

Design and Preliminary Evaluation of a Flexible Exoskeleton for Manual Lifting

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(ABSTRACT)

A flexible and passive exoskeleton is presented in this paper. The exoskeleton uses carbon fiber beams to provide an energetic return to its wearer and relieve their lower back muscles. The design of the exoskeleton and potential elastic mechanisms are described, and the results of biomechanical testing are given. The exoskeleton decreased the erector spinae muscle activity by 21-39.7%.

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(GENERAL AUDIENCE ABSTRACT)

A flexible and passive wearable device, or exoskeleton, is presented in this paper. Utilizing carbon fiber beams, the un-powered exoskeleton provides assistance to the wearer during lifting. By storing energy as the wearer bends and returning it to the body as they straighten, the muscles have to work less. If muscles work less, then the risk of low back pain or low back disorders hopefully decreases. The design of the exoskeleton, tradeoffs between different types of springs to store energy, and the results of biomechanical testing are presented. The exoskeleton decreased the amount the low back muscles worked by 21-39.7%.

Dedication

*This thesis is dedicated to the people who wore the exoskeleton, and will hopefully wear it
in the future.*

Acknowledgments

First I would like to thank my committee chairman, Dr. Alan Asbeck, for making me a part of the Assistive Robotics Lab. Under Dr. Asbeck's guidance I have not only gained confidence in myself as a technically strong engineer, I have also gained confidence in my skills as a creative engineer. Dr. Asbeck's enthusiasm for mechanical concepts supported by technical excellence has provided a challenging and fulfilling learning environment, one of which I am grateful to have been a participant.

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Finally, I'd like to thank my family. To my mom, thank you for listening to me talk (or vent) about my work for so many hours on the phone. To my dad, thank you for the constant encouragement to "just get it done", and to my brother, thank you for the random visits to the lab, you always improved my day. You all are my best cheerleaders.

I cannot begin to cover the numerous ways my fiance has helped me through this journey; thank you, Brian, for all of your support, and for always being up to answer my frustrated MATLAB questions. I cannot wait for both of us to be done with graduate school and start our life together.

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List of Abbreviations

γ	Effective body angle measured from the back slider to the hip assembly to the leg slider
ϕ	Angle from the horizontal to the bottom backpack strap vector
θ	Angle from the horizontal to the top backpack strap vector
F_B	Force from the bottom extension
F_T	Force from the top extension
F_{CF}	Force produced by the carbon fiber
F_{TORSO}	Reaction force of the body from the carbon fiber
BNDR	Bending non-Demand Return
BW	Body weight
CF	Carbon fiber
cm	Centimeters
FG	Fiberglass
J	Joules
LES	Lumbar erector spinae muscle
MMH	Manual Material Handler
N	Newtons

NGR Natural gum rubber

PLAD Personal Lift Assist Device

SF Safety factor

TES Thoracic erector spinae muscle

WSAD Wearable Stooping-Assist Device

Attribution

I contributed extensively to the design and prototyping of the exoskeleton presented in this thesis. Primarily, I was vital in the decision to use carbon fiber beams, the main factor of the exoskeletons novelty. I also helped generate ideas for techniques to integrate carbon fiber exoskeleton. After ideation, I was responsible for helping bring designs to fruition. My contributions mainly centered on the main mechanisms to have carbon fiber attached to the body, including clamping of the carbon fiber, allowing sliding, and the soft interfaces of the exoskeleton. Developing the exact configuration that enabled comfortable lifting was achieved through iterative design and building prototypes. I was able to help design and construct the exoskeleton up to a point where it was ready for machined parts.

I also contributed to some of the biomechanics testing. I wrote large portions of the institutional review board applications, which gained approval, and then participated in a few experiments of the data collection for electromyography.

For analysis of the exoskeleton, I compiled the comprehensive elastic review, which is a combination of data from literature, mechanical testing, and calculations. I collected, processed, and analyzed the data from two subjects for calculating the energetic return of the carbon fiber on the exoskeleton. Following that, I also wrote the code to calculate the slider movements. In relation to the electromyographic results, I performed the statistical analysis of the signals. My final contribution is this thesis, which I wrote in totality.

Chapter 1

Introduction

In recent years, research in exoskeletons has grown rapidly. From exoskeletons that support the full body to exoskeletons for assisting the hand during daily activities [4, 5], wearable devices are being developed for improving the daily life of numerous people. Powered exoskeletons provide many benefits to the user, but have limitations due to their bulkiness, heft, and expense. Passive exoskeletons, or unpowered exoskeletons, provide assistance without motors or batteries, which enables lightweight, and potentially cheaper solutions [6].

The exoskeleton presented here is passive, lightweight, flexible, and low-profile. By using carbon fiber instead of alternative methods, the exoskeleton is able to apply a restoring moment to the body without inhibiting motion. Section 2.2.2 shows the key differences between energetic mechanisms such as carbon fiber, titanium, elastic bands, and springs. Further analysis of the exoskeleton is necessary to demonstrate effectiveness. Energetic analysis of the exoskeleton and biomechanical benefits of wearing the exoskeleton is in Section 2.4. Future applications and studies on the exoskeleton are detailed in Chapter 3.

Chapter 2

Design and Preliminary Evaluation of a Flexible Exoskeleton

Back injuries account for 20% of reported occupational injuries per year. While the causes of these injuries range from falls to overexertion, all injuries are costly both to the company and the individual. One way to decrease the rates of injury is to decrease the loading on the spine. Passive exoskeletons apply a restoring moment at the hip of the wearer which enables the forces on the spine to be reduced. Contrary to previous exoskeletons that incorporate elastic bands or gas springs, we present an exoskeleton that implements carbon fiber beams to store energy and return it to the wearer. We discuss the design of the exoskeleton and some general considerations for lift-assistance exoskeletons. Carbon fiber is compared to alternative methods of energy storage and assessed for exoskeleton applications. We also characterize our exoskeleton's energy storage and its effect on the back muscles during lifting. Compared to no exoskeleton, wearing the exoskeleton reduces the muscle activity of the thoracic and lumbar erector spinae muscles between 27 and 39% during freestyle lifting.

