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Engineering Honors Program
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Capstone Final Report: Strength Augmenting Robotic Exoskeletons

Introduction:

In our society today, many technologies that were once only dreamed of in science fiction novels are now becoming a reality. Cars can drive themselves, and we are going to be traveling to the distant planet of mars very soon. However, one of the most interesting developments is in the area of human augmentation. In addition to prosthetic limbs and brain implants that allow one to directly interface with technologies, there are exoskeletons. Exoskeletons, a technology once considered only feasible by billionaire super geniuses in fictional superhero stories are now becoming a reality. Exoskeletons are a versatile, efficient and non-invasive way to help remedy physical disabilities and enhance a user's strength. Exoskeletons require no surgical implants in order to function properly, making them a safer option as compared to some other potential medical enhancements a person can make.

There are many different professions that could greatly benefit from the creation of exoskeletons. These occupations typically require heavy lifting over long periods of time. For occupations such as a firefighter, soldier or first responder, lives depend on their ability to do their job effectively. However, many of these occupations require very heavy gear, which will slow them down and make their job more difficult. For example, a firefighter must carry up to 77 pounds of gear while going into burning buildings to save lives[1]. This unfortunately means that no matter how strong this firefighter is, they will inevitably be slowed down by their heavy

[1] "How Much Does Firefighter Gear Weigh? - Career Trend." 5 Jul. 2017, https://careertrend.com/about-4760940-much-does-firefighter-gear-weigh.html. Accessed 14 Dec. 2020.

gear. This results in it being harder for them to do their job, and could potentially cost lives. If an exoskeleton were created that could carry this load for the firefighters, then they would be able to do their job more effectively, and save more lives.

Figure 1: Weight breakdown of basic firefighter gear[2]. This is the minimum amount of gear a firefighter has to wear in the field. This can easily get heavier as mentioned above.

Another area in which exoskeletons can help is in the shipping and manufacturing industry, large factories and warehouses require their workers to lift heavy objects for long periods of time. After years of doing this work, an individual working in one of these industries can experience extreme joint wear and potentially require a surgery that will prevent them

[2] "The New York Times > New York Region > Image ...." 11 Jun. 2005, https://archive.nytimes.com/www.nytimes.com/imagepages/2005/06/11/nyregion/20050612_GEAR_GRAPHIC.html. Accessed 14 Dec. 2020.

from working in the future. This is a huge loss for the employee, as they will no longer be able to work and also a loss for the company, as they will likely have to pay for the employees surgery and have to pay to hire and train a new employee. For example, in automotive factories, workers are required to to hold heavy rivet guns above their head for many hours a day. This repeated process could eventually lead to shoulder joint damage, requiring a surgery that could cost over thirty thousand dollars[3]. If there were an exoskeleton that could support the weight of these tools, this surgery cost could be eliminated, saving money and grief for both the employee and company

As shown in figure 2 (page 4), exoskeleton prototypes to help remedy these situations have already begun development. These designs are all part of a growing exoskeleton industry that will be worth over $5 billion by 2025[4]. My project is part of a design team at the university of Michigan (M-STARX) that aims to help join this industry by designing exoskeletons that can augment an individual's strength in a similar fashion. We have designed two exoskeletons, a pneumatically powered upper body exoskeleton and a motorized lower body exoskeleton. Over the past 4 years, I have made contributions to the design of the pneumatic systems of our upper body exoskeleton, the ankle system of our lower body exoskeleton, and I oversaw all design projects last year as president of M-STARX.

