FIREFIGHTING EXOSKELETON TO REDUCE STRESS AND STRAIN

Team EXO

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ABSTRACT

Overexertion stress and strains and musculoskeletal disorders are the leading causes of injury in firefighters. Lower back injuries resulting from lifting are prevalent in both fire and Emergency Medical Service (EMS) calls. Exoskeletons which provide specialized support during repetitive movements have been increasingly implemented in construction, manufacturing, and healthcare settings in recent years. However, the unique temperature, weight, fit, and quick donning requirements of an exoskeleton suited for use in firefighting renders current commercial exoskeletons unsuitable for firehouse implementation. Team Exo aimed to close this gap in research by exploring the requirements and testing methods of a firefighting exoskeleton. Several iterations of the exoskeleton were completed and categorized into three distinct prototypes. The exoskeleton consisted of dual-spring housings, leg attachments, and an upper body harness. The spring system worked with a cable and plunger to compress the spring while squatting, and decompress when rising; resulting in a loading of the spring on descent, and an assistive lifting force on ascent. Several testing phases were completed, including competing at the American Society for Testing and Material (ASTM)'s 2025 Exo Games and further testing at the National Institute of Technology (NIST). The final prototype of the exoskeleton functioned as a facilitator for the gluteus and hamstring muscles that assisted the user in lifting. Testing focused on user-reported comfort and perceived assistance through a wide variety of firefighter specific movements and followed the current industry-wide standards of exoskeleton testing. Further testing with electromyography (EMG)s, models, and cardiopulmonary exercise testing (CPET) would be beneficial, and should be expanded on when more comprehensive testing standards are

established. Further modifications for compatibility with firefighting gear and material improvements would also be necessary for firehouse implementation.

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1. INTRODUCTION

Overexertion injuries and musculoskeletal disorders are the most common injuries sustained from firefighting duties. They result from intense periods of movement and lifting in high stress environments while wearing heavy turnout gear and equipment. Lifting heavy hoses, reaching repeatedly overhead for fire overhaul, deploying and climbing ladders, and the wide variety of other tasks and movements performed on the job contribute to these injuries (Campbell & Hall, 2024). Firefighters also respond to Emergency Medical Services (EMS) and other emergency calls, often more frequently than fire-related incidents. These calls are also hazardous and may lead to on-site injuries, overexertion stresses and strains, and long term musculoskeletal disorders. Common and strenuous EMS tasks include lifting patients on stretchers and maneuvering them through limited space. In both fire and EMS calls one of the most prevalent and easily addressed injuries is lower back strain when lifting due to improper form and heavy loads (Friedenberg et al., 2022).

This investigation aimed to reduce overexertion and musculoskeletal disorders in firefighters by designing a firefighter-specific passive exoskeleton. The focus of the exoskeleton was to reduce lower back strain injuries while lifting. Although the exoskeleton is not focused on arm movements and may not assist in non-lifting lower body exercises, it is important the unit did not hinder or alter those movements in any way. Any alteration to the firefighters natural movements during any task could potentially cause injuries.

Exoskeletons have been increasingly implemented in workplace environments in recent years. They most prevalently have appeared in factory, manufacturing, and construction settings where repeated motions are common (Flor-Unda et al., 2023). These applications are well suited for a body part specific exoskeleton that can assist in highly specific and repetitive movements. Exoskeletons have also recently received attention for use in health-care to aid in lifting patients, and in military settings to assist with long term exertion (Flor-Unda et al., 2023).

Commercially available exoskeletons are unsuitable for use in firefighting for several reasons. Most are large and bulky making them unusable for firefighters who need to wear the exoskeleton under turnout gear. Furthermore, they are intended to assist the wearer with repetitive movements in a controlled environment. The significant variety of tasks done by firefighters in volatile settings renders these exoskeletons non-feasible. An exoskeleton for firefighters also must be non-powered to prevent added danger to the firefighter resulting from electronics or batteries in a high-heat environment. Although the exoskeleton will not be exposed directly to the heated outside environment in a fire call as it must fit entirely under the turnout gear, it must still be constructed from heat resistant material. The exoskeleton must also be compatible with the current fire protection gear in most firehouses. An exoskeleton incorporated into the personal protective equipment (PPE) itself would be ideal, but is not a feasible goal for current research. Firefighting gear has been meticulously designed for the firefighters needs and the funding costs to implement these designs means dramatic alterations cannot be expected at the present time. The other requirements listed above are more adequate targets for current advancements.

Team EXO is a multidisciplinary undergraduate research team that formed through the Gemstone honors research program at the University of Maryland. The team consists of seven students from a variety of STEM disciplines, including mechanical engineering (Connor Bosco and Brett Ingram), bioengineering (Jessica Mense), fire protection engineering (Liam Smith), aerospace engineering (Tom Bigot), electrical engineering (Donald Spriggs), and geology (Nicholas Salanitri). These varying backgrounds allowed the team to draw on a wide array of expertise, resources, and professional networks, which significantly contributed to the development and refinement of the project.

The research group aimed to close the gap in exoskeleton development by designing an exoskeleton that meets firefighter's unique requirements. The team began by conducting informal interviews with firefighters of different backgrounds, positions, and geographic areas to hear first hand what the firefighters expected from an exoskeleton. Participants were asked about which movements were most common, which parts of their body experienced the most pain after a call, and what requirements the exoskeleton would have to meet for them to feel comfortable wearing one on the job. Feedback was overwhelmingly positive with all agreeing that if an exoskeleton proved to prevent injuries and increase the safety of their jobs, they would be interested in implementation in fire houses.

The passive exoskeleton was to be built based on the above requirements, and focused on the lower back. A dual-spring design was devised to allow room for the Self Contained Breathing Apparatus (SCBA) tank. A harness would attach the spring system to the upper body, and leg straps would connect it to the lower. The springs would compress when the user squats

down, effectively loading the spring, and lengthen when the user stands up, releasing stored energy. The design would act as assisting hamstring muscles, and encourage the user to lift with their legs instead of their back.

The authors built a first full prototype after initial designs using CAD, 3D printing polymers, and rudimentary nylon harnesses and leg straps. Initial mobility and assistance tests resulted in design and material improvements resulting in a second prototype using an upgraded harness, weight belt, and nylon printed spring housing and leg attachments. This second generation prototype was entered into the American Society for Testing and Materials (ASTM) International Exoskeleton Games (ATSM Exo Games) for student teams around the globe. The team earned 1st Place in Design and 2nd Place Overall. At the competition the team tested the exoskeleton on the National Institute of Standards and Technology (NIST) course that is used to test commercial exoskeletons. The team received feedback from ASTM testing and standard members, firefighters, military personnel, U.S. Army Combat Capabilities Development Command (DEVCOM) representatives, and NIST partners. Using this information the team constructed a subsequent exoskeleton with improved leg attachments, cable clamps, and fit adjustability. The new prototype was then taken to NIST for a final round of testing.

The testing proved to be one of the biggest limitations in exoskeleton research. Technology designed to work with the human body is a challenge to test because it cannot be tested separately from the person. While electromyography (EMG) and modeling softwares are commonly used for exoskeletons, they come with their own limitations. For this reason, to determine the effectiveness of the exoskeleton the team utilized the current NIST standard for

testing and used the Rate of Perceived Exertion Scale to rate exertion, breathlessness and fatigue during physical activity.

Other limitations also arose in implementing the exoskeleton into practice. The exoskeleton needs to be disengageable so the firefighters could stop the assistance of the exoskeleton if needed. The design must also be slim to ensure the seamless integration into turnout gear. Although the dual-spring design was intended to leave room for the SCBA tank, the current placement on the lower back would still impede the placement of the harness used to secure the tank to the user's body. In terms of the turnout gear itself, the team found little to no interference, but a true integration of the design into the firefighter's PPE was outside the scope of this project. The final prototype included improvements on adjustability and fit on different body types. But with the fit of the exoskeleton being so integral to its function, and the widespread fit issues with PPE for female fighters, this adjustability could be improved greatly and would be necessary for future work. Material improvements for a longer lasting and more heat-resistant design would also be advantageous to practical implementation.

Much future work and firefighter involvement is needed to approach firehouse implementation. With increasing interest in exoskeletons for first responders and future improvements in testing and standards, this research will help contribute to advancements in the exoskeleton field.

2. LITERATURE REVIEW

According to the U.S. Bureau of Labor Statistics firefighters have one of the highest rates of injuries and illnesses of all occupations. The National Fire Protection Association's (NFPA) *2021 United States Firefighting Injuries Report* found that wounds, cuts, bleeding, or bruising only accounted for 13 percent of reported injuries. Smoke or gas inhalation (10 percent) and thermal stress (8 percent) were responsible for even less. The leading cause of injuries among firefighters on the fireground was overexertion and strain (40 percent) while sprains and muscular pain injuries accounted for approximately two out of five injuries (40 percent). A study published in the *American Journal of Preventive Medicine* presented similar findings, reporting that sprains and strains were responsible for the largest portion of injuries among firefighters in firefighting, training, and patient care activities (Taborri *et al.*, 2021).

These injuries are common for several reasons. One major contributor is the heavy weight of their gear. Firefighting turnout gear weighs between 45 and 80 lbs (20 to 36kg) (*How Much Does Firefighter Gear Weigh?*, 2025). The heaviness of the equipment is intended to keep the wearer as safe as possible, as well as being durable enough to withstand the intensity of each call over a long period of time. A study published in the journal of *Current Sports Medicine Reports* determined modern PPE "imposes a considerable physiological burden because of its weight, insulative properties, and restrictiveness". The firefighters themselves also have incredibly physically taxing responsibilities with long work periods where overtime and 24-hour shifts are common (*Firefighters*, 2025). The NFPA attributes the bulk of the firefighting stress and strain injuries to musculoskeletal disorders due to chronic exposure to lifting of heavy

objects, abnormal postures, intense and repetitive exertion, as well as frequent overhead work. These disorders increase with frequency and duration and usually reside in the lower back, knees, and shoulders for firefighters (Vu *et al*., 2017).

Although there have been technological attempts to incrementally reduce firefighter injuries through task specific technologies, it has yet to be addressed as a whole. For example, in recent years the automatic stretcher has helped firefighters acting as EMS to lift heavier patients into an ambulance. But this technology does not assist with the strenuous task of lifting 400-500 lb patients and then carrying them down hallways, stairs, and walkways (M. Lancaster, personal communication, 2023). A carrying device called the Mega Mover can be used to accomplish this goal, but the tarp-like apparatus with attached handles can only be used when enough space is available so it is rendered unusable in tighter spaces (*GRAHAM MegaMover Transport Units | Life-Assist.Com*, 2022). The tasks completed by firefighters are too varied to create a separate solution for each. A solution that protects firefighters themselves through many tasks and situations they may encounter is the only way to effectively address the stress and strain on their bodies.

ASTM defines an exoskeleton as "a wearable device that augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body," *(Ervin, 2024)*. There are three primary ways to classify exoskeletons: by target location on body, intended function, and power source. The target location on the body specifies where the exoskeleton will attach and assist the wearer, for instance, the upper or lower back, shoulder, or legs. The intended function can refer to the industry or specific job the exoskeleton is designed for. The third

categorization denotes how the exoskeleton is powered. Many exoskeletons have an external power source to provide power for actuation. Electricity is the most common method, but hydraulics may also be used. Other "passive," exoskeletons use power generated by the wearer's movement. Springs are commonly used to store this energy and distribute it elsewhere on the body.