2.1 Introduction

Manual material handlers (MMH) repetitively lift objects in order to move freight from distribution centers to trucks, trucks to pallets, and pallets to shelves. In the process, they perform motions such as lifting, pushing, pulling, holding, and carrying objects. These tasks are performed by 2.6 million workers across the country each day [7]. These motions can be metabolically costly or can cause overexertion, both of which can lead to pain and injuries [8, 9]. Injuries from manual material handling can occur in almost any part of the body, including the back, shoulders and arms, and legs. In total, these occur at the rate of 297.8 per 10,000 workers per year [10], and back injuries occur the most frequently, accounting for 20% of the total [9]. In addition to causing medical issues for workers, injuries from lifting cost companies billions of dollars in reparations and the loss of over tens of millions of productive days [8, 11].

Recently, exoskeletons have been introduced as a solution to these increasing health issues in the workplace [12, 13, 14]. One review reported seven passive (unpowered) exoskeletons in existence that assist the back [6]. Only a few passive exoskeletons have come to market or have been published since the review [15, 16].

Despite this prior work, there exist opportunities for further research into the basic elements of exoskeleton design, including the methods of energy storage and release, and the human interface. Further investigation into elastic mechanisms and comfortable connections are necessary if we are to move toward the ubiquitous use of exoskeletons in industrial settings [6]. To that end, in this work we present a novel exoskeleton to assist the back during manual lifting. Our exoskeleton design incorporates flexible beams to permit the body to move freely in both bending and twisting. Along with its design, we present a comprehensive comparison of the different methods of storing energy and returning it to

the wearer, and present initial results demonstrating the exoskeleton’s function and effect on the body during lifting.

In the following sections, we first elaborate on the biomechanical necessity for exoskeletons and review the prior work on passive exoskeletons in more detail. We subsequently describe the exoskeleton’s design in Section 2.3, and compare different elastic mechanisms in Section 2.2. We present measurements of our exoskeleton and biomechanical results from its evaluation on test subjects in Section 2.4, followed by conclusions in Section 2.5.

2.1.1 Biomechanical Background

Numerous studies have described the effects of repetitive lifting on the body in different poses and environments [17, 18, 19]. While our exoskeleton is intended to assist those performing any type of lifting, it is particularly aimed at assisting workers who stock and palletize or depalletize. To that end, in this review we focus on the literature that pertains more specifically to these activities. Palletizing and stocking both require frequent lifts and bending, and palletizing has been shown to require a significant metabolic effort, using 25 to 35% the maximal aerobic capacity [20]. Some industrial activities do not require frequent bending or lifting. Assembly operations usually require a worker to be oriented towards a table or conveyor belt, and then to hold a static position for the majority of the workday. While this position is fatiguing, it does not lead to high injury rates [10].

Performing palletizing and stocking can increase the risk for developing low back pain and disorders. One study showed that box mass and shelf height were two key factors for increased risk of developing low back disorders. From the bottom of a pallet, each 4.45 kg increase in box weight causes a 130% increase in spine compression when compared to a box stacked on a shelf 95 cm higher. Spine compression is one key factor in determining

low back disorder risk [21].

To find the exact amount of spinal compression at the L5/S1, an extensive biomechanical study is required. One way to estimate the spinal compression, however, is to use the electromyography (EMG) [22]. Passive exoskeletons apply an extensor moment near the hip to reduce the spinal compression; changes in muscle activity signal a reduction in spinal compression, which in turn confirms a moment being applied to the hips [23]. In exoskeleton studies, erector spinae muscles are focused on in particular due to their high contribution to spinal loads, while other muscles are included to ensure there are no adverse changes in muscle activity. Most papers on lifting exoskeletons test the amount of muscle reduction in the thoracic erector spinae (TES), lumbar erector spinae (LES), latissimus dorsi, and rectus abdominis [6]; we will present our results for the TES and LES in Section 2.4. These muscles form the key muscles for the low back, and are commonly associated with low back studies [17, 24].

Techniques to pick up boxes range from a pure stoop lift to a squat lift. A stoop lift is where the legs remain straight and the back bends, while a squat lift involves the legs bending and the back staying straight. It is known that stoop lifting is less costly metabolically than squat lifting, and squat lifting is generally accepted as the better option for reducing low back pain and injuries due to the reduced compressive loads in the spine [25]. Freestyle lifting is usually a combination of stoop and squat lifting styles, and furthermore depends on the lifter's specific kinematics. These lifting styles will be referenced throughout the paper.

2.1.2 Review of Passive Exoskeletons

In this section, a brief review of passive exoskeletons is provided; de Looze et al. [6] provides a comprehensive review for active and passive exoskeletons. Passive exoskeletons do not use any external power sources such as motors or batteries. Instead, they work by storing energy elastically while a person bends forward during a lift, and returning that energy to the wearer to help them stand up straight again. These exoskeletons have employed a variety of different materials for storing energy, including rubber bands, torsional springs, or gas springs [15, 26, 27, 28], and use various mechanisms to couple the forces from the exoskeleton to the body. In the following review, exoskeletons will be separated into two different categories for further discussion: (i) elastic bands and (ii) gas springs and metal springs.

Exoskeletons with Elastic Bands

Rubber or elastic bands are a common technique for passively returning energy to the wearer due to their high energy density. Many previous exoskeletons utilized rubber in conjunction with rigid support structures to accomplish the same goal of relieving the back muscles [14, 29, 30]. They have resulted in various degrees of success in reducing muscle activity.