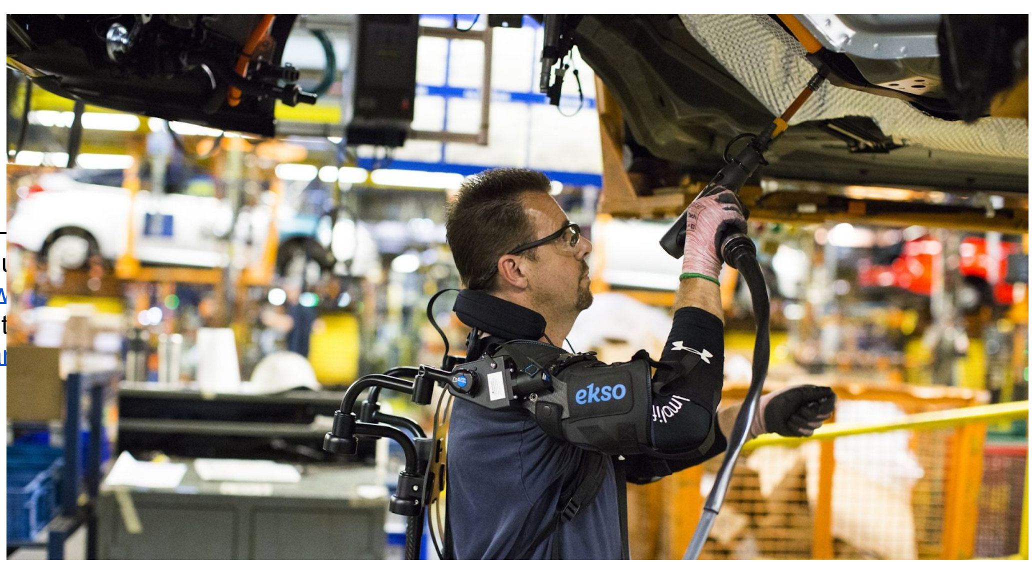

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Figure 2: Upper body exoskeleton prototype for factory workers to help prevent workplace injuries[5]. As you can see, this factory worker is required to keep this drill in this overhead position for long periods of time. This could cause severe joint damage. The exoskeleton prototype being used in the image above aims to prevent this in a similar way to my project.

Questions/Problems Addressed:

We wish to assess how to properly build an exoskeleton that is easy to use, cost effective and has a low metabolic cost. Metabolic cost is a metric that compares how tired one gets while wearing an exoskeleton as compared to their level of exhaustion while not wearing the exoskeleton[6]. The metabolic cost is typically measured as a percent, where 100% indicates that the exoskeleton has no impact on how tired you get. If this percentage is under 100%, it means that the exoskeleton makes you more tired than when you are not using it. It is important for exoskeleton design to have the metabolic cost be greater than than 100%, since this shows that the user will get less tired while wearing the exoskeleton as compared to not wearing it.

Another important factor we wanted to consider in the design of our exoskeleton was cost. Currently, exoskeletons on the market can cost up to $45,000 or more[7]. This

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[5] "New Exoskeleton Does the Heavy Lifting for Factory Workers." 9 Nov. 2017, https://www.nbcnews.com/mach/science/new-exoskeleton-does-heavy-lifting-factory-workers-ncna819291. Accessed 14 Dec. 2020.

[6] "The exoskeleton expansion: improving walking and running ...." 19 Feb. 2020, https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-020-00663-9. Accessed 16 Dec. 2020.

[7] "Exoskeleton developers must improve capabilities, cost, says ...." 13 Aug. 2019, https://www.therobotreport.com/exoskeleton-developers-must-refine-capabilities-cost-says-maxon/. Accessed 16 Dec. 2020.