Exoskeletons work by transferring load from the arms, shoulders, or legs to the body's core. This allows the extremities to perform their tasks for longer and with less fatigue. Powered exoskeletons might use motors and other components to achieve this, while passive exoskeletons typically use spring mechanisms. The effectiveness of exoskeletons can be difficult to track as reduction of strain on the body often comes at the cost of reduced comfort or mobility. In a review of the ShoulderX shoulder supporting exoskeleton, EMG measurements reported participant's shoulder flexor muscle activity was reduced by 80%. However, participants experienced high discomfort around the shoulder region so usability was decreased (Golabchi et al., 2022). A holistic approach must be taken to actually determine the efficacy of an exoskeleton design for the desired task.

Exoskeletons are usually specific to one or a few parts of the body. Given the complexity of the human body, little to no commercially available exoskeletons focus on a wide range of muscles or movements. For example, an exoskeleton intended to be used on the manufacturing floor for automobile construction may assist with holding the user's arm above their head for long periods of time but would not also be used to assist them in lifting.

Powered exoskeletons for reducing back strain have been increasingly used in workplaces in recent years. German Bionic's 2023 Apogee shown in Figure 1exoskeleton is currently being tested in healthcare clinics in Rosenheim, Germany with assisting workers in lifting patients. Their slightly adapted Apogee+ exoskeleton is tailored more for industry applications. The company recently partnered with Servco Pacific Inc to bring the exoskeleton into automotive workplaces in Hawaii in 2021 as well as in Canadian tire warehouses in 2022 (markus, 2024). Exoskeletons such as these provide active assistance through electric motors and actuators powered by batteries. These are not feasible for use in firefighting due to the extreme temperatures they are exposed to on fire calls.



Figure 1: Apogee exoskeleton (*Apogee High-Tech for the Care Sector*, 2025)

When considering powered exoskeletons for use in only EMS related calls issues still arise. Powered exoskeletons come with their own complications like high costs of buying and maintenance (Vallée, 2024). They are also bulky and large which would be a hindrance, especially when considering residential EMS responses and the tight spaces and stairs the

firefighters need to navigate. The firefighters also require a huge range of mobility and a variety of movements, which powered exoskeletons intended for use in healthcare are not equipped to provide. The Apogee exoskeleton is designed only for “lifting”, “lowering”, “walking”, and “prolonged bending” (“Apogee | Active Exoskeleton with Lifting and Walking Support,” 2025). The constraints of such exoskeletons are not permissive for the unexpected movements that arise in emergency situations.

Powered exoskeletons that do not use batteries, such as Innophys’ 2015 Muscle Suit Exo-Power exoskeleton in Figure 2, which are less expensive and more heat resistant, still tend to be too large for use by firefighters. The Muscle Suit Exo-Power is a pneumatic exoskeleton that has been implemented in some factories and warehouses in Japan (Saltmarsh, 2021). Its wider frame is intended to increase thermal comfortability by decreasing the surface area touching the user, but does render it unsuitable for firefighters.



Figure 2: Muscle Suit Exo-Power Exoskeleton (Saltmarsh, 2021)

True passive exoskeletons shown in Figure 3provide several advantages that assist in their feasibility for implementation in firehouses. They are less constrictive, are simple to clean

and maintain, are more user friendly, and are usually significantly more affordable (Vallée, 2024). Innophys has a 2017 exoskeleton with a slimmer fitting design than the Muscle Suit Exo-Power Exoskeleton called the Muscle Suit Soft-Power. This exoskeleton design incorporates elastic straps that extend when bending over and contract when standing again. Similar passive exoskeletons which also utilize elastic straps for lower back support include the HELK exoskeleton by GOGA (2019), the LiftSuit by Auxivo (2018), and the SoftExo Lift 6 by HUNIC GmbH (2019) (*Industrial Archives - Exoskeleton Report*, 2025).



Figure 3: From left to right: Muscle Suit Soft-Power, HELK, LiftSuit, SoftExo Lift 6 (*Industrial Archives - Exoskeleton Report*, 2025)

A similar elastic strap based exoskeleton is the 2020 SABER in Figure 4. The SABER exoskeleton, a test military exoskeleton designed by HeroWear in partnership with DEVCOM, comes closest to meeting firefighter's specific requirement for an exoskeleton (Marinov, 2022). Military members and firefighters experience similar workplace tasks. They both have highly

strenuous jobs and a versatile set of movements performed. The SABER exoskeleton was specifically designed to assist military members in lifting and moving heavy equipment. It was also designed to be lightweight and made of materials that could be worn all day, for both women and men (*Apex 2 Press Kit | HeroWear*, 2023). These materials are intended to be thermally comfortable as well, and their softer nature technically classifies the SABER as an "exosuit". The fit of the exosuit is relatively flush to the body in an effort to be compatible with a wide range of body armor and military equipment.



Figure 4: SABER Exoskeleton (Marinov, 2022)

The SABER exosuit was originally a project stemming from HeroWear's Apex 1 exoskeleton that was adapted into the Apex 2 in 2023 after testing with the US Army (*Apex 2 Press Kit | HeroWear*, 2023). The Apex 2, shown in Figure 5, is a commercially available passive exosuit designed for use in warehouses involving heavy lifting and bending. The Apex 2 essentially functions as an extra set of back muscles that helps to reduce spinal disc compression. It was found to reduce strain on back muscles by 14-43% and overall muscle fatigue by 29-47% (*The Science Behind the Apex | HeroWear*, 2023). Users reported experiencing increased

endurance and easier lifting as well. The Apex 2 was also proven to not increase abdominal muscle activity, negatively impact other muscle groups, or hinder overall walking stability.



Figure 5: Apex 2 Exoskeleton (The Apex 2 Back-Assist Exosuit | HeroWear, 2023)

Although the Apex 2 exosuit does meet many of the requirements for firefighters it is lacking in two critical areas. First, the design of the backstraps and the coil are not implementable in coordination with the firefighting turnout gear. The harness of the SCBA tank sits flush against the hips of the firefighter. This would not allow for proper extension and contraction of SABER's elastic straps, which would be squeezed between the user and the harness. More importantly, the SCBA tank itself, along with the metal plate of the harness beneath the tank, would sit directly on top of the coil piece in the center of the back. This would lead to improper fit of the harness and potential improper use of both pieces of equipment. Secondly, the Apex 2 has a quick release of the exosuit, enabling it to be quickly disengaged if needed. This is a major safety advantage for firefighters, and any emergency responders. A quick release ensures that if the exoskeleton is ever a hindrance to the firefighter it can be immediately disengaged in an emergency situation, preventing harm to the user. The Apex 2's quick release is located on the shoulder strap of the upper body harness. It involves squeezing a small plastic clip. Although this is an ideal placement for warehouse workers, it would not be accessible to

firefighters underneath their turnout gear. This is especially true when wearing the SCBA harness which would again sit directly on top of the component (*Apex 2 Press Kit | HeroWear*, 2023).

Passive exoskeletons have been increasingly explored in recent years and are beginning to be implemented in workplaces where worker injuries are common. Current commercial exoskeletons have seen some success in medical and rehabilitation settings, as well as in construction, manufacturing, and warehouses. Firefighting is a profession with extraordinarily high rates of musculoskeletal disorders which makes firefighters a population that could benefit greatly from exoskeleton implementation. The unique requirements for such implementation makes designs in other fields largely untransferable. The research presented herein aims to further past research by designing an exoskeleton for firefighters specifically.

3. METHODS

Overview

This section details the process the investigators followed in determining the functional requirements of the design and the data collection procedures. It also presents the detailed methodology and findings of the authors' work on the exoskeleton's design with a focus on its mechanical framework, prototype manufacturing, and user trials.

Design requirements

The development of the passively powered spring exoskeleton was guided by the specific biomechanical and user requirements demanded by firefighters and first responders as they carry out their work. By conducting a literature review and performing interviews with first responders across the industry, the researchers identified objectives to guide the design process. These objectives reflect the specific challenges faced by first responders in their harsh and demanding work environments, and the need for a novel exoskeleton able to match all of their requirements in a practical, effective, and user-friendly manner.

Several of the design requirements revolve around the exoskeleton being able to operate in the hazardous conditions firefighters find themselves in, such as fires, floods or storms. The exoskeleton ideally needs to be able to withstand high temperatures, dust, water, and strain. This is the primary reason the engineering team pursued a passively powered exoskeleton with no powered motors or batteries. The first prototypes were not built with materials able to withstand

these conditions, as they needed to be inexpensive and simple to manufacture for multiple prototypes. They were instead designed with the intention of implementing robust materials, such as various alloys or metals, in later designs.

The most critical factor in exoskeleton development is the ease of use including lack of obstructiveness to the body and comfortable fit. There is, by necessity, a human factor to the design. Even if the exoskeleton is effective, if it is not comfortable or easy to wear in the day-day conditions first responders experience then it will not be worn. Therefore, it is crucial that it be simple and intuitive to don and doff quickly, so as to minimally interfere with the user's ability to respond quickly to emergencies. Furthermore, the design needs to integrate seamlessly with existing gear and allow for a relatively full range of motion - such as climbing, crawling, going up stairs, sitting down, etc. Given the large amount of equipment around the belt and the SCBA tank in the center of the back, it is clear many contemporary exoskeleton designs would be incompatible with most first responder's gear. For this reason the researchers designed a dual housing for the spring housings to leave space for the oxygen tank and harness to go in between the two spring housings.

Another key functional requirement concerned the exoskeleton's ability to provide a meaningful mechanical advantage, delivering a responsive and effective assistive force to the user's body. Without clear benefits to mobility or load reduction, adoption by firefighters would be unlikely. The system needed to enhance performance noticeably and naturally, adapting dynamically to the user's movements without requiring active control.

Within these objectives, a number of quantitative and functional requirements were identified to guide the design process and evaluation of each prototype. Modifications to these requirements were made as necessary during the design and testing process to streamline efforts and focus on realistically achievable goals within the scope of the research.

The requirements (in no particular order) are as follows:

The exoskeleton should not cost greater than $1,000.00 for either purchase or replacement. This requirement was implemented to assure the exoskeleton would be affordable and accessible for both professional and volunteer fire companies.

The exoskeleton should ideally weigh less than 15 lbs, with a 20 lb acceptable limit during design. This requirement was established to guarantee the exoskeleton would not become an extra weight burden for firefighters, which would make any potential benefit negligible.

There should be a maximum spring tension of 50 lbs of force. This requirement was defined to ensure the restorative spring force would not overpower the human wearer and cause risk of injury.

The exoskeleton with modification should fit 90% of possible wearers, between the 10th and 90th percentile. This requirement was introduced to verify the exoskeleton could fit and assist a wide range of body types.

A wearer should be able to put on and secure the exoskeleton in less than 30 seconds. This requirement was crucial for firefighters who must be able to "gear up" in less than 80 seconds for fire and 60 seconds for EMT (*NFPA Standard 1710*, 2025). Limiting the time it takes for a firefighter to put on the exoskeleton greatly increases the likelihood of its adaptation and use as intended.

The exoskeleton should fit underneath the current firefighter turnout gear, both coats and pants. This required the researchers to design around the firefighters pre-existing gear and proved to be the main constraining requirement for a dual spring system. The exoskeleton could not interfere with the SCBA or other additional PPE. This would also encourage smoother integration with the gear in the future developments.

The exoskeleton should be comfortable enough for extended use. There should be no visible marks on the user's skin after an extended period of use up to 2 hours. This requirement verifies the exoskeleton would be comfortable enough to not inhibit a firefighters movement or work during prolonged use like a structure fire. It also reduces the chance of the exoskeleton causing abrasions to skin due to rubbing or pressure.

The exoskeleton should not transfer more than 1464.4 kJ/m2 = 205 W/m2 of heat to the wearer's body from turnout gear. This requirement was included to confirm the thermal material properties of the exoskeleton would be safe and comfortable for the user and was primarily satisfied by placing the exoskeleton under the turnout gear.

In addition to these requisites, others were considered for future development.