Of the exoskeletons using elastic bands for energy storage, the PLAD has been studied the most extensively [26, 29, 31, 32]. On the PLAD, a hip belt is worn, which has a pelvic spacer bar protruding from the back. Four elastic bands connect the spacer bar to the shoulders, while one connects from the spacer bar to the shin bone on each leg, in parallel with the hamstring muscle. As the wearer bends forward, the elastic bands stretch, building a restoring moment. The six elastic bands' tension ranges from 25-160 Newtons (N) at

their maximum extension to provide assistance during lifting. The PLAD reduced the low back muscle usage by 14% for the LES, and 27.6% in the TES averaged across all lifting styles [29]. By optimizing the tensions per subject, the PLAD reduced the mean activity in the thoracic and lumbar erector spinae muscles by 38% in squat lifts and 37% in stoop and freestyle lifts at the cost of greatly increasing the muscle activity in the legs [26]. During asymmetrical tasks, the average reduction for LES was 23.9% and for the TES, 24.4% [31]. However, the PLAD had no effect on lowering the metabolic cost while using the exoskeleton, and 40% of the test subjects complained of knee discomfort [31].

One of the more recent exoskeletons developed by Lamers *et al.* also uses elastic bands [15]. As compared to the PLAD, it does not use a pelvic spacer on the back of the hips, but rather places the elastic against the body. Two crossed-over elastic bands connect from the upper-body interface to the lower-body interfaces, which are located on the thighs instead of below the knee (as on the PLAD). During static leaning, erector spinae muscles were reduced from 23-43% and during dynamic lifting, erector spinae muscles were reduced by 14-23% [15].

The wearable stooping-assist device (WSAD) is one of the few powered exoskeletons that is for stooping and low back disorders. It also uses elastic bands, but modulates the tension in the elastic during lifting through a servo motor. In a static 90° position, the WSAD reduced the TES and LES by 42% and 47% respectively; dynamic lifting motion was not studied [13].

One device used a combination of elastic bands and a fiberglass rod acting in bending, resulting in a 23% reduction in the erector spinae during a static bend [33].

Exoskeletons with Gas or Metal Springs

Metal springs or gas springs have also been incorporated into a few passive exoskeleton designs [14, 28, 30, 34, 35].

The Bending Non-Demand Return (BNDR) weight transfer device implements torsional springs at the hip to apply a torque to the wearer during lifting [30]. With a rigid support structure and simplistic thigh and chest pads, the BNDR is able to reduce loads on the L5-S1 joint and LES and TES muscle activity. One factor the researchers of the BNDR included is flexion-relaxation (FR). A person who exhibits the FR phenomenon will have an erector spinae with eccentric activity in the lumbar region. While bending forward at the trunk, the electrical signal of the erector spinae increases up to a point, then suddenly decreases, and typically becomes silent at full lumbar flexion [36, 37]. For subjects who did not exhibit FR, the average LES activation was reduced by 26% during static stooped postures, but the TES had no significant reduction; however, during flexion/short lifts, the peak LES activity decreased by 23% and the TES decreased by 17% [37]. Subjects with FR had lower reductions in muscle activity. Peak values of the task EMG data were normalized to peak MVC values for reduction calculations for the flexion/short lifts, while the average of the signal was taken for the stooped posture [37].

Berkeley's human engineering laboratory also built a passive exoskeleton; the device uses a coil spring and cable system in conjunction with a star-shaped cam to modulate the restoring moment at the hip. During static lifting, the erector spinae muscles were reduced by 44% and 54% for 4.54 kg and 13.6 kg loadings respectively [14].

The Laevo, one of the few commercially available exoskeletons, may have the most minimalist design to date and is very lightweight with a mass of 2.3 kg; its main elastic mechanism is a gas spring in conjunction with a cam [28]. The Laevo reduces the TES by 37%,

and LES by 14% during a simulated assembly task (static holding), however, subjects reported discomfort in their armpits and on their chests during the tests[28].

Another commercial exoskeleton, backX (US Bionics, Inc., Berkeley, CA), also uses gas springs to provide a restoring moment at the hip [38]. The backX uses rigid support structures and soft goods to interface to the body, creating a restoring moment at the hip. The top of the exoskeleton is anchored to the torso with shoulder straps and a pad in the center of the chest. The lower half of the exoskeleton has thigh pads and a rigid connection to the gas spring located at the hip, which is used to store energy. During a static stoop task, the backX reduces the TES by 75.5% and the LES by 56.5% [34].

Another exoskeleton, the passive spine exoskeleton, was worn by three subjects and had an average of 40.4% reduction in the TES and 9% reduction in the TES for one of the stooped positions [35]. This exoskeleton implemented extension springs along the chest and legs with a rotating cam to apply push and pull forces.

In contrast to previous work, we investigated the use of a composite leaf spring made of carbon fiber as the sole energy storage element in the exoskeleton, hypothesizing that it would provide improved energy return and assistance for the back while remaining lightweight. Also, while some previous exoskeletons resulted in complaints of discomfort during their use, our exoskeleton uses soft interfaces and perpendicular forces to achieve a design with minimal discomfort. The soft interfaces are shown in Figure 2.2, and Appendix C is the compiled comfort surveys.

In the following sections, we first present an analysis of the energy requirements of a passive lift-assistance exoskeleton, and compare various means of energy storage in terms of their density, hysteresis, and cycle life (Section 2.2). We then present the design of our exoskeleton (Section 2.3), and provide analysis for the design of its components. We present

experimental results characterizing our exoskeleton in Section 2.4, and conclude in Section 2.5.

2.2 Exoskeleton Comparative Design Analysis

2.2.1 Design Goals

Exoskeletons are wearable, mechanical devices, and thus are required to fit on the human body. Along with limitations due to body size, there are also volumetric considerations depending on the environment of the wearer. For example, in an industrial setting, it may become necessary for the wearer to pass by operating machinery or fit into small spaces such as under shelves, in a car, or in a tractor trailer. Therefore, the form factor of the exoskeleton (or the distance away from the body) should be minimized to reduce interference with the environment.

