is the maximum weight that the system should total (ER5). A device that is too heavy will be impossible for certain users with more severe conditions, which is unacceptable as those individuals are the most in need of the product. The ability to accommodate users of all weights (ER4) as well as different foot sizes (ER2) are significant as, once again, the device is intended for all users with conditions that require the assistance that this device can provide. High torque (ER3) is related closely with the accommodation of users of all weights. The device is intended to assist users rather than fully support them, however a motor with a higher torque will provide aid to users with more severe conditions who require the extra assistance. The temperature of the motor (ER6) is an important requirement. The motor, depending on placement, can transfer heat to the battery and the user's leg, which burns the user's skin. It can also cause the battery to overheat due to the covering material and design used, which is what we plan on preventing with our design. Ingress protection (ER8) is very important to the design, as the device will eventually be intended for general use, and the motor, battery, and PCB need to be safe from the environment. The battery capacity (ER7) will be necessary once this device is intended for general use, however as the design is still a functional prototype and only used within the lab, the battery does not need to last for a full day. Energy efficiency is the lowest rated requirement (ER1), because the current design can operate for about four hours, and selecting a new battery and motor are some of our current tasks. The above engineering requirements can be listed out as follows:

- ER1: Energy efficient (Run for at least 30 minutes before battery hits 25%)
- ER2: Accommodate different shoe size (at least .27m)
- ER3: High Torque (at least 10 N-m)
- ER4: Supports users of all weight (at least 90 kg)
- ER5: Lightweight (under 3 kg)
- ER6: Temperature of motor (under 70 °C)
- ER7: Battery Capacity (~1000 mAh)
- ER8: Ingress Protection (at least IP 45)

2 Top Level Testing Summary

Experiment/Test	Relevant DRs	Testing Equipment Needed	Other Recourses
Exp1: Weight and COM	ER5: Under 3kg CR6: Lightweight	Scale	Access to device from Lerner's Lab
Exp2: Initial run of device	ER1: Energy Efficient ER3: High Torque ER7: Battery Capacity CR4: High Battery Life	Device, PCB, Battery, Motor	Programmed PCB
Exp3: Ingress Test	ER8: Ingress Protection	Motor and PCB/battery housing, water	Probe, Spray bottle, determined by target IP rating
Exp4: Thermal Test	ER6: Temperature of Motor	Arduino, DAQ, motor & housing	Alternate motor housings
Exp5: Final test on human	ER2: Accommodate Different Shoe Size ER4: Supports Users of All Weight ER1: Energy Efficient ER6: Temperature of Motor CR1: Durable CR2: High range of motion CR3: Comfortable CR5: Adjustable CR6: Lightweight	Assembled device, treadmill	Test Lab

3 Detailed Testing Plans

The following is a detailed summary of the physical testing plan that we will put our ankle-exo through, our approach, any variables that might come into play, and the expected results. This summary will include all the details to answer or fulfill the engineering or customer requirements for our Exoskeleton.

- Controlled patient walking test: (CR2, CR3, CR5, CR6, ER2, ER4, ER5)
  Our Patient test will consist of a patient using the exoskeleton walk while we measure their walking path on a specialized treadmill in the robotics lab. This equipment we will use can measure the stride of the user and we can compare it to the stride of the user without the ankle Exo and determine where the benefits of the device are coming from and where shortcomings might be. This equipment in the robotics lab consists of a treadmill, a COM plate detection device, and multiple cameras to track the user. We can test our device on different users of size and weight to see the difference as the user changes. We hope to see in our results that our design will be comfortable for users from 50lbs to 200lbs, from shoe sizes 4 to 10 (men's), and be comfortable and adjustable enough for each one of our users.

- Stress testing: (ER1, ER3, Er6, ER7, ER8, CR1, CR2, CR4)
  This test will include the initial run of the device as well as pushing the device to its limit. Our team plans to take our Exo in an outdoor environment and run it multiple times until we drain the battery or have continually run the Exo for over an hour. Our goal with this test is to find our battery life and test if the electrical components get hot enough to cause us to stop testing. Our hope for our test is to have our design be water ingress protection against the environment and run on one battery for a total of 20 minutes and the components do not overheat for the full hour of stress testing.