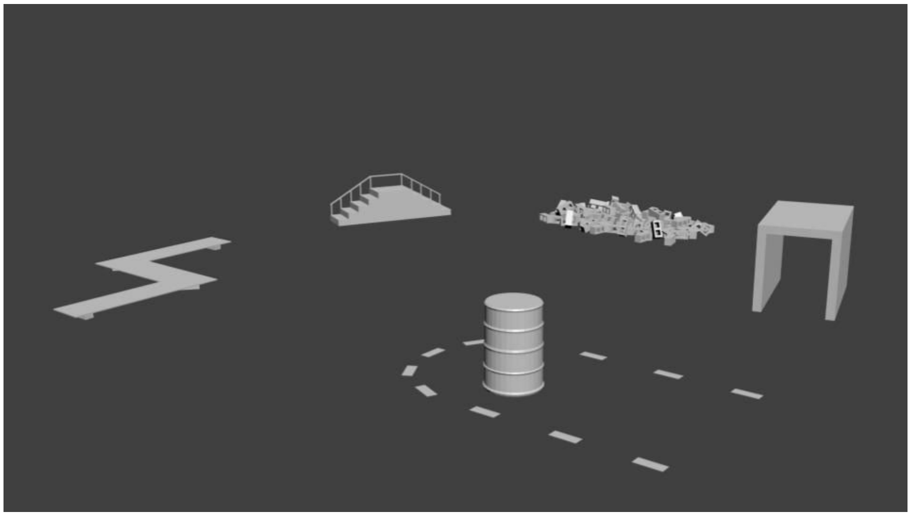
is an incredibly high price for both corporations and the public, meaning at this price it will be very difficult to get exoskeletons to be adopted into our society. Because of this, we aim to design an exoskeleton that is fully functional, yet significantly cheaper than what is currently on the market.

Our final technical goal is to ensure that our exoskeletons are easy to use. We hope that exoskeletons will be able to be used as a tool for individuals that need to lift heavy objects in order to do their jobs correctly and more efficiently, in addition to helping reduce long-term joint damage. In order to allow these individuals to do this, we aim to ensure that the exoskeleton is easy to use and require little to no training to operate. We aim to make the exoskeleton easy to put on and take off, and have it operate in a way that will make you feel as if it is not there, besides the physical assistance it can provide to the user.

One more goal of this project is to help spread knowledge about exoskeleton design and research around the country and globe. To facilitate the commercial adoption of exoskeletons in a timely manner, it would be valuable to have a diverse group of people that share unique and creative ideas pertaining to the design of exoskeletons. To make this happen, we have developed and hosted the first collegiate exoskeleton competition. We have had schools from around the country travel to Ann Arbor to show off their exoskeleton designs at this competition, and have had interest from colleges outside the country.

Competition:

The competition we created consists of three parts, a design review, an obstacle course and a metabolic efficiency test. The design review is scored by a panel of judges. In the past the judges have consisted of professors, graduate.Phd students, engineers working in industry, people in the military and the chief of a local fire department. This score is combined with the score from the obstacle course and metabolic cost test to determine a winner. The obstacle course, as seen in Figure 3 (page 7) aims to test how well an individual can move over various terrains and perform different tasks in the exoskeleton while having a load of 25 pounds on their backs. In addition to the obstacle course, there is also an assessment of how quickly a user can put their exoskeleton on and then take it off the two years the competition has run (2018 and 2019), our team placed second the first year and first the second year. Unfortunately due to COVID, the competition could not be held this year, but there are plans to hold it at Michigan State in the future. We have had teams from across the country be involved in the competition, and interests internationally from colleges in places such as Egypt and Canada. So far, this competition has been an excellent way to share ideas and knowledge about exoskeletons. Each team involved has used portions of the other teams designs in their next exoskeleton prototype, making each year's designs a vast improvement on the previous year. We hope to continue this competition in the future and look forward to learning about the designs of the other teams once we are able to compete again after the pandemic ends.



`**Figure 3:** Obstacle course for the competition. This obstacle course is designed to test how well an individual can move over various terrains and perform different tasks in the exoskeleton while having a load of 25 pounds on their backs.