The exoskeleton should relieve the weight of the torso. That is, if a person bends forward by some angle, the exoskeleton should ideally completely offset the weight of their torso, such that their trunk muscles no longer have to support the load. In this way, the same amount of effort can be used to lift an equivalent mass. First, we must determine the torso's weight and energy required to lift it. According to the CDC, the average weight for working age males (20 years to 69 years) in the 50th percentile is 87.1 kg [39]; this is the representative weight to estimate the exoskeleton's energy requirement. The energy requirement was computed by assuming a 50th percentile male bends at the waist such that their torso angles forward 75 degrees from vertical, and finding the change in potential energy. Seventy-five degrees is roughly the torso angle that corresponds to lifting an object up from the floor with a squat lift. In a squat lift, while the knees move forward and so the

total hip angle is large than 90° only the torso's weight creates a torque against the exoskeleton. Thus, the exoskeleton should be sized to offset the weight of the torso angled 75° from vertical.

In stoop lifting, the back may bend to larger angles than this, e.g. 90° from vertical, but the thighs remain vertical. In this pose, an exoskeleton sized to offset the weight of the torso at 75° will provide 97% of the moment to support the torso. In summary, to make an exoskeleton compatible with both stoop and squat lifting, we assumed that it must offset the torso at 75° . Using anthropomorphic data [40, 41] to approximate the height changes of the arms, head, and torso segments and mass, we are able to calculate an energy requirement of 103.0 Joules (J), which we will round to 100 J.

If the exoskeleton is able to support the weight of the torso, the same amount of muscle usage and energy can be devoted to lifting an object of equal or lesser mass than that of the torso. In this way, the exoskeleton will provide the maximum assistance to the person. If the exoskeleton provides more energy than this or does so in a way which leads to a corresponding force greater than that provided by the body, then the wearer will have to use their stomach muscles to curl against the exoskeleton when they bend forward. Ideally, the exoskeleton will provide an appropriate amount of restoring moment so that the user does not have to work against it while bending down to pick up an object. Additionally, to provide maximum assistance in the long-term, the exoskeleton needs to be able to endure the stresses of repetitive lifting. For example, Marras *et al.* reported an estimated 166 lifts/hr for workers performing palletizing [42]. Extrapolating this to a 40 hour work week and 50 work weeks per year results in 332,000 lifts per year which must be assisted by an exoskeleton, assuming a laborer is wearing the exoskeleton every shift and lifting consistently. Ideally, an exoskeleton should be able to withstand usage for at least three years, or a total of 10^6 lifts. This value, 10^6 , will be used to compare elastic mechanisms

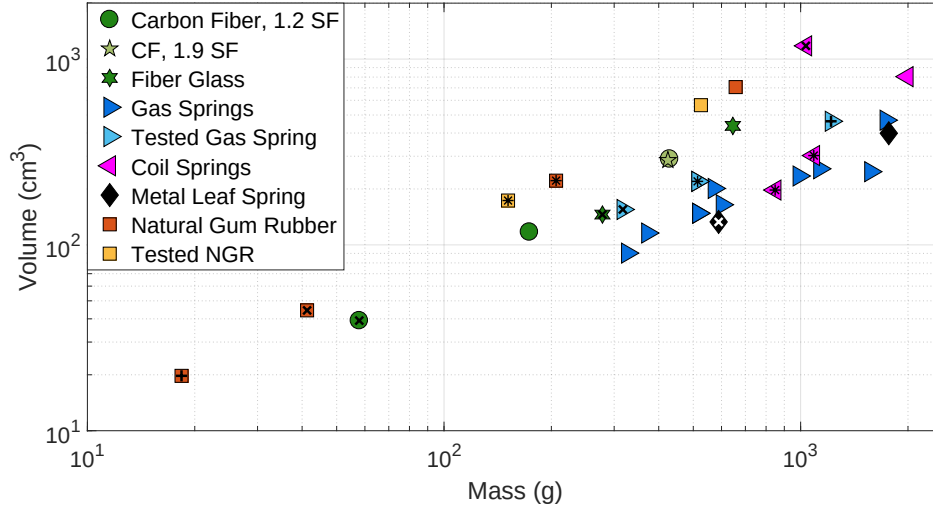


Figure 2.1: Composites (fiberglass and carbon fiber) are represented by different shades of green. Carbon fiber was tested with a safety factor of 1.8, and is the light green star. The light green circle overlapped by the star is the theoretical result. Fiber glass is represented by green hexagrams. Some of the composites (green) and metal leaf spring (black) symbols have x-marks, which represents moment end loading on a cantilevered beam. Gas springs are symbolized by right pointing triangles. Three different types of gas springs were tested and displayed in light blue: 578 N max force (x), 1258 N max force (*), and 2135 N max force (+). The other gas springs (blue) are estimates from data provided by suppliers. Coil springs are in magenta and left-pointing triangles. The triangle with an x in the center is a compression spring, and the asterisks represent torsion springs; the empty magenta triangle is a die spring. Finally, natural gum rubber (NGR, durometer rating of 40) is shown as squares. Empty squares are rubber extended to 50% of its original length, while the *, x, and + filled squares are 100%, 200%, and 300% elongation respectively. Orange squares are estimated and yellow squares are experimental data. Exact suppliers can be found in Appendix A.

and establish optimal materials for exoskeleton use in Section 2.2.2.

2.2.2 Elastic Mechanism Considerations

Many materials or structures can be used to store energy and then return it. We investigated composites, titanium, gas springs, coil springs, and elastic bands to establish a de-

sign space based on constraints such as volume, mass, hysteresis, and cycle life. The exact materials and the suppliers used are in Table 2.4 and Appendix A.

In Figure 2.1, we plot the volume and mass of different elastic mechanisms that will provide 100 Joules (the optimal value as discussed in Section 2.2.1). The composite and titanium calculations assume a safety factor of 1.2 of the yield stress (excluding the tested composite and its stress-matched estimate). The coil and gas springs were taken to 90% of their maximum stroke length, and the rubber was taken to different values of elongation as specified below. For three of the elastic mechanism types, carbon fiber, fiberglass, and titanium, there are two different loading conditions: a cantilevered beam with an end point load, and a cantilevered beam with an end moment load (represented by an x through the symbol). Cantilevered beams with point loadings have a non-uniform stress distribution along the length of the beam, while a cantilevered beam with a moment applied at the end creates a uniform stress along the length of the beam, and will have optimal energetic return.