These two physical tests will determine whether our product will be durable enough to finalize the design. However, our team does expect that after testing we may need some changes to our Exo or its design. Our team has planned for this accordingly through the purchasing of multiple different parts and the flexibility in our budget to make some part changes if need be.

4 Specification Sheet Preparation

4.1 CR Summary Table

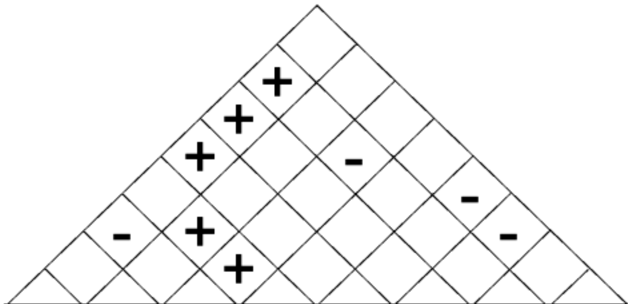
Customer Requirement	*CR met? (✓ or X)*	*Client Acceptable? (✓ or X)*
CR1: Durable	✓	✓
CR2: High Range of Motion	✓	✓
CR3: Comfortable	✓	✓

CR4: High battery life	✓	✓
CR5: Adjustable	✓	✓
CR6: Lightweight	✓	✓
CR7: Affordability	✓	✓

4.2 ER Summary Table

Engineering Requirement	*Target*	*Tolerance*	*Measured/ Calculated Value*	*ER met? (✓ or X)*	*Client Acceptable? (✓ or X)*
ER1: Energy efficient	*<30 mins*	*±10 mins*	*53 mins*	✓	✓
ER2: Accommodate shoe size	*.27 m*	*± .05 m*	*.22m*	✓	✓
ER3: High torque	*<10 N-m*	*± 5 N-m*	*12.5 N-m*	✓	✓
ER4: Supports users of all weights	*90 kg*	*± 30 kg*	*90kg*	✓	✓
ER5: Under 3 kg	*<3 kg*	*± 1 kg*	*1.168 kg*	✓	✓
ER6: Temperature of the motor	*<70° C*	*± 70° C*	*54.5 ° C*	✓	✓
ER7: Battery Capacity	*1000 mAh*	*± 500 mAh*	*650 mAh*	✓	✓
ER8: Ingress Protection	*IP45*	*IP44, IP67*	*IP45*	✓	✓

5 QFD



Design Requirements / Customer Requirements	Importance (1-5)	Energy efficient	Accommodate different shoe sizes	High torque	Support users of all weights	Under 3 kg	Temperature of motor	Battery Capacity	Ingress Protection	1 Worst	2	3	4	5 Best
Improvement Direction														
Durable	3		3		6	6	6		9		C	AB		
High range of motion	5			9								B	AC	
Comfortable	4		3		3	3	3						A	
High battery life	3	9		6			9	9					B	
Adjustable	3		3		6								C	A
Lightweight	5			3		9			3				B	AC
Affordability	5							3	3		C	B		
Technical Importance: Absolute		27	30	78	48	75	57	42	57					
Technical Importance: Relative		7%	7%	19%	12%	18%	14%	10%	14%					
Design Competitive Assessment — **Worst: 1**								B	C					
2					C		B	C	B					
3		AB		B		C	C							
4				C	A	B			A					
Best: 5		C	A	A		A								
Target Value		90	0.3	1000	90	2	70	1000	54					
USL		60	0.27		120	3	155		68					
LSL		30	0.22	500	30	1.5		500	52					
Units		mins	m	mNm	kg	kg	C	mAh	IP					

The last five columns (1 Worst to 5 Best) are the Customer Competitive Assessment.

A	Caplex Exo
B	Utah Knee
C	ETM Motor