The exoskeleton should be robust and not lose functionality over a period of one year of use or in abrasive environments. This was established to assure the exoskeleton would remain viable over a long enough period of time to be useful for a fire company.

The exoskeleton should be easily disabled when functionality is not required. The firefighter should be able to easily disable the spring tension force while wearing the exoskeleton. This strengthens the exoskeleton's comfort, practicality, and enables the user to prevent undo injury if a malfunction were to occur or the user found themselves in an unexpected position unsuited to the spring system.

Testing Methods

The team considered a number of testing methods: EMGs, models and simulations, NIST pressure sensing vest, and cardiopulmonary exercise testing (CPET); but none were well suited for the early stage exoskeleton prototypes. EMG is a technique for evaluating and recording the electrical activity produced by skeletal muscles and is a common testing method for exoskeletons. However, the EMG electrodes are only able to measure muscles just under the surface of the skin. They can also only be placed on a few muscles at a time. (Latasa et al., 2016) This makes it difficult to test how the exoskeleton affects muscles outside of those groups using EMGs. This is an especially important consideration in exoskeleton testing where the suit must not adjust the movements of the user to add strain to another area of the body. Models and

simulations have also been used in past research. These can help with designing and optimizing exoskeletons but the information gained from these models does not confirm real human comfort and ease (Bengler et al., 2023). A potential new NIST pressure sensing vest could be used to quantitatively detect pressure points from the exoskeleton but is still in development. CPET has also been used for exoskeleton testing to consider the overall metabolic energy consumption when wearing an exoskeleton compared to without (Slade et al., 2022). This method of testing is helpful in the latter stages of exoskeleton testing rather than in the early design process.

Given the team's aim to further research in an exoskeleton built specifically for firefighters and the timeline for this research project, the testing of this exoskeleton was primarily based on comfort and ease of movement during physical tasks performed by firefighters. Before the first prototype was built, elastic resistance bands were attached to a manufactured spring housing and a few preliminary physical tests were conducted. Shown in Figure 6, the intention was to assemble a rudimentary version of how the spring would function to ensure the overall placement of the housing, wire, and leg attachment would be comfortable and effective.



Figure 6 : Proof of concept test

This proof of concept test showed that the back housing - spring material - leg attachment configuration of the exoskeleton would not be overly cumbersome to the user's movement, while still providing the lifting support on the body that was wanted from the design. The tension of the elastic band (although much lower than possible from a spring) on the leg and back did not cause a reduction in range of motion.

First prototype

The first prototype shown in Figure 7 of the passively powered exoskeleton was developed as a proof of concept to validate the feasibility of the spring acting on the lower back and leg muscles. This prototype was intentionally designed to be simple, inexpensive, and quick to manufacture. The focus was to have a working prototype to test for any potential issues with the design. The design was divided into three primary components: the spring housing, the harness system, and the leg attachment mechanism.



Figure 7: Prototype 1

The spring housing shown in Figures 8 and 9 served as the central component of the exoskeleton, as it was designed to securely hold the spring in place while allowing it to compress and decompress from the movement of the body around it. In order to allow for the compression of the spring by the movements of the user, a plunger mechanism was incorporated into the housing. The plunger compresses the spring when pulled upon by the leg as the user squats down with the exoskeleton on, and gives the user a restorative force once they return back to a standing position. There was also a plastic plunger that was clamped onto the cable that allowed for the spring to pull on the cable and vice versa. Additionally, since the exoskeleton was designed with the use of firefighter gear in mind, the spring housing was split into different compartments, to allow for space for equipment. To this end, two spring housings were designed and fabricated using Polylactic Acid (PLA) and Fused Deposition Modeling (FDM) type 3D printing.



Figure 8: Initial mockup of harness with spring housings

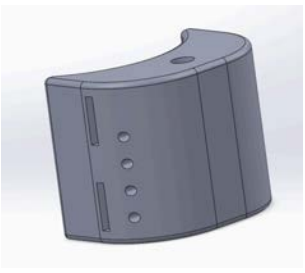


Figure 9: Spring housings on first prototype

The leg housings shown in Figures 10 and 11 allows for the transmission of the force from the spring and cable to the quadriceps and hamstrings. The cable would enter the leg housing from top of the leg, and be clamped on the other side with the use of a wide cable clamp. On either side of the clamp were two metal rods that could be screwed into the leg housing. This secures the cable clamp into one location, and allows for smooth operation of the exoskeleton without sudden slips or twists. An effective method of connecting the cable to the leg attachment had not yet been determined.







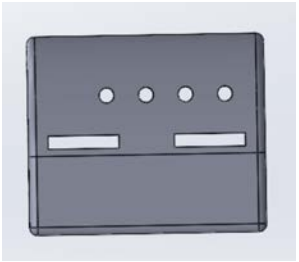


Figure 10: Initial mockup of leg attachment

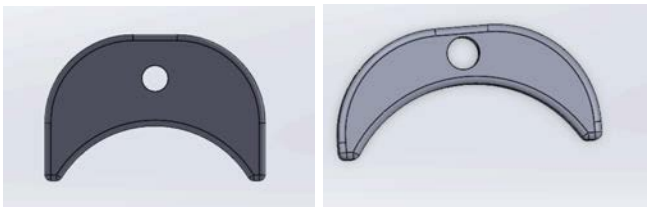


Figure 11: Initial leg housings compared to first prototype

While this first prototype successfully demonstrated that a dual-housing spring system was possible in principle, several mechanical and ergonomic challenges were discovered during testing. One of the most significant issues was the poor fit of the upper-body attachment shown in Figure 12 made out of stretching straps and loose pieces of fabric.



Figure 12: First mockup of upper body harness

This method of connecting the exoskeleton together and attaching to the user's body lacked adjustability and often remained loose, shown in Figure 13, leading to a perception of

instability during movement. The spring housing would move around the back whenever the user would move, causing tension or slack in the metal cable. Additionally, due to the loose nature of our makeshift harness, the prototype could only be worn effectively by adding multiple layers of clothing underneath, which was contrary to the original design of the exoskeleton worn *under* turnout gear.



Figure 13: Upper body harness on first prototype

This also led to the springs not actuating as intended. The spring system was designed to be engaged only by the bending of the body around the pivot point at the hips, with this movement compressing the spring. However, due to the loose-fitting nature of the cable housing, the cable housing was unable to stay fixed relative to the lumbar region of the back, which caused an inconsistent slack and tension in the cable. This resulted in an inconsistent force transmission from the spring to the lower limbs, resulting in the exoskeleton resisting the user instead of assisting them.

Another early design challenge involved the original spring housing and leg attachments, which were found to be excessively large, making them uncomfortable for the user. The size was initially intended to increase the structural integrity of the plastic, but the result made the components impractical for use. The team also found properly fitting the leg component to be challenging. Additionally, because the leg attachment was placed behind the hamstring, it caused discomfort to the user when they sat down. The team decided any future designs had to be as flush as possible to the body – small enough as to not hinder movement, and comfortable enough to ensure prolonged use was possible.

After the first full prototype assembly, the spring housing was tested prior to attachment to the human body to verify the plunger, spring, and wire system functioned correctly inside of the spring housing during compression and decompression. The prototype was placed on a flat surface, as shown in Figure 14. The springs were manually compressed by pulling on a leg attachment with the back spring housing secured. The compression force of the spring was measured using a luggage scale. This objective was to confirm the prototype could be safely worn on the body before more rigorous testing of the exoskeleton was performed.



Figure 14: Force tests on first spring prototype

Throughout the testing process, the exoskeleton was worn by several different team members to evaluate the fit and size adjustability on different bodies. As shown in Figure 15, a simple squat was performed to assess the performance of the springs within the exoskeleton. The user performed a deep knee flexion, picked up an empty box, stood up with the box, and then squatted back down to replace the box on the ground. There were no external weights used in these tests. They were body-weight exercises and items lifted up were intentionally light to test the motion before the actual lifting force. Feedback from the user was recorded regarding any feeling of impedance while bending down and loading the spring and any assistance as the user stood up and decompressed the spring. The fit and slip of each exoskeleton component was examined as well.

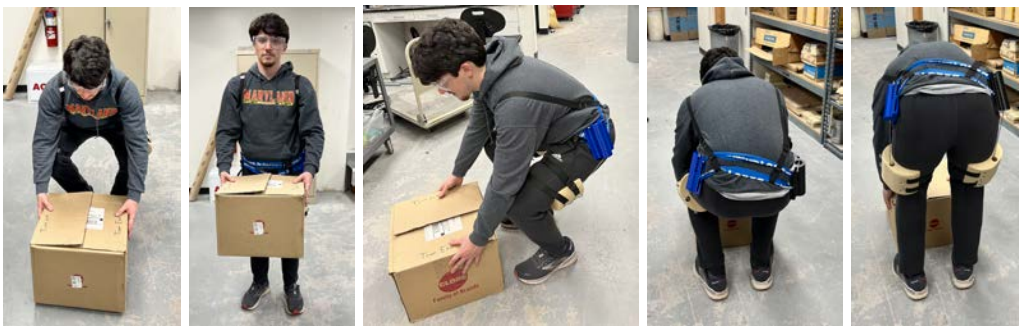


Figure 15: Box lift test with first prototype

Next the exoskeleton was tested with basic movements, shown in Figure 16, to determine which movements would engage the exoskeleton. A list of basic movements performed by a firefighter outside of their assigned tasks was identified. An incremental progression of each movement was defined. This included but was not limited to:

1. **Walking:** Flat surface, up/down small incline, up/down steep incline
    a. Right foot: 6” step, 1’ step, 1’ 6” step, 2’ step, etc.
    b. Left foot: 6” step, 1’ step, 1’ 6” step, 2’ step, etc.
    c. Slow walking pace (60-79 steps per minute) for 10 seconds
    d. Normal walking pace (80-90 steps per minute) for 10 seconds
2. **Walking Backwards:** Flat surface, up/down small incline, up/down steep incline
    a. Right foot: 1’ step, 2’ step
    b. Left foot: 1’ step, 2’ step
    c. Slow walking pace (60-79 steps per minute) for 10 seconds
    d. Normal walking pace (80-90 steps per minute) for 10 seconds
3. **Squat:** At 30° angle, 60° angle, 90° angle, past 90° angle
    a. Feet shoulder width apart: 1 squat, 2 squat, etc.
    b. Feet wider than shoulder width apart: 1 squat, 2 squat, etc.
    c. Feet at preferred, comfortable distance and comfortably quick pace: 5 squats
4. **Stairs:** Up/Down stairs, one stair at a time, one round walking and one round jogging
    a. Right foot forward: 1 stair, 2 stairs, 6 stairs
    b. Left foot forward: 1 stair, 2 stairs, 6 stairs
5. **Jogging:**
    a. Light jog: 5 sec, 20 sec, 30 sec, 45 sec, 1 minute
    b. Light run: 5 sec, 20 sec, 30 sec, 45 sec, 1 minute

During testing each movement was marked with the corresponding tags DNE (did not engage), C (comfortable), NC (not comfortable), E (engages), PE (partial engagement), PC

(partial comfort) and D (displacement) based on user feedback and visual monitoring. A review of the exoskeleton's performance was also collected after each movement. This included how the exoskeleton's fit may have changed throughout the tasks, during which movements the exoskeleton assisted the user, and whether the exoskeleton altered or hindered any movements.



Figure 16: Calisthenics tests with first prototype

Second Prototype

The design of the second prototype was focused on increased tangibility and effectiveness. To address the sizing and material issues, we made significant modifications to both the leg attachment and the spring housing. The original components were oversized and impractical for comfortable wear, so the spring housing was redesigned to be smaller and more streamlined. This reduction in size helped improve the overall fit of the exoskeleton and ensured the housing would not interfere with the user's movement. The comfort and functionality of the leg attachment was also improved. As shown in Figure 17, the design was made more compact and conformed better to the shape of the hamstring, minimizing any discomfort during use. Additionally, a proper attachment mechanism was incorporated to securely connect the cable to

the leg attachment, ensuring stable force transmission from the spring system to the user's lower limbs. These changes were critical in creating a more efficient and user-friendly exoskeleton.