Different amounts of elongation of natural gum rubber (NGR) were compared for energetic return. Figure 2.1 demonstrates how increased elongation causes reductions in the mass and volume of the necessary rubber to achieve 100 J of energetic return. NGR can achieve up to 600% elongation before ultimate failure, however, the life span at those levels is dramatically decreased; as such, Figure 2.1 only goes to 300% elongation as a factor of safety. Two levels of elongation, 50% and 100% were tested with an Instron machine and a 5 kN load cell. Initial length was measured for each trial, and the appropriate amount of extension applied. The loading curves were then used to calculate the energetic return of the rubber. The yellow squares in Figure 2.1 are the results of those calculations. After extracting the k value from the collected data, an estimate using Hooke's law ($F = kx$) was calculated for 50% and 100%; due to some non-linear properties of NGR, the estimated

energetic return proved to be 13% lower than the experiment, which is why the orange squares for the respective elongation values have higher mass and volume than their respective counterparts in yellow.

The tested carbon fiber was taken to 53% stress, which corresponds to a cycle life of close to 10^7 as seen Table 2.3. The light green circle that is behind the light green star is the corresponding estimate using a beam with point loading. Within 2% of each other, this test case demonstrates that our experimental and estimated (using beam bending formulas) values are dependable. The calculated result has higher mass and volume because carbon fiber behaves non-linearly, which enables a reduction in mass and volume necessary for 100 J.

The heaviest and largest in volume mechanisms are the coil springs. Other types of springs such as extension springs were considered, but the mass and volume necessary to achieve 100 J was far beyond even the coil springs shown in Figure 2.1. Out of the twenty-eight configurations in Figure 2.1, the materials with the lowest mass and volume are carbon fiber and natural gum rubber. Under moment loading and with a safety factor of 1.2, the carbon fiber is comparable to the 200% natural gum rubber (but with slightly higher mass and lower volume than NGR). The natural gum rubber with 300% elongation has the lowest mass and volume. Volume and mass are important considerations for a passive exoskeleton, however, they are not the only factors that affect the overall performance. Factors such as hysteresis and life cycle will be examined in the next sections.

2.2.3 Hysteresis

Hysteresis is the loss of energy during the loading and the unloading of an elastic element. In the case of a passive exoskeleton, the wearer bends forward and transfers potential en-

ergy to the exoskeleton, and thus loads the elastic element. When the wearer then stands back up, the elastic elements unload and return the stored elastic energy to the wearer minus the losses due to hysteresis. Any hysteresis losses reduce the net benefit that the exoskeleton can provide during lifting. Additional losses can occur from the soft goods or from the human tissue displacing, since they both act as lossy series springs between the skeleton and the exoskeleton [43]. Friction between rigid components of an exoskeleton will also cause energetic losses.

Elastic Mechanism	Load Cell (kN)	Stress Level	Type	Speed (mm/min)
Carbon Fiber	50	53%	Comp	25
Natural Gum Rubber	5	50%	Ext	20
Natural Gum Rubber	5	100%	Ext	50
Gas Spring (2135 N)	5	90%	Comp	10
Gas Spring (1258 N)	5	90%	Comp	20
Gas Spring (578 N)	5	90%	Comp	50

Table 2.1: Test conditions for the materials in Table 2.2. Ext is extension and comp is compression tests.

Gas springs, NGR, and CF were tested using an Instron machine following the conditions in Table 2.1. After loading and unloading samples, the area under the loading and unloading curves was found using the trapezoidal integration method, and the hysteresis was calculated. The results of this testing are shown in Table 2.2. For comparison purposes, titanium and fiber glass (Garolite G10/FR4) are included although the data was extracted from other sources [1, 2]. Out of our materials of interest, titanium has the lowest hysteresis with approximately 0% hysteresis and gas springs have the largest amount with

approximately 15%.

Elastic Mechanism	Hysteresis (Avg %)
Gas Spring (578 N max)	16.6
Gas Spring (1258 N max)	14.7
Gas Spring (2135 N max)	13.8
Natural Gum Rubber (50%)	4.3
Natural Gum Rubber (100%)	4.2
Carbon Fiber	2.9
Titanium *	0.35
Fiberglass (G10/F4) *	9.35

Table 2.2: Hysteresis values for various elastic mechanisms. Data marked with an asterisk was extracted from other sources [1, 2].

2.2.4 Cycle Life

Elastic mechanisms will endure varying amounts of stress throughout their lifetime. Understanding the expected life cycles of elastic mechanisms is key for predicting the durability and life cycle of the exoskeleton itself. Table 2.3 presents a summary of the cycle life data for the elastic mechanisms of interest as found in the literature [44, 45, 46, 47, 48, 49, 50]. In this discussion, the stress ratio is the ratio of the minimum stress to maximum stress applied during the fatigue cycling; for example a ratio of 0.1 means that a material will be loaded to a maximum stress σ , and then the stress is gradually reduced to a minimum of 0.1σ such that it is still bent, with the load still in the same direction. The stress is then increased again, and the cycle repeats.