Upper Body Exoskeleton Design (SAM-E):

Our single arm motorized exoskeleton, or SAM-E was our first design when M-STARX started in 2015. This exoskeleton is designed with the intention of increasing what you can carry with your upper body. When I joined the team in 2017 it was the first project I worked on. The design at the time consisted of a motor attached to cables that when activated move the arm. I was initially tasked with improving the motor-cable system, but instead I decided to go another route. I was interested in utilizing pneumatics in order to operate the exoskeleton. I did some research on these and discovered the McKibben air muscle[8]. These pneumatic muscles can be inexpensively made, only requiring a latex tube, wire sheathing and some hose fittings. They are also easily attachable to any exoskeleton frame since they only require two attachment points and a hose to supply them with air. Finally, each air muscle can lift approximately

[8] "Making a Simple Air Muscle | Make - Makezine." 21 May. 2015, https://makezine.com/projects/make-40/joseph-mckibben-and-the-air-muscle/. Accessed 16 Dec. 2020.

45 pounds each (due to torque on the actual exoskeleton you need several muscles to achieve this rate). Figure 4 shows how these pneumatic muscles operate.

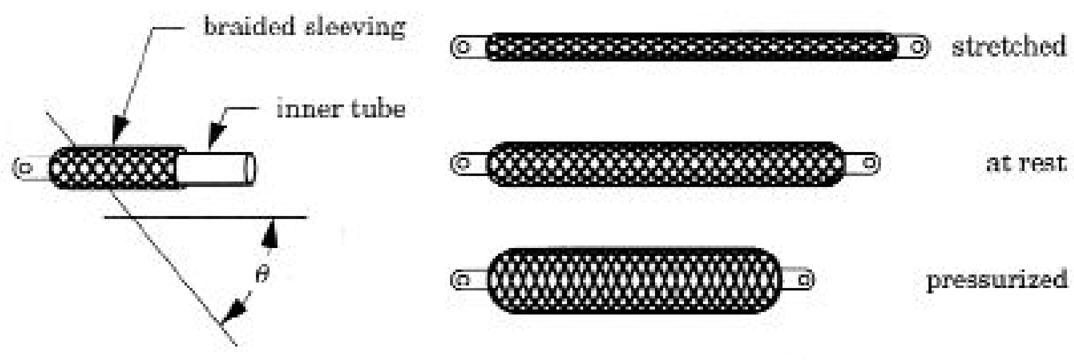


Figure 4: McKibben air muscle design[9]. When the muscles are pressurized, they contract and decrease in length. When they are empty they return to their resting position at their initial length.

I spent the remainder of this year and a summer designing these muscles and an exoskeleton frame to attach them to. These muscles were supplied with air through a regulator, air tank and a compressor. The exoskeleton was controlled through a myoelectric sensor which reads signals from the users muscles and inflated or deflated the pneumatic muscles based on its readings. Figure 5 shows our most recent design for SAM-E. We also plan on changing the name to a more fitting one since the exoskeleton is no longer motorized.

[9] "Braided muscle, McKibben Muscle. - ResearchGate." https://www.researchgate.net/figure/Braided-muscle-McKibben-Muscle_fig6_247194653. Accessed 17 Dec. 2020.

Figure 5: Most recent design of SAM-E.

The exoskeleton overall works well. With 2 air muscles, the user can lift an additional 45 pounds while wearing the exoskeleton, Its biggest flaw pertains to the myoelectric controls. The muscular signals that the sensors read are very noisy, and we have not been able to filter out this noise. In the future, this is the main hurdle we are looking to overcome with this design.

Lower Body Exoskeleton Design (MLX):

Our second design is our Modular Leg Exoskeleton. This design aims to increase what a user can carry on their back by 75 pounds. This is also the exoskeleton we use to compete in our competitions. The main objective of this exoskeleton is to reduce the metabolic cost of the user. Through testing of our previously lower leg exoskeleton, we discovered that making the exoskeleton light, comfortable and esnuting that it follows the users natural gait cycle is critical to reducing the users metabolic cost. To help realise these objectives, we built an entirely new exoskeleton prototype over the year of 2019. This exoskeleton has four motors, one at each hip and knee. While walking, these motors provide a rotation which counteracts the load on the users back, negating the weight of the exoskeleton and the load. There is also a spring system on both ankles that help further counteract this load while the user is walking. We also made the exoskeleton more modular, to allow for easy repairs and for a wide range of users with different heights to comfortably use the exoskeleton. We also used different sport pads and straps to secure the exoskeleton properly. Finally, we made all of our parts hollow, and only used lightweight materials such as aluminum to ensure the exoskeleton is lightweight. Figure 6 shows our most recent design of MLX.