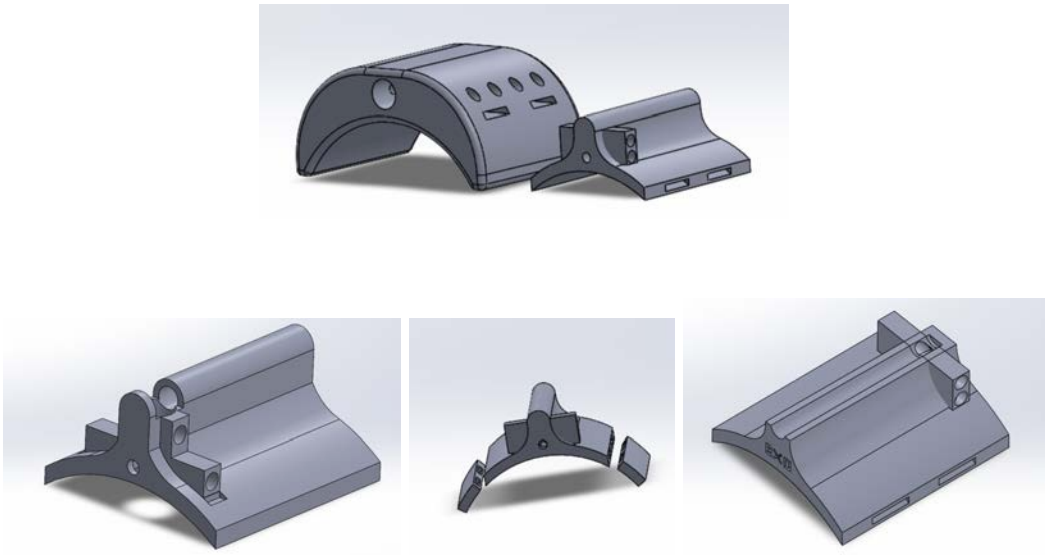


Figure 17: Top: first prototype leg attachment (left) compared to second prototype leg attachment (right)

Bottom: other iterations of leg attachment

The new leg and spring housing attachments were fabricated with additive manufacturing similar to the previous attachments, however with a new type of printing and material. Whereas the old attachments utilized FDM, often also referred to as Fused Filament Fabrication (FFF), the new attachments were manufactured with selective laser sintering (SLS). The material used in SLS was powdered nylon which resulted in a stronger unit with isotropic strength, compared to the anisotropy found within the layers of FDM printing. Powdered nylon proved to be a much more resilient material than PLA, allowing many tests without failure.

The team also replaced the upper-body attachment system with a more adjustable setup, using a harness structure similar to the back of a backpack and pairing it with a weight belt, as shown in Figure 18. The harness consisted of straps that could be adjusted to fit the contours of the user's torso, ensuring a more secure and stable attachment. With these adjustments, the spring was able to actuate effectively during hip flexion, addressing previous issues with movement and stability.



Figure 18: Prototype 2 harness attached to weight belt

The weight belt was incorporated into the design to provide additional support and prevent any upward movement of the exoskeleton during use. The belt also allowed the user to utilize their abdominal muscles while performing lifting movements, which moved muscular strain away from the back, consistent with the primary goal of our exoskeleton. The new system ensured that the spring housing remained fixed in place and also allowed for improved fit across users with varying body dimensions. One limitation faced by the team at this step in the design process was the placement of the spring housing. Initially designed to be widely spaced across the back, this position caused the cables to slide to the outside of the user's glutes when squatting

down, preventing proper spring compression. To address this, the housings were moved closer in towards each other, as shown in Figure 19. However, this adjustment reduced compatibility with turnout gear and will need to be addressed in future design iterations.



Figure 19: Originally placed spring housing (left) and revised placement (right)

Initial testing contributed to the alterations and redesigns of the exoskeleton and resulted in an improved prototype. As shown in Figure 20, this exoskeleton was again tested with the user squatting into a deep knee flexion position, lifting an empty box, standing back up, and delivering the box to the ground again. These tests were conducted to verify the spring housing system continued to function as intended and to ensure the updated material and design changes did not introduce any fit or comfort issues.



Figure 20: Unweighted box lift and return to ground test with second prototype

Subsequent testing involved incrementally increasing the load to evaluate the exoskeleton's performance under more realistic conditions. As shown in Figure 21, approximately 30lbs was added to the box, which was again lifted from the ground and set back down. The turnout gear was donned and the test was repeated. A weighted (~10 lbs) backpack was added on top of the turnout gear, the box was weighted with an additional ~10 lbs backpack, and the test was repeated. The added weight made it easier for the user to assess the assistance of the exoskeleton in lifting, particularly in identifying the angle of knee flexion at which the exoskeleton engaged and disengaged. The increasing weight also provided insight into how the exoskeleton may have been distributing forces to elsewear in the body.



Figure 21: From left to right: weighted box lift, turnout gear box lift, turnout gear weighted box lift with added weighted backpack

Brief physical tests were also conducted with the second prototype, as shown in Figure 22. These tests aimed to assess the overall fit of the new prototype, identify any components that caused user discomfort, and to determine whether any movements were hindered or assisted differently compared to the first prototype.

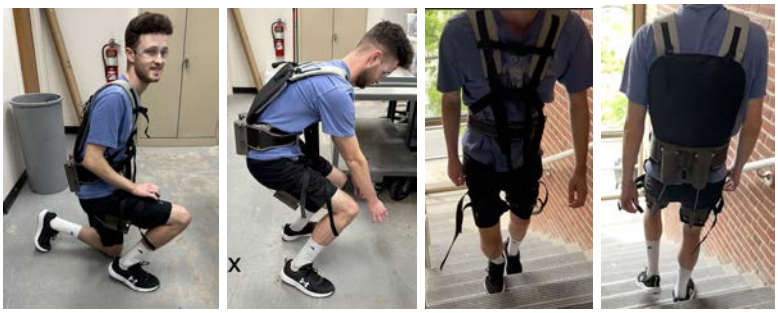


Figure 22: Calisthenics tests with second prototype

The subsequent phase of testing progressed from basic movements into the actual tasks performed by firefighters. These tests were initially conducted at ASTM International's Exo Technology Center of Excellence's annual competition, the ATSM Exo Games. This international competition invites student teams to design and build exoskeletons, and provided an opportunity for the designs to be assessed according to the industry standards set by ASTM's exoskeleton and exosuits committee. The 2024 ASTM Exo Games focused on first responder exoskeletons. Challenges were predefined by the committee and were designed and assembled in partnership with NIST. Each task was performed by one team member for 15 minutes, during which the team member completed as many repetitions of the specified task as possible. The

challenges were based upon, and mirrored, the most common tasks performed by various subsections of first responders. Many of these exercises closely resembled movements conducted by firefighters, even if the task itself is not one generally carried out by firefighters themselves. For this reason challenges aimed at EMS, police, or Bomb Units were also included in testing. Furthermore, many of the tasks involve upper body motions. This exoskeleton is not intended or capable of assisting upper body movements. But due to the combinatory nature of most firefighting activities these exercises were also included in testing. This was primarily to affirm the exoskeleton did not hinder upper body mobility and to assess any change of exoskeleton fit or comfort during these movements. The challenges included the Bomb Walk, Cache Packaging and Deployment, Crawl Space, Don/Off and Vehicle Entry, Fire Overhaul, Fire Hose Deployment, and Townhouse Search tests.

For the Bomb Walk in Figure 23, the user donned a 25 lb weighted vest and picked up two 15 lb weights (i.e., load cylinder artifact), one in each hand. The user then walked 50ft, placed the weights on the ground, kneeled down to complete a manual dexterity test, retrieved the two weights, and walked back 50 ft (*ASTM International Exo Games 2024 Challenges*, 2024).



Figure 23: Bomb Walk Test - ASTM Exo Games

The Cache Packaging and Deployment in Figure 24 involved assembling the Ropak, moving the pallet of totes (19.8” x 13.8” x 11.8") from the floor into the Ropak container (40” deep X 48” wide X 36” tall) and back out again. The boxes were a variety of weights (up to 40lbs) (*ASTM International Exo Games 2024 Challenges*, 2024).



Figure 24: Cache Packaging and Deployment Test - ASTM Exo Games

The Crawl Space test in Figure 25 specified that the user was to don the fire helmet, gloves, and flashlight, crawl through the simulated 4-foot culvert pipe for 16 ft, and turn around and come back (*ASTM International Exo Games 2024 Challenges*, 2024). The flashlight was held in one hand for the entirety of the task, and the helmet could not touch the top of the space.



Figure 25: Crawl Space Test - ASTM Exo Games

The Don/Off and Vehicle Entry in Figure 26 test entailed donning the exoskeleton, opening the vehicle and entering the cab, buckling the seatbelt and pulling out an object from the car console. The user then unbuckled the seatbelt, exited the vehicle and closed the door, and finally removed the exoskeleton (*ASTM International Exo Games 2024 Challenges*, 2024).

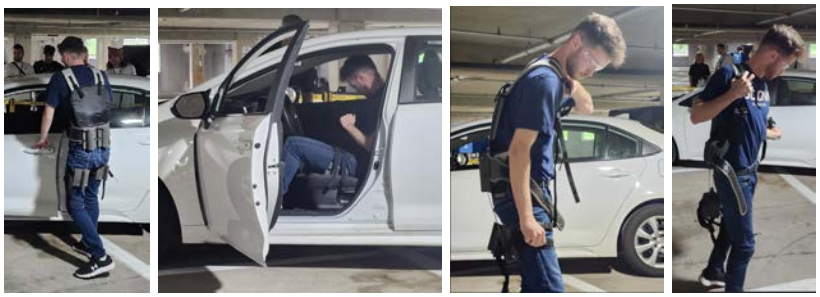


Figure 26: Don On/Off and Vehicle Entry Test - ASTM Exo Games

The Fire Overhaul Test in Figure 27 had the user don a fire helmet and gloves and use a fire hook to push open a weighted overhead ceiling tile, pull open a vertical wall tile, and pull up a weighted floor tile (*ASTM International Exo Games 2024 Challenges*, 2024).

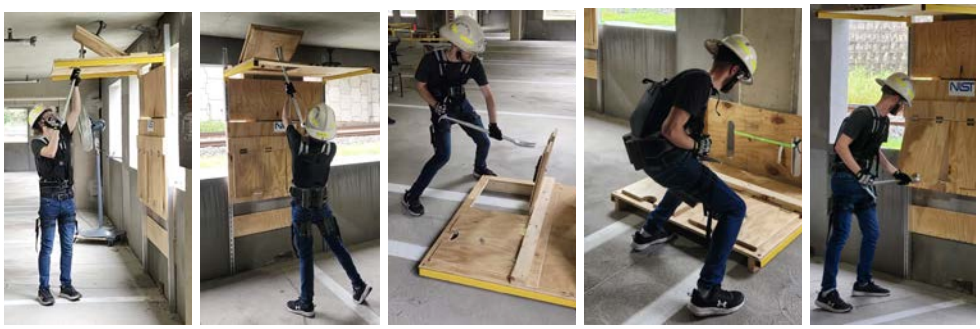


Figure 27: Fire Overhaul Test - ASTM Exo Games

The Fire Hose Deployment Test in Figure 28 included taking a fire hose off a table, rolling it out, dragging and connecting the hose to the coupler, rolling up the hose, and returning it to the table (*ASTM International Exo Games 2024 Challenges*, 2024).