Nitrogen gas springs vary from 125,000 to 250,000 cycles according to various suppliers [50, 55]; this value is highly dependent on the manufacturer. Rubber's lifetime increases substantially when the minimum stress endured is high. For example, if rubber is extended by 75% initially, and is further extended to 125% for a total of 50% elongation, the life

Elastic Mechanism	Cycle Life (Cycles)	Source
NGR 300%	10^3	[44]
NGR 200%	10^5	[44]
NGR 100%	$5 \cdot 10^5$	[44]
NGR 35%	10^6	[51]
NGR 50%	10^6	[44]
NGR 200% $\rightarrow$ 400%*	10^7	[44]
NGR 250% $\rightarrow$ 300%**	$8 \cdot 10^7$	[44]
Carbon Fiber $\gamma = 0.92$	$3 \cdot 10^2$	[52]
Carbon Fiber $\gamma = 0.83$	10^2	[52]
Carbon Fiber $\gamma = 0.8$	10^4	[46]
Carbon Fiber $\gamma = 0.73$	10^6	[46]
Carbon Fiber $\gamma = 0.51$	10^7	[52]
Glass fiber $\gamma = 0.26$	10^3	[53]
Glass fiber $\gamma = 0.21$	10^6	[47]
Glass fiber $\gamma = 0.14$	10^7	[53, 54]
Titanium $\gamma = 0.24$	10^7	[49]
Nitrogen Gas Springs	$2.5 \cdot 10^5$	[50, 55]

Table 2.3: Cycle life for materials of interest. Multiple entries are shown for each material to show how the cycle life varies with the maximum applied strain. All NGR samples assume 0% initial strain with the exception of those denoted by an asterisk; the single asterisk has a 200% initial strain with 200% elongation, and the double asterisk has an initial strain of 250% and 50% elongation. Cycle life is shown for glass fiber, carbon fiber composites, and Titanium tested with a stress ratio of 0.1. γ is defined as the applied stress divided by maximum material stress.

cycle can increase by an order of magnitude compared to rubber starting a zero extension to 50% elongation [45]. Therefore, if cycle time is the primary parameter, rubber should be used with a high initial tension.

Care must be taken in combining the results shown in Table 2.3 with those shown in Figure 2.1. The calculations shown in Figure 2.1 assume a minimum safety factor of 1.2, or a γ value of 0.83. Most of the results in Table 2.3 that show very high cycle lifetimes ($> 10^6$) occur at lower γ values (< 0.6). Also, the specific materials tested may be different be-

tween Table 2.3 and Figure 2.1. For example, the natural gum rubber in Figure 2.1 has a durometer rating of 40, while the NGR in the Table 2.3 has a durometer rating of 50. Additionally, particular resins or epoxies used to fabricate fiberglass or carbon fiber could cause variations. Without mechanical testing performed on the exact materials, there is no way to confirm the exact number of life cycles for the mechanisms presented in Figure 2.1; however, the information presented is still valuable because it presents the relative magnitude of the cycle life for each material. The comparisons drawn from Table 2.3 are based on magnitude differences, which absorbs error due to variations that may occur based on exact material composition.

Material	Supplier
Carbon Fiber	CSTSales.com T770L2
Gas Spring (578 N max)	Bansbach
Gas Spring (1258 N max)	Ameritool
Gas Spring (2135 N max)	Custom Dadco
Natural Gum Rubber	McMaster-Carr 6856K14

Table 2.4: Suppliers of tested materials

In summary, many of the elastic storage mechanisms are possible to use for passive exoskeletons depending on the requirements for weight, volume, hysteresis, and cycle life. Among the materials examined, carbon fiber stands out as having perhaps the best combination of low weight and volume, low energy loss, and a possible high cycle life (assuming the maximum stress is chosen carefully). Based on this analysis, we used carbon fiber to store energy in the exoskeleton we designed.

2.3 Exoskeleton Design

2.3.1 Overview of Exoskeleton Design

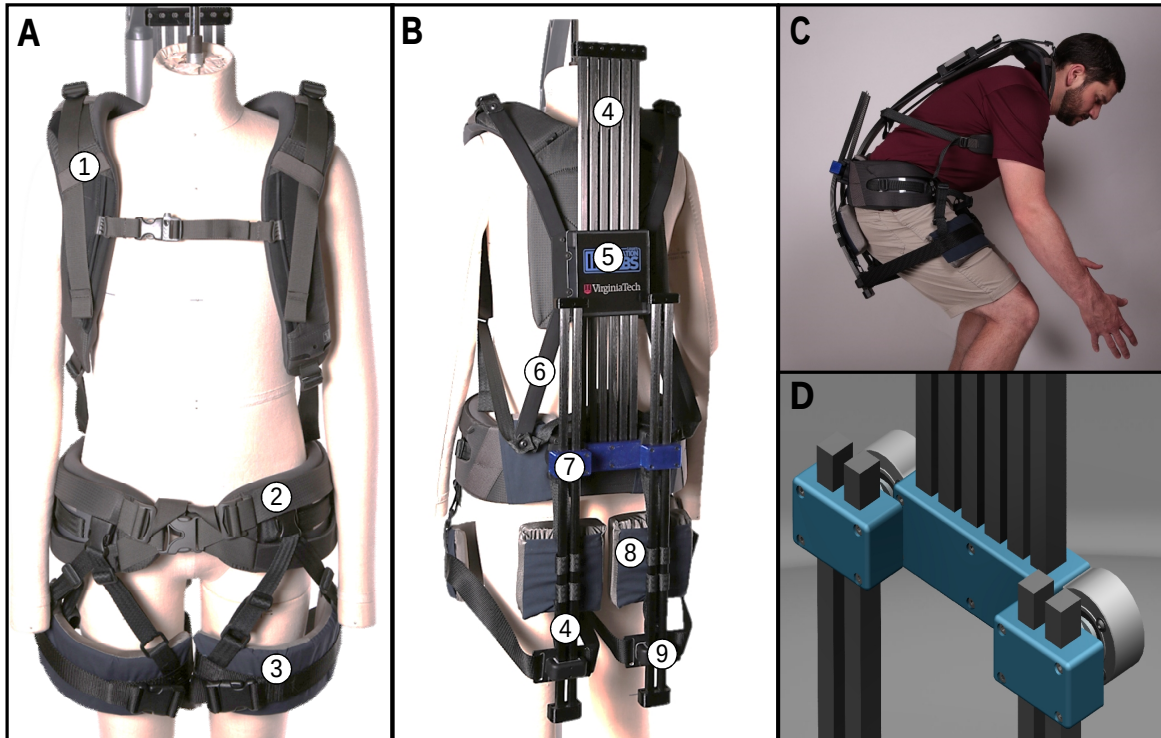


Figure 2.2: The front of the exoskeleton (A) displays the soft interfaces. The back of the exoskeleton (B) contains the carbon fiber. (C) is an example of the shape produced during lifting. A more detailed view of the hip assembly (B7) is visible in (D). The shoulder straps (1) are connected to the carbon fiber (4) through aluminum extensions (6) and a back assembly (5). The hip belt (2) ensures the weight of the exoskeleton remains on the hips, while the thigh cuffs (3) connect to the carbon fiber through leg sliders (9). Posterior support cushions (8) form the final soft interface.