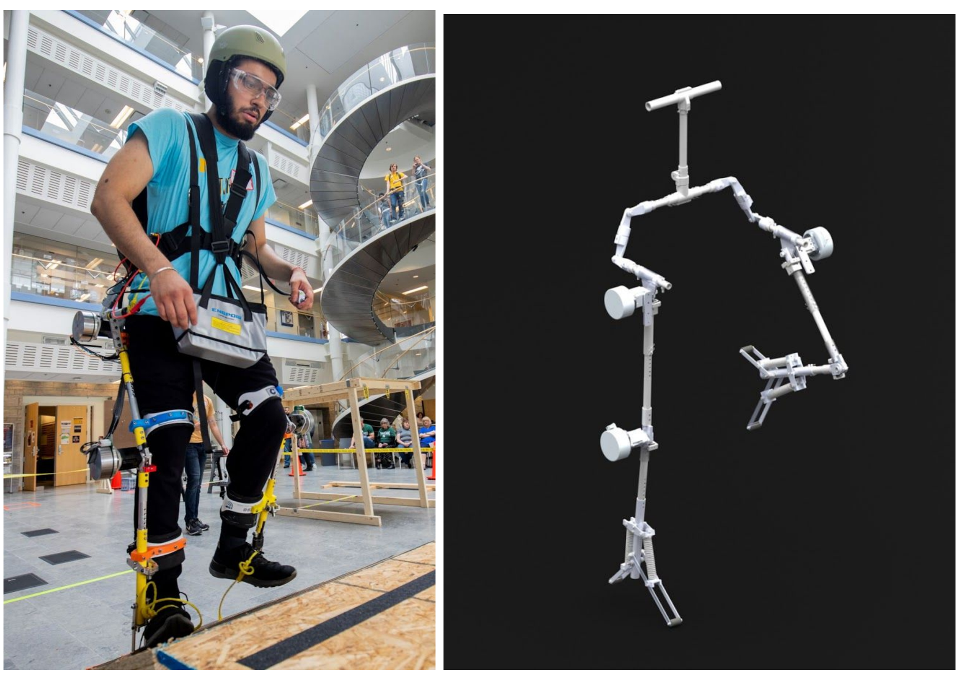


Figure 6: Most recent MLX design and CAD model.

Our most recent MLX design can successfully carry a load of 75 pounds for the user and makes great strides towards achieving a positive metabolic cost. While we were unable to test the metabolic cost of this exoskeleton due to COVID-19 related concerns cancelling the competition, we look forward to confirming our tests in the future. For now, over the next year we hope to improve upon this design further. We are looking to further improve the spring system on our ankle to ensure that there are no tripping hazards while using the exoskeleton. We also are looking into incorporating carbon fiber into our design to further decrease its weight. Finally, we are looking into implementing a machine learning algorithm that will learn how the user walks so it can better imitate their gait cycle, further reducing the metabolic cost of the user.

Conclusions:

Over the past four years, M-STARX and I have made great strides in creating two state of the art exoskeletons. We have designed an upper body exoskeleton that can increase what the user can carry by 45 pounds and a lower body exoskeleton that can increase what a user can carry by 75 pounds. Both exoskeletons achieve their objective of reducing the strain applied to a user's body by heavy loads. We have also succeeded in our objective of spreading and sharing knowledge about exoskeleton design around the world with our competition. That being said, we still hope to improve upon our exoskeleton designs and our competition in the future with continued research and development.