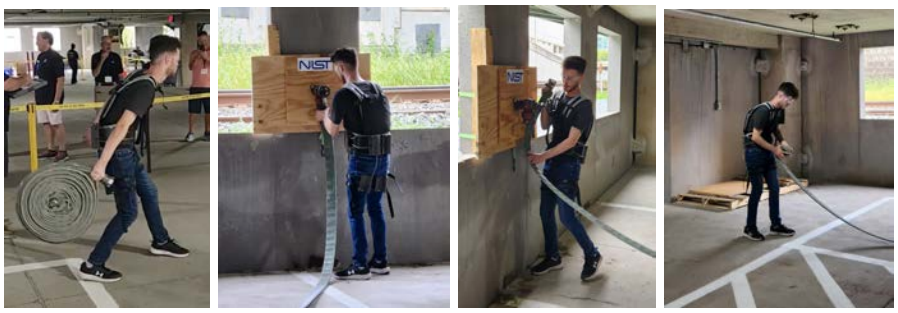


Figure 28: Fire Hose Deployment Test - ASTM Exo Games

The Stairs Test in Figure 29 dictated that the user start behind a designated start/end location, walk towards the stairs, climb the stairs, turn 180 degrees, descend the stairs, and return to the original marker (*ASTM International Exo Games 2024 Challenges*, 2024).



Figure 29: Stair Test - ASTM Exo Games

Finally, the Townhouse Search Test in Figure 30 involved walking 20 ft over uneven terrain and through obstacles to find 20 different objects of interest using proper search technique (*ASTM International Exo Games 2024 Challenges*, 2024).



Figure 30 : Townhouse Search Test - ASTM Exo Games

Along with the repetitions completed, the slip and fit alterations occurring throughout longer sustainments of the movement were evaluated. The longevity performance of the exoskeleton, noting any breakage or loosening, was recorded. Any conspicuous hindrance of movement was noted as well as patterns of stress or strain on the body. The competition occurred over several days and any physical effects of the exoskeleton were assessed daily with a particular attention to the different areas of the body where the exoskeleton may be redistributing the force.

After the ATSM Exo Games additional tests were conducted to acquire a force/displacement curve for the individual springs used in the final prototype. The purpose of these tests was to determine the amount of force exerted on the user by the exoskeleton at any given position. These tests were performed in a manner similar to in Figure 18 showing force

testing for the first prototype. Bench testing was used to determine the force in Lbf it took to displace the exoskeleton's leg attachment to varying amounts, in 0.5 in. increments from 0 in. up to 3.5 in, which was the farthest increment the researchers were able to extend it.

Third Prototype

After testing the second prototype at the ATSM Exo Games, it was clear to the team the original springs provided too much resistance when the user bent down and forward. This made tasks like getting onto their knees difficult for the user because there was a strong force keeping them from squatting all the way down. With the increased force from the spring, the cable often slipped out of the clamp when the user attempted to rise from their knees or squatted down until exoskeleton failure. This would cause the cable to disconnect from the leg attachment, often leaving one spring active and the other inactive. Fitting the cable clamp back into the leg attachment was also extremely challenging which wasted time for the user when trying to complete tasks quickly. This also required tools that were a specific size for the nuts on the clamp. The third prototype shown in Figure 31 eliminates these two major issues.



Figure 31: Prototype 3

The first modification was replacing the existing springs with two longer springs with a reduced spring rate. Making the spring longer increases the range of motion for the user due to the increased length for the spring to compress before it reaches its maximum compression. The free length was increased from 5.0 in. to 7.0 in. The spring rate was also reduced from 5.7 lbs/in to 3.2 lbs/in. This also increases the user's range of motion and mobility as it requires less force to bend down. Due to these changes, the springs also have a reduced maximum load force of 15.1 lbs when fully compressed compared to 22.2 lbs in the second prototype. This means the two springs give a maximum assistance of 30.2 lbs of force in the third prototype compared to the original 44.4 lbs of force. Although this reduces the maximum force by 14.2 lbs, it significantly improves the user's mobility while donning the exoskeleton.

The second improvement made was increasing the cable clamp strength. To do this, the team used epoxy to bind the surface of the cable to the cable clamp. This removed the ability of the cable to slip from the clamp when the springs are pulling on the cables. The reduced force of the new springs also assists in preventing cable slippage. Strips of glue were also added to the leg straps to provide traction against the user’s pants and prevent the straps from sliding with movement.

Upon completion of the third prototype, another round of testing was done at the NIST facilities in Gaithersburg, Maryland, where the standard test setups used at the ATSM Exo Games were originally created, and are now permanently housed. Due to the varied relevance of

the original ATSM Exo Games tests to firefighting itself, not all tests were recreated. The testing priority was determined by the tasks the exoskeleton broke most often on, or that the exoskeleton was the greatest hindrance to completing. Priority was also given to tests where the exoskeleton provided the most assistance previously to ensure that the improvements did not negatively affect those tests. First the Bomb Walk Test was performed again for a total of 10 minutes. However, the obstacle course used at the ATSM Exo Games was unavailable, so a walk around other test setups with a cardboard box obstacle was used. The team planned to perform the Cache Packaging and Deployment Test, however, it was unable to continue after the Bomb Walk Test shown in Figure 32 due to reasons discussed in a later section.



Figure 32: Bomb Walk Test - NIST Gaithersburg

Because not all tests were able to be completed during the first day of testing at NIST, another day of testing was done after replacing parts broken during the first day with more durable versions. The tests performed, in order, were Fire Hose Deployment, Fire Overhaul, Cache Packaging and Deployment, and the Bomb Walk. These were the tests that had previously

caused the exoskeleton to break, were where the exoskeleton hindered the user previously, or where the exoskeleton provided the most assistance. The Fire Overhaul test was performed three times per test to increase exertion and better see the difference between with and without the exoskeleton. The Bomb Squad Walk Test was also performed three times per test for the same reason. The Cache Packaging and Fire Hose Deployment were long enough tests that exerted the user enough that it was not deemed necessary to perform the task three times per test. The Cache Packaging and Deployment Test was performed with 32 lbs of weight added to each box. For the NIST retesting the Ropak was not available so the boxes were placed on the floor then reassembled on the pallet. All tests were first done with the exoskeleton, then after a rest period, performed without the exoskeleton. The effectiveness of the exoskeleton was measured by rating exertion, breathlessness and fatigue with and without the exoskeleton using the Rate of Perceived Exertion Scale.

4. RESULTS

In testing the spring housing mechanism while not on the user, the investigators viewed no deformation of the attachment material or slipping of the cable clamps and determined that the cable-spring design worked as intended and was safe for the wearer. While testing the exoskeleton in basic mobility and box lifting, the investigators did note that some adjustments were needed while in a standing position before the user could begin testing. Without proper fit, the intended neutral position of the cable-spring system could be unintentionally engaged. These adjustments allowed the user to progress towards the mobility tests described in an earlier section, the results of which are presented below.

The progression of these movements were intentionally incrementally small to ensure the safety of the user and to explore the limitations of the first prototype. For this reason not all increments are included in the following tables and are instead summarized as the general fit, comfortability, assistance, and hindrance analysis of the prototype. Each of the movements that are included were marked with the corresponding tags DNE (did not engage), C (comfortable), NC (not comfortable), E (engages), PE (partial engagement), PC (partial comfort) and D (displacement) based on user feedback and visual monitoring. General feedback from the researcher is listed below each movement as a note.

Table 1

Walking on Incline

Movement	Tag
Step right foot 6”	DNE
Step right foot 1’	DNE
Step right foot 1 6”	E, C
Step right foot 2’	PE, C
Step left foot 6’	DNE
Step left foot 1’	DNE
Step left foot forward 1’6”	E, C
Step left foot forward 2’	DNE
Step right foot 1’ and left foot to meet it	DNE
Slow (60-79 steps per min) walking pace: 10 sec	PE, C
Normal (80-90 steps per min) walking pace: 10 sec	PE, C
Step right foot backward 1’	DNE
Step right foot backward 2’	E, C
Step left foot backward 1’	DNE
Step left foot backward 2’	E, C

Notes: Leg strap tightness was felt at normal walking pace for 10 seconds.

Table 2

Squatting

Movement	Tag
Feet shoulder length apart: 1 squat at 30° angle	E, C

Feet shoulder length apart: 2 squats at 30° angle	E, C
Feet shoulder length apart: 1 squat at 60° angle	E, C
Feet shoulder length apart: 2 squats at 60° angle	E, C
Feet shoulder length apart: 1 squat at 90° angle	PE, C
Feet shoulder length apart: 2 squats at 90° angle	PE, C
Feet shoulder length apart: 1 squat deeper than 90° angle	PE, C
Feet shoulder length apart: 2 squats deeper than 90° angle	PE, C
Feet wider than shoulder length apart: 1 squat at 30° angle	E, C
Feet wider than shoulder length apart: 2 squats at 30° angle	E, C
Feet wider than shoulder length apart: 1 squat at 60° angle	E, PC
Feet wider than shoulder length apart: 2 squats at 60° angle	E, PC

Notes: The belt moved and loosened with squatting motion. Leg strap tightens when engaged.

This caused the strap to dig into the thigh and become uncomfortable after long periods of time.

Table 3

Stairs

Movement	**Tag**
With feet at preferred, comfortable distance apart, squat down at quicker, comfortable pace at preferred angle 5 times	E, PC
Step up 1 stair with right foot and bring left foot to meet it	PE, C, D = 1.5 in.
Step up 2 stairs with right foot and bring left foot to	PE, C, D

meet it	
Step up 1 stair with left foot and bring left foot to meet it	PE, C D = 1.5 in.
Step up 2 stairs with left foot and bring left foot to meet it	PE, C, D
Step up 6 stairs starting with right foot (3 stairs per foot) and bring right foot to meet it	E, C
Step up 6 stairs starting with left foot (3 stairs per foot) and bring left foot to meet it	E, C
Starting with right foot jog up 2 stairs (1 stair per foot) and bring right foot to meet it	DNE, C
Starting with left foot jog up 2 stairs (1 stair per foot) and bring left foot to meet it	DNE, C

Notes: When stepping up 3 stairs at a time the leg straps cause an awkward unnatural movement.

Table 4

Jogging

Movement	**Tag**
Light jog for 15 sec	PE, C
Light jog for 20 sec	PE, C
Light jog for 25 sec	PE, C
Light jog for 30 sec	PE, C
Light jog for 45 sec	PE, C
Light jog for 1 min	PE, C
Light run for 5 sec	PC, PE

Notes: Leg straps tighten with engagement. Leg is slightly pulled when running. This altered the user's gait.

During these tests the investigators found that while the user bent down to engage the spring by making a bowing motion or performing squats and lunges, the user could feel the exoskeleton trying to pull them up. The force being applied to the body during the largest displacements of the spring made these positions uncomfortable to maintain. Generally severe discomfort was not experienced and no components broke during testing.

Testing of the second prototype prior to the ATSM Exo Games closely mirrored the first prototype tests. It was completed mainly to assess qualitative comfort and continued feasibility and safety. The researchers reported improved fit and functionality of the second prototype, with less slippage and less adjustments needed between repetitions. This allowed the user to proceed with a higher variety of motions without fear of breakage or injury, and enabled the investigators to explore the exoskeleton use at its maximum range. The range of motion in bending at the hips when lifting boxes was hindered slightly more due to the addition of the sturdier harness, but a more consistent and targeting lifting force was experienced. The user again reported a notable lifting force aiding in rising. The force of engaging the spring and holding the position was still difficult, but no severe discomfort was felt. The team was satisfied the exoskeleton was safe to wear for testing in the ATSM Exo Games trials.