We next provide an overview of our exoskeleton design (Figure 2.2). The exoskeleton components can be categorized into two groups: (a) soft components, which come into contact with the wearer's body, and (b) mechanical components which form the structure of and provide energy storage for the exoskeleton. As shown in Figure 2.2A, soft components in-

clude the chest harness (1), hip belt (2), thigh cuffs (3), and posterior support cushions (Figure 2.2B(8)). The mechanical components are shown in Figure 2.2B, and they include carbon fiber beams along the back and back of the legs (4), a back slider assembly (5) which includes an “X”-shaped structure that extends to the wearer’s shoulders and sides of their hips (6), a central hip block (7, close up view in Figure 2.2D), and leg sliders (9). All of the mechanical elements are on the backside of the wearer, which maintains a minimal profile and allows the exoskeleton to be only a few centimeters beyond the body, and allow unrestricted access to space in front of the body.

The exoskeleton operates as follows. When a person bends forward, their torso pulls forward on the shoulder straps and thigh cuffs, which in turn pull the back slider assembly and leg sliders, respectively. These in turn pull the carbon fiber (CF) structure, bending the CF into a “C” shape (Figure 2.2C). As the person bends, the back slider and leg sliders move up and down the carbon fiber to accommodate the kinematic differences between the carbon fiber and the wearer’s skeletal structure. Since the friction between the sliders and carbon fiber is low, the sliders ensure that the force from the CF on the wearer is approximately normal to the wearer’s body at the shoulders and thighs. A reaction force to the body is created by the hip belt and posterior support cushions pushing inward on the wearer’s lower back and pelvis. The combination of the forces on the body creates an extension moment about the hips and lower back, pulling the wearer toward a vertical position.

2.3.2 Soft Interfaces

By using off-the-shelf goods for the chest and hips, and in-house designs for the thigh cuffs and posterior support cushions, the device maintains comfort and minimizes point load-

ings. The soft interfaces (excluding the posterior support cushions) are displayed in Figure 2.2A.

For the chest harness, backpack straps designed for use with a frame hiking backpack were attached to the exoskeleton through the back assembly. The straps are able to adjust in length on both the top and bottom, which enables the cushion to be optimally positioned around a wearer's chest and shoulders. At 8.9 centimeters (cm) wide and cushioned for approximately 25 cm of length, the straps provide a large surface to apply the restoring force on the torso. An additional cross strap connects the straps and prevents shifting on the chest during lifting.

The hip belt, also originally designed for a hiking backpack, distributes the weight of the exoskeleton (~ 4.5 kg) to the pelvis and anchors the hip assembly to the wearer. The hip belt provides cushioned support around the circumference of the hips with an adjustable buckle in the front. The belt can adjust for hips ranging from 80.6 cm to 132.1 cm in circumference. For sizes smaller than 80.6 cm, the belt can easily be exchanged for a smaller one since it is anchored to the hip assembly through three bolts. One modification to the hip belt is an extra 2.5 cm thick cushion on either side of the spine in the lumbar region. This enables the forces at the lumbar region to provide support during lifting, and improves comfort.

Due to the forces from the carbon fiber on the legs, the thigh pads should ideally be wide, conformal to the body, and strong. The thigh pads provide a large area to distribute forces across the thigh, since they are approximately 11.4 cm tall and an arc length of ~ 29.2 cm. They are composed of a layer of two centimeter thick EVA foam (McMaster Inc.) and a 1.588 mm thick piece of aluminum secured within a fabric covering. Adjustable webbing connects the thigh pads to sliders on the leg carbon fiber, and a triangular configuration of adjustable webbing prevents the thigh pads from sliding down.

The final soft interface on the exoskeleton is the posterior support cushion. These cushions are shown in Figure 2.2B(8) and are made of 4-6 cm thick EVA foam and a sheet of 0.15 cm thick plastic in a spandex pocket. Two rows of looped webbing attach the posterior support cushion to the carbon fiber. The cushions support the wearer's backside during lifting. This feature was necessary due to the interaction between the body and carbon fiber. While the beams do bend during lifting, the curvature can be enhanced and the body cushioned (i.e. the force distributed over a larger area) by including posterior support.

2.3.3 Mechanical Components

The exoskeleton device has three machined sections to constrain the carbon fiber: the back assembly, the hip assembly, and the leg assembly.

As mentioned in Section 2.3.2, the backpack straps are attached to the back assembly. In Figure 2.2B, the back assembly (5) has a back plate with four aluminum extensions (6), which attach to the top and bottom of the backpack straps on each side of the body. The back plate is made of an anodized aluminum plate with two brackets that span the six columns of carbon fiber beams; the brackets and straps ensure that the carbon fiber follows the wearer closely. Each bracket is lined with Teflon to minimize frictional losses. A strip of webbing bolted to the hip assembly ensures that the back assembly does not extend too far upward. During bending, if the back assembly is not restrained in this manner, under some circumstances it can slide all the way to the top of the carbon fiber beams. If unconstrained, the beams push the back assembly toward the wearer's head, leading to the chest harness sliding up on the wearer's torso. In this case, the wearer must work to initiate the lift until the slider has surpassed the maximum of the curve created by the

carbon fiber. Then, the carbon fiber will assist the wearer throughout the remaining part of the lift. The exoskeleton's webbing does not allow for the slider to achieve this situation.

The aluminum hip assembly is responsible for constraining all of the carbon fiber beams on the exoskeleton. The assembly is anchored to the hip belt and can be seen in Figure 2.2D. The torso and legs of the exoskeleton each contain several stacks of carbon fiber beams (CST-The Composite Store, Tehachapi, CA). On the torso, there are six stacks of beams, and each leg has two stacks of beams. Each stack typically has 5, 6, or 7 beams, which can be selected based on the wearer's weight. The mechanism accommodates up to 8 beams and fewer beams can be used as well. The distribution of beams throughout the structure was determined empirically by what felt the most comfortable to several test wearers. For the data in the rest of this paper, the exoskeleton was outfitted with 7 beams in each stack, which corresponds roughly to wearers of weights 77-95 kg.

Each beam has the dimensions of 1.8 mm thick x 11.1 mm wide x 609.6 mm long. This thickness of 1.8 mm was chosen so that each beam can bend with a radius of 18 cm for a maximum stress of 1.43 MPa. This is 83% of the yield stress of the material, giving a factor of safety of 1.2 at maximum curvature. Curvature of the beams smaller than this radius is unlikely due to the presence of the wearer's back and posterior, which will enforce a larger curvature.

Besides securing the carbon fiber, the hip assembly is also designed to allow the wearer to perform hip abduction. This is accomplished with two bearings and a steel pin on each leg clamp. The hip abduction rotation is limited to moving fifteen degrees by a stiff rubber compressed between two aluminum stops. A version was tested without rubber springs, which allowed the leg assembly to rotate freely; in this version the leg assemblies were observed to rotate outward to large angles (> 60 degrees) during lifting as the exoskeleton

found the lowest energy state.

Sliders on the legs complete the connection of each thigh to the carbon fiber. Made of aluminum and lined with Teflon, these sliders connect to the 5.08 cm-wide webbing of the thigh straps and move along the leg carbon fiber to account for the length change that occurs when bending. Webbing attached at the hip assembly to the sliders prevent the leg sliders from falling to the bottom of the leg carbon fiber. 3-D printed end caps are used on the ends of the torso and leg carbon fiber stacks to keep the beams contained and aligned properly.

The flexibility of the carbon fiber and the soft interfaces allow for freedom of movement and provide support in any configuration. Twisting, stooping, or squatting are a few of the common poses a person can perform in the exoskeleton.

2.3.4 Adjustability

An optimal fit occurs when the carbon fiber closely follows the body during bending. With proper positioning, an optimal fit is more likely to occur. Adjustments at the thighs, hip, and chest accommodate different individuals. Webbing and buckles adapt to variations in the diameter of the thighs, hips and chest. As mentioned in Section 2.3.2, the hip belt may be exchanged for smaller or larger sizes easily. The sliders on the back and legs allow the exoskeleton to accommodate wearers of various heights. By not permanently anchoring the sliders, the chest straps and thigh straps may be positioned on the body arbitrarily. The combination of sliders and soft interfaces enables the exoskeleton to be worn by persons within the weights of 62-105 kg and heights of 152-200 cm.

An additional degree of freedom for adjustment is the carbon fiber itself. With the ability to change the amount of beams in the hip assembly (Figure 2.2D), the carbon fiber

beams may be adapted for different ranges of weights. Our standard configuration (that corresponds with the aforementioned body weight values) is 42 beams on the trunk, and 28 beams in total on the legs.

2.3.5 Slider Analysis

The back assembly (Figure 2.2B(5)) slides up and down the carbon fiber to accommodate the kinematic difference between the exoskeleton and the person, which occurs because the person's body bends around the spine and hips, while the carbon fiber is offset several centimeters or more from the body's center of rotation. There is very low friction between the slider and the carbon fiber, leading to the back assembly shifting with the wearer's back as they bend. To better understand how the overall back assembly should be designed, the equilibrium condition of the slider was studied (Figure 2.3).

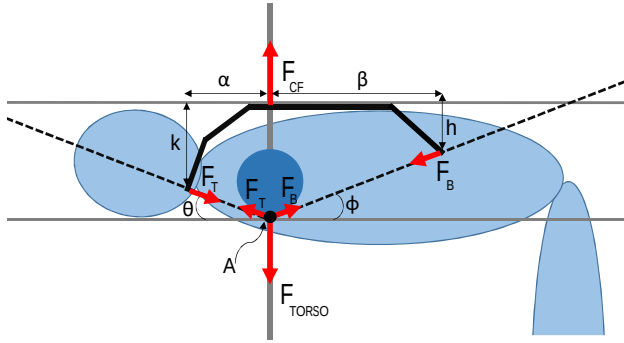


Figure 2.3: Free body diagram of the forces on the torso. F_{CF} is the force from the carbon fiber, and F_T and F_B correspond to the top and bottom extensions' forces. F_{TORSO} is the reaction force of the body (to the carbon fiber). θ and ϕ are the angles between the vertical and the straps of the backpack (top and bottom straps respectively).

Figure 2.3 shows a side view of a person's body bent 90 degrees at the waist, with a simplified diagram of the back slider assembly. The shoulder is shown as a darker circle, and the carbon fiber is assumed to be horizontal at the point where it is directly above the

shoulder. In our analysis, we assume that the force from the carbon fiber, F_{CF} , is normal to the slider due to the low friction ($\mu = 0.10 - 0.19$ [56]) between the Teflon in the back assembly and the carbon fiber. The forces F_T and F_B correspond to the forces from the top and bottom extensions of the back assembly, respectively. F_{TORSO} is the reaction force of the body from the carbon fiber. The dashed lines represent the locations of the ends of the backpack straps where they connect to the extensions. As long as θ is equal to ϕ (they are symmetric across the centerline of the carbon fiber force), $F_T = F_B$ will be true, and moments will be balanced. In other words, the forces will be balanced if the ends of the top and bottom extensions are positioned on the dashed lines originating from the front of the shoulder, and the dashed lines