At the ATSM Exo Games the number of repetitions was recorded for each team; although the final scores were not disclosed to the individual teams for purposes of fair competition

judging. For this reason the results of the testing at the ATSM Exo Games primarily focused on the perceived physiological effect of the exoskeleton usage for an extended period of time as well as the structural performance and failures of the design. Structurally the exoskeleton remained intact and operational during the Stair, Townhouse Search, Fire Hose Deployment, Fire Overhaul, and Donning On and Off and Vehicle Entry Tests. The investigators recorded the duration of several of the Donning On and Off trials and the results are presented below.

Table 5

Recorded Time to Don and Doff Exoskeleton in ATSM Exo Games

Trial	1	2	3	4	5	6
Donning	35 sec	47 sec	33 sec	35 sec	43 sec	35 sec
Doffing	8.5 sec	7.93 sec	7.73 sec	NR	NR	NR

Throughout the ATSM Exo Games there were multiple instances of component failures in two primary areas. The first was in the spring housing. On the first day of testing the plunger in the spring housing tilted and became trapped inside the spring housing at the latter half of the interior. This caused the spring to lock in the engaged position. The investigators were able to push the plunger back to level, which dislodged the plunger and allowed the spring to decompress. During the Crawl Space Test while the user was attempting to rise from a kneeling position the cable slipped through the cable clamp. The housing had to then be disassembled from the harness so the clamp could be removed and reattached correctly. During the Bomb Walk Test the cable slipped out of the barrel of the leg attachment entirely. The cable was

trimmed 0.5 in. and was fed back through the barrel hole. The cable slipped again during the Cache Packaging and Deployment Test while the user was attempting to stand up from one knee while the posterior leg pushed against the leg to stand. To prevent breakage the researcher was compelled to wear the weight belt looser than intended to reduce the stress on the cable, and also experienced difficulties squatting very low to the ground in a manner that felt natural. This was particularly prevalent in the Fire Hose Deployment Test which necessitated the user to reach down to the ground and walk forward to roll up the hose. The second area of malfunction occurred in the leg straps, which consistently loosened with longer periods of leg movement. This dysfunction occurred throughout all tests and required frequent tightening by the user. These straps also required the most time to secure and release in the Donning On and Off Test.

For the duration of the tests, if the exoskeleton was fitted properly and had not broken, the design did effectively encourage the user to utilize their legs instead of their back when squatting and lifting. This is likely due to the addition of the weight belt in the design. Bending forward without leg bending was mildly hindered. After 4 days of consistent use in challenges the user reported no back pain or soreness. The researcher experienced the feedback of the spring engaging and disengaging with the appropriate movements and perceived an assisting force when standing up from a squatting position. The researcher also reported an increased engagement of their quadriceps muscles and soreness in their trapezius muscles.

The second round of off-the-user spring testing suggested the new spring eliminated any concerns about the exoskeleton's use-to-failure that were prevalent in the ATSM Exo Games.

This testing resulted in the force displacement data shown in Table 6, with a bottom out force of 33 lbs being deemed acceptable for continued testing.

Table 6

3rd prototype spring testing

Displacement (in)	lbs
0	0
0.5	2.4
1	4
1.5	6.5
2	8
2.5	9.7
3	10.5
3.5	12.3

The force/displacement testing of the spring yielded a linear relationship, as shown in Figure 33. The black line represents the experimental data, while the gray line represents the trendline, indicating that the force required to displace the spring increases proportionally with displacement.

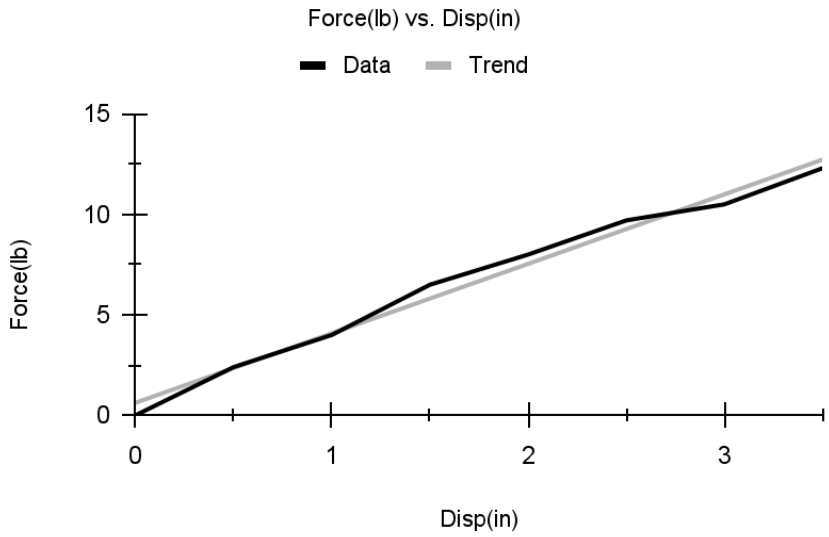


Figure 33: Force/Displacement graph of one spring on the final prototype

When the team tested the exoskeleton at NIST in Gaithersburg, the Bomb Walk Test was performed again with the improved design utilizing the feedback from the ATSM Exo Games. Approximately 8 minutes into the 10 minute test, the user bent over to reach one part of the test as seen in Figure 32, and the cable of one side of the exoskeleton slipped from its clamp and became loose. This caused the spring and clamp to rapidly move upwards into the dead stop of the housing, causing the top of the housing to fracture, as seen in Figure 34. The clamp slipping on the cable being the first point of failure was expected and designed for. If the housing did not unexpectedly fracture, then the clamp slipping would be the easiest failure to repair as demonstrated during the ATSM Exo Games. This point of failure is also the least dangerous to the user and their surroundings. To prevent this unintended fracture from happening again, the distance from the top edge of the housing to the hole for the dead stop was doubled in future designs. Despite the early failure, during this round of testing the user reported less slippage of

the exoskeleton, more range of motion and more assistance provided by the exoskeleton than previous versions.



Figure 34: Failure of housing - NIST Gaithersburg

During the second day of testing at NIST Gaithersburg results of the test were gauged on the rate of perceived exertion (RPE) scale from 1-10, ranging from minimal exertion to maximum exertion. The user reported results are shown below.

Table 7

Fire Hose Deployment Results

	W/ Exo 1	**W/ Exo 2**	**W/ Exo 3**	**W/O Exo**
TASK	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**
Take hose off table	1	1	1	1
Roll out hose	2	2	2	2
Drag to coupler	1	1	1	1

Connect then disconnect from coupler	1	1	1	1
Roll up hose	4	3	3	4
Bring hose back to table	1	2	2	2

Table 8

Fire Overhaul Results

	W/ Exo 1	**W/ Exo 2**	**W/ Exo 3**	**W/O Exo**
TASK	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**
Use fire hook to push open weighted ceiling tile	5	4	4	5
Use fire hook to pull open vertical wall tile	4	4	4	4
Use fire hook to pull up weighted floor tile	4	4	4	5

Table 9

Cache Packaging Results

	W/ Exo1	**W/ Exo 2**	**W/O Exo**
TASK	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**
Move Ropak	1	2	5
Pick up totes from floor	4	4	3
Bring totes to Ropak	2	2	3
Put totes in Ropak	4	3	4
Take totes out of Ropak	3	3	2
Bring totes to floor area	4	4	5

Table 10

Bomb Squad Walk Results

	W/ Exo 1	W/ Exo 2	W/ Exo 3	W/O Exo
TASK	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**	**RPE (1-10)**
Put on vest	2	2	2	1
Pick up weights	3	3	3	3
Walk 50 ft	2	2	2	2
Place weights on ground	3	3	3	3
Kneel, squat, or sit down	2	2	2	1
Manual dexterity task	1	1	1	1
Stand/retrieve weights	3	3	3	3

5. DISCUSSION

The initial mobility tests in creating the first prototype proved to be successful. The early tests resulted in mostly qualitative reassurance of the safety and feasibility of the design. These tests acted less as definitive results and more of a guide for the investigators for future iterations. The applications of these results to the current prototype was limited due to significant changes in fit and materials. Initially the team used these results to better understand and assess the comfort of the design and its functionality in a firefighting environment. Feedback from initial interviews with local firefighters was central to the design, and alterations were made based on the user's assessments of those requirements. The evaluation of exoskeleton success in redistributing forces away from the lower back and legs was based on largely subjective feedback. The off-the-user spring testing performed prior to the ATSM Exo Games enhanced the researcher's safety estimates of the exoskeleton but did not provide definitive feedback on how those forces would actually behave when applied to the human body.

The ATSM Exo Games provided more usable results. The exoskeleton generally performed well with the user expressing a largely positive experience. The assistance in lifting acted as a facilitator for the gluteus and hamstring muscles. The lack of lower back engagement due to the structure of the harness was a desired result. However, this restriction may be beneficial in encouraging leg and gluteus muscle utilization, the potential limitation of forward bending movements (such as toe touches) should be considered. Any alteration to the firefighters natural movements during any task could potentially cause injuries. The increased muscle involvement in the hamstrings can be attributed to the active engagement of those muscles while squatting with proper form. This muscle activation may have been exacerbated by the force of

compressing the spring on the squat descent. Passive exoskeletons do require the user to “load” the exoskeleton but this should be monitored to avoid a net increase of exertion. The soreness of the trapezius muscles is possibly a consequence of the harness pulling down on the shoulders while the weight belt was not properly secured. It may also be attributed to a force distribution to the shoulders which should also be monitored. The structural failures of these tests were addressed in the final prototype. During the Exo games, there was an instance where all exoskeletons were given to the panel of judges, who had several hours to examine, wear, or test the exoskeletons. They determined that Team EXO’s design provided the most optimal mechanical support and particularly praised it for this aspect. While the prototype was and still is a work in progress, this was an encouraging sign that the team is on the right track.

For the second spring testing, the resulting data indicated a linear relationship between force and displacement. This means that for the purposes of the exoskeleton, the spring is operating within the elastic limit of its stress/strain curve, following Hooke’s law, with force directly proportional to displacement. This is an ideal characteristic for an exoskeleton application, as it ensures predictable and controllable resistance during use. This also means the team can correlate the force exerted with the displacement of the springs linearly, making it easier to determine the total exerted force when performing different actions with the exoskeleton. Based on the graph, the spring's stiffness appears sufficient to provide the necessary support for the exoskeleton's functionality. Overall, the spring's behavior aligns with the design expectations, confirming its suitability for the exoskeleton application.

The first round of testing at NIST in Gaithersburg gave us useful information on the limitations of our design, and showed a new failure mode that we had not considered possible before. The failure mode of the cable slipping from its clamp was anticipated, and designed for, however, the impulse that the spring generated when allowed to suddenly expand from maximum compression was not. This failure allowed us to make final design changes to ensure robustness and minimize failures. The testing that was able to be completed also pointed towards the functionality of the redesign being more beneficial to the user than previous iterations.

The final round of testing at NIST in Gaithersburg proved the design had advanced enough to act as a fully functional exoskeleton. The full range of the spring was utilized and when experimented with to evaluate failure, the cable and spring effectively bottomed out without harm to the user or exoskeleton. There were no mechanical failures of the exoskeleton during this testing. A lifting force was experienced by the user. It should be noted that the only user in this testing was a member of the team, and there may have been some bias in the reporting of RPE values. If further testing is to occur with this project, IRB approval should be applied for to allow us to use non biased participants in testing. Furthermore, none of the tasks performed exceeded a 5 on the RPE scale, which suggests that the duration of the tasks should be increased to use more of the scale, which will allow any differences while using the exoskeleton to be more apparent.

Overall, the testing on the exoskeleton thus far has centered on the physical perceived comfort, fit, and performance of the exoskeleton as well as the strength and consistency of the exoskeleton relating to longevity, breakages, and slippage. These attributes were critical to

prioritize, but were largely qualitative. Testing was structured to maximize the quantitative analysis of each task including movement specifications, repetition and time qualifications, as well as using the Rate of Perceived Exertion Scale. The NIST set up utilized to perform the final prototype tests is the current standard for commercial exoskeleton testing. However, the basis of each measurement was rooted in the user's perception of the exercise, their fatigue, and the exoskeleton. As discussed previously, this testing dilemma is common among exoskeleton development. Although EMGs, modeling software, CPET, and pressure-sensing clothing also have their limitations they can provide additional information, however limited in scope they may be. For this reason the development of these exoskeletons could potentially benefit from these avenues of testing in the future until a more comprehensive testing alternative is standardized.

6. EQUITY-IMPACT REPORT

Firefighters are a crucial member of those classified as first responders. It is critical that they are able to be ready at a moment's notice in emergency situations. Any extra time needed to to suit up can be a matter of life or death. Therefore it was essential that the design does not add any unnecessary delay to the suit-up process. The goal was to develop an exoskeleton that can be worn by any firefighter, no matter the shape or size, without adding to their response time. Had we had more time for development, we would be able to create an exoskeleton that would be adjustable to fit a greater variation in body sizes and occupations. The main challenge towards this goal was the exoskelton's height adjustability, as the cable length determined the ideal user's height. Additionally, the exoskeleton should be quick and easy to strap on underneath turnout gear. In future iterations we would create a secure fit with a simple click system.

The primary purpose of the exoskeleton was to mitigate firefighter's injuries so that they can be more effective in helping others. Through discussions with firefighters the team learned about their more common injuries to ensure the design addressed their needs. Because one of the most common injuries is stress on the lower back, the exoskeleton design focuses on supporting the lower back and utilizing the legs and gluteus muscles. Ultimately, the team hopes this technology will be implemented into diverse fire departments, enabling firefighters to better protect themselves while they are protecting the community.

The design also prioritizes affordability, making it available to fire stations across socioeconomic backgrounds. The manufacturing costs are relatively low, ensuring that most fire departments can afford the technology.

An additional benefit of our exoskeleton is the reduced cost of injuries and finding replacement workers. Fire departments have various resources which they must allocate for paying injured firefighters while they recover, injury insurance, and replacing workers while they heal. These costs can be extreme compared to the cost of our exoskeleton, so reducing injuries over time is a direct physical and financial benefit of our exoskeleton. This also applies to all ranges of firefighting including wildfire and structural. While this exoskeleton was designed for structural firefighters, its benefits also translate to wildfire firefighters, increasing the impact our device can have on safety and costs. Specific tasks wildfire firefighters take on are clearing brush and building firewalls; these are repetitive tasks that build strain overtime which our exoskeleton can help reduce. The exoskeleton, if worn as a part of a firefighter's station wear, can also be taken on non-fire calls, such as EMS and rescue calls, which make up a majority of a fire department's day-to-day operations. Support from an exoskeleton would help firefighters with tasks such as lifting an EMS patient or performing lifting tasks around the fire station.

7. CONCLUSION

Team EXO's primary goals were to explore the design of an exoskeleton for firefighter use. Over the four years of the project, the team designed and tested successive iterations of a lower back-based spring-powered exoskeleton. This involved not only the design of the exoskeleton itself, but also the definition of the situations where an exoskeleton might be best applicable and the test methods to determine the feasibility of a particular exoskeleton design. The project came at an important moment in the development of exoskeletons for firefighters, considering the new interest in determining standards by bodies like ASTM and NIST.

The team expected the majority of research to focus on the design of a singular exoskeleton for firefighter tasks. The issue of testing and acquiring useful data was highlighted throughout the research process. Quantitative methods of data collection, such as EMG testing, were considered, but due to time and resource constraints more subjective measures were used to evaluate the performance of the exoskeleton. RPE provided a useful way to transform subjective experience of performance to numbers for comparison, but left gaps when it comes to repeatability between different user tests. This problem of data made it difficult to accurately determine performance of an exoskeleton.

The work of ASTM and NIST over the past year to determine and set standard test methods represents a great stride in the topic. The team's work on determining test methods likewise contributed to the growing knowledge base regarding exoskeletons in firefighting. Particularly, the development of refined calisthenics test methods allowed the team to properly

test for range of movement and identify deficiencies in the exoskeleton's ability to conform to user movements. This work will give future researchers a headstart in classifying the movement performance of their exoskeleton designs.

With regards to the exoskeleton developed by Team Exo, a number of conclusions can be made. They are listed below in no particular order.

1. Ensuring that the exoskeleton does not interfere with a fire fighter's existing gear remains one of the most important requirements and challenges for this class of exoskeleton.

With every iteration of the Team Exo exoskeleton design, one of the first considerations made was taking into account the overall footprint of the design on the human body. Any design that interferes in any significant way with the turnout gear or SCBA tank of a firefighter should not be considered for development. This requirement eliminates a number of potential exoskeleton designs. The team’s exploration of ideas mirrors designs shown at the ATSM Exo Games - strap based exoskeletons powered by restoration force of springs or bands.

2. A dual spring exoskeleton attempted to address the issue of conforming to a SCBA tank, but made certain movements awkward for the wearer. The current lower placement of the weight belt and springs would interfere with the SCBA harness, and the spring housings were moved close together. These would have to be altered in future designs.

The Team Exo design attempted to satisfy the above requirement, but at a cost to the comfort of the wearer in certain positions. It was found during calisthenics and task testing that extending or retracting one leg at a time could feel unnatural to the wearer because of the offset tension. While a certain level of awareness is expected to be present due to the effects of the exoskeleton, too much could become distracting to the wearer and detract from the purpose of helping firefighters. At worst it could lead to wearers compensating their movement and losing the benefits of having the exoskeleton. This presents just one way that the gear requirement forces design tradeoffs in other aspects of the exoskeleton performance.

3. The dual spring exoskeleton had benefits to the user in situations where the lower back and legs would be engaged normally.

The main benefits of the Team Exo exoskeleton came from tasks where the user would need to bend over and engage their lower back and legs. Tasks such as lifting objects, placing objects, and using heavy tools to apply force to objects were made easier with the support from the exoskeleton. Further testing would need to be conducted to classify all of the movements where the exoskeleton provides benefits to the wearer. These are the tasks most likely to cause lower back strain and injury, so this presents a case where a fire fighter could be made safer with the exoskeleton.

4. Material selection remains an important consideration for future research and implementation.

Due to lack of time and resources, the material selection process was limited to what could be easily sourced from University of Maryland fabrication labs and online commercial sellers within budget.

Overall, the Team Exo project was a success in exploring the practical requirements of exoskeletons for firefighters as well as outlining the test methods that need to be used to evaluate comfort and performance. There has been clear interest in exoskeletons for emergency responders in recent years and the feasibility of such devices has been shown from an engineering perspective. Future research must continue to involve firefighters more closely to determine how exoskeletons could fit into current firefighting practice and procedures. The use of exoskeletons needs to fit into the greater operating procedure before they can be put to any real world use.

It will likely be many years before the first exoskeleton is implemented in a fire department, but this work establishes a foundational body of research and initial testing. With standardized test methods developed, future work can begin on designs and mechanisms that specifically address the unique operational and environmental requirements of firefighting.

REFERENCES

Apex 2 Press Kit | HeroWear. (2023, February 22). https://herowearexo.com/press-kit/

Apogee | Active Exoskeleton with Lifting and Walking Support. (2025). *German Bionic*. Retrieved November 18, 2024, from https://germanbionic.com/en/solutions/exoskeletons/apogee/

Apogee High-tech for the care sector. (2025). German Bionic. https://germanbionic.com/en/apogeeplus/

ASTM International Exo Games 2024 Challenges. (2024). ASTM International Exo Technology Center of Excellence. https://www.etcoe.org/new-events-webinars/exogames2024

Bengler, K., Harbauer, C. M., & Fleischer, M. (2023). Exoskeletons: A challenge for development. *Wearable Technologies*, *4*, e1. https://doi.org/10.1017/wtc.2022.28

Campbell, R., & Hall, S. (2024). *United States Firefighter Injuries*. Retrieved September 29, 2022, from https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders/Firefighter-injuries-in-the-United-States

Ervin, J. (2024, March 4). Medical Exoskeletons, A Transformative Technology. *https://www.astm.org/news/medical-exoskeletons-ma24*

Firefighters: Occupational Outlook Handbook: : U.S. Bureau of Labor Statistics. (2025). Retrieved September 29, 2022, from https://www.bls.gov/ooh/protective-service/firefighters.htm

Flor-Unda, O., Casa, B., Fuentes, M., Solorzano, S., Narvaez-Espinoza, F., & Acosta-Vargas, P. (2023). Exoskeletons: Contribution to Occupational Health and Safety. *Bioengineering (Basel, Switzerland)*, *10*(9), 1039. https://doi.org/10.3390/bioengineering10091039

Friedenberg, R., Kalichman, L., Ezra, D., Wacht, O., & Alperovitch-Najenson, D. (2022). Work-related musculoskeletal disorders and injuries among emergency medical technicians and paramedics: A comprehensive narrative review. *Archives of Environmental & Occupational Health*, *77*(1), 9–17. https://doi.org/10.1080/19338244.2020.1832038

Golabchi, A., Chao, A., & Tavakoli, M. (2022). A Systematic Review of Industrial Exoskeletons for Injury Prevention: Efficacy Evaluation Metrics, Target Tasks, and Supported Body Postures. *Sensors*, *22*(7), 2714. https://doi.org/10.3390/s22072714

GRAHAM MegaMover Transport Units | Life-Assist.com. (2022). Retrieved November 11, 2022, from https://www.life-assist.com/products/details/939/graham-megamover-transport-units/

How Much Does Firefighter Gear Weigh? (2025). https://firefighterinsider.com/firefighter-gear-weight/

Industrial Archives—Exoskeleton Report. (2025). Retrieved November 18, 2024, from https://exoskeletonreport.com/product-category/exoskeleton-catalog/industrial/

Lancaster, M. (2023). *Informational interview with Montgomery County active firefighter* [Personal communication].

Latasa, I., Cordova, A., Malanda, A., Navallas, J., Lavilla-Oiz, A., & Rodriguez-Falces, J. (2016). Limitations of Spectral Electromyographic Analysis to Determine the Onset of Neuromuscular Fatigue Threshold during Incremental Ergometer Cycling. *Journal of Sports Science & Medicine*, *15*(1), 148–157.

Marinov, B. (2022, August 16). *SABER Brings Mass Adoption Of Military Exoskeletons One Step Closer To Reality*. https://www.forbes.com/sites/borislavmarinov/2022/08/16/saber-brings-mass-adoption-of-military-exoskeletons-one-step-closer-to-reality/?sh=5d45ef83366b

markus. (2024a, July 11). Robotic exoskeletons from German Bionic make work easier for nursing staff at RoMed Kliniken in Rosenheim. *German Bionic*. https://germanbionic.com/en/robotic-exoskeletons-from-german-bionic-at-romed-klinik en-in-rosenheim/

markus. (2024b, September 25). German Bionic and Servco Inc. Partner to Distribute Apogee e-exoskeletons. *German Bionic*. https://germanbionic.com/en/servco-partnership/

Muscle Suit Exo-Power—Exoskeleton Report. (2024, December 5). https://exoskeletonreport.com/product/muscle-suit-exo-power/

NFPA Standard 1710. (2025). https://www.iaff.org/wp-content/uploads/Departments/Fire_EMS_Department/30541_S ummary_Sheet_NFPA_1710_standard.pdf

Saltmarsh, A. (2021, March 10). *Innophys: Flexing Their Muscles With Exoskeletons*. DirectIndustry E-Magazine. https://emag.directindustry.com/2021/03/10/innophys-flexing-their-muscles-with-exosk eletons-japan-smart-factory/

Slade, P., Kochenderfer, M. J., Delp, S. L., & Collins, S. H. (2022). Personalizing exoskeleton assistance while walking in the real world. *Nature*, *610*(7931), 277–282. https://doi.org/10.1038/s41586-022-05191-1

Statistics. (2024). U.S. Fire Administration. Retrieved November 18, 2024, from https://www.usfa.fema.gov/statistics/

Taborri, J., Pasinetti, S., Cardinali, L., Perroni, F., & Rossi, S. (2021). Preventing and Monitoring Work-Related Diseases in Firefighters: A Literature Review on Sensor-Based Systems and Future Perspectives in Robotic Devices. *International Journal of Environmental Research and Public Health*, *18*(18), Article 18. https://doi.org/10.3390/ijerph18189723

The Apex 2 Back-Assist Exosuit | HeroWear. (2023, March 7). https://herowearexo.com/the-apex-2-back-assist-exosuit/

The Science Behind the Apex | HeroWear. (2023, March 7). https://herowearexo.com/the-science-studies-behind-the-apex-back-exosuit/

Vallée, A. (2024). Exoskeleton technology in nursing practice: Assessing effectiveness, usability, and impact on nurses' quality of work life, a narrative review. *BMC Nursing*, *23*, 156. https://doi.org/10.1186/s12912-024-01821-3

Vu, V., Walker, A., Ball, N., & Spratford, W. (2017). Ankle restrictive firefighting boots alter the lumbar biomechanics during landing tasks. *Applied Ergonomics*, *65*, 123–129. https://doi.org/10.1016/j.apergo.2017.06.006

APPENDICES

I. Budget

At our project initiation, the team developed a proposed budget for the following year. This is displayed in the table below. This included categories such as acquiring standard firefighting including turnout gear. While this cost was estimated at $500, the team was able to receive these items free of charge Globe Manufacturing Company, LLC. The team also allocated $500-600 for materials to make for prototype construction and the final product. Additionally, the team planned to attend a conference within driving distance of the University of Maryland and budgeted $300 for associated attendance expenses.

CATEGORY	JUSTIFICATION	COST
Firefighter's PPE	Testing and fitting the exoskeleton with a standard suit	$500.00
Structure/Mechanic Materials	Needed to build and join together structural materials into an exoskeleton	$300.00
Fixture Materials	Textile materials for comfort	$200.00
Accessories	Materials for appearance (marketability)	$50.00
SFPE Annual Conference 2023	Meeting in Bethesda Maryland with Fire Safety Engineers	$300.00
Total Cost		$1,350.00

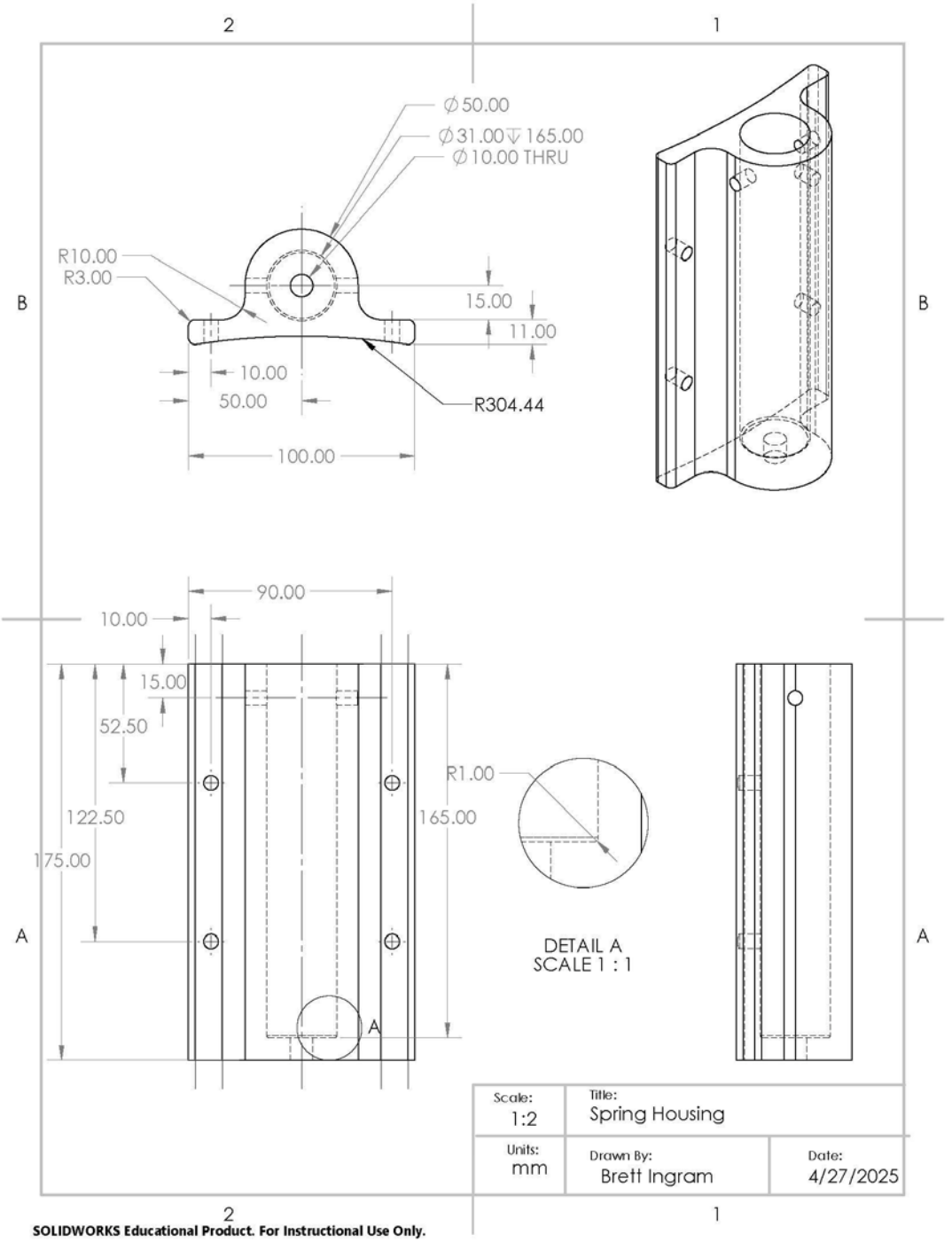
Actual expenses were close to the team's initial projections. The final $885 for materials for all prototypes and tools was well under the $3,000 raised on Maryland Day in 2023. However, instead of the original planned conference, the team attended the Exo Games with a cost of approximately $2,000. This event comprised the majority of the project's budget, but provided an ideal testing environment and access to experts in the field. In this competition, the team also won a $1,000 prize, which helped offset the expenses of the conference, reducing the cost to

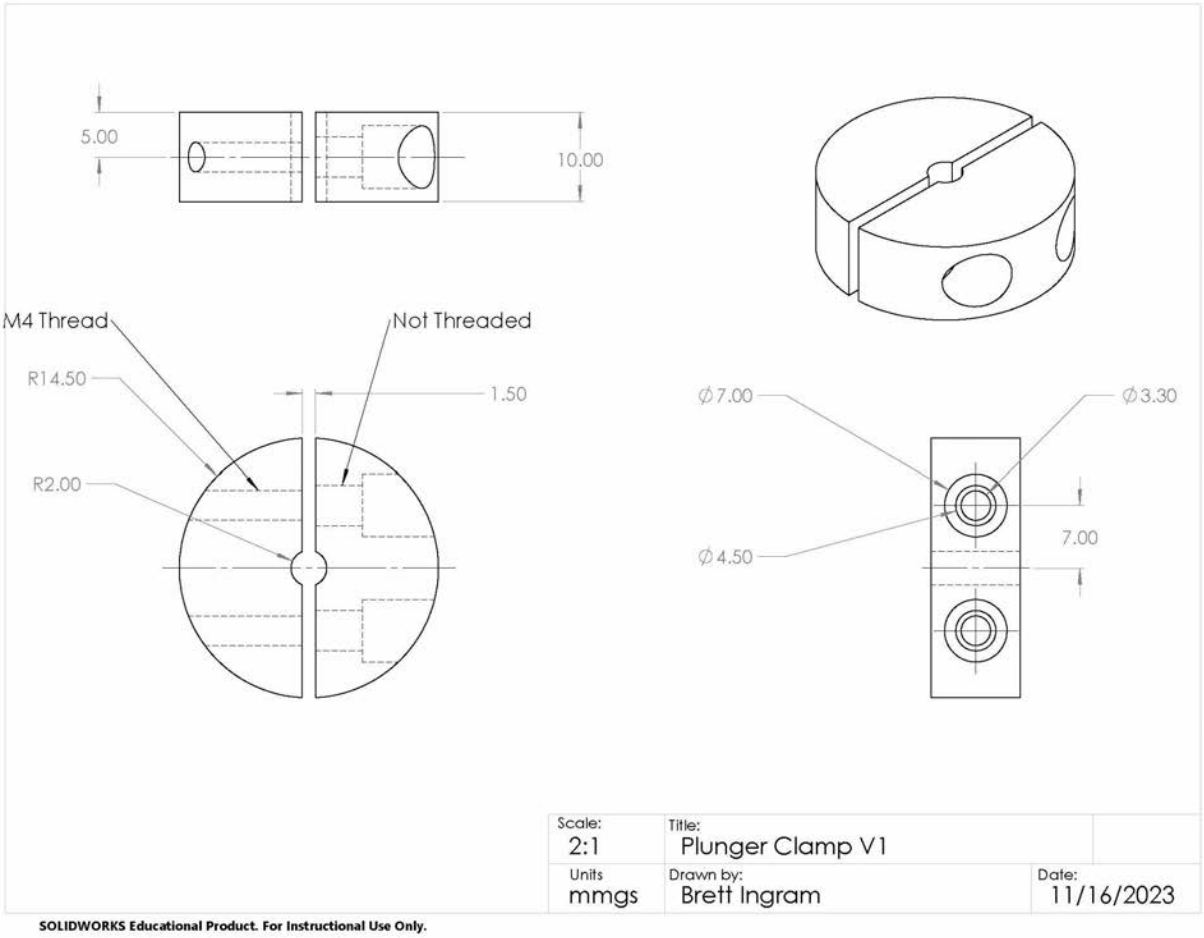
approximately $1,000. The team's final expenses were within $500 of the original budget projection.

The Exo Games Bill of Materials below outlines the cost of all parts used in the final prototype. While most materials were inexpensive and readily available, the most significant expenses were those associated with 3D-printed parts, including custom designed springhousings and leg attachments.

Qty	Vendor	Description	Unit Price	Cost
1	Total Pro Fitness	Weight Belt	$49.95	$49.95
1	Amazon	Harness	$56.98	$56.98
2	UMD Tech	Leg Attachment Print	$14.63	$29.26
2	UMD Tech	Spring Housing Print	$33.00	$66.00
2	The Spring Store	Springs	$27.45	$54.90
1	Harbor Freight	Cable	$8.99	$8.99
1	McMaster	Screws and nuts	$30.39	$30.39
1	Amazon	Nylon Webbing & Clips	$15.99	$15.99
		Approximate	Total	$312.46

II. Technical Drawings




5.00
10.00
M4 Thread
Not Threaded
R14.50
1.50
R2.00
Ø7.00
Ø3.30
Ø4.50
7.00
Scale:
2:1
Title:
Plunger Clamp V1
Units
mmgs
Drawn by:
Brett Ingram
Date:
11/16/2023
SOLIDWORKS Educational Product. For Instructional Use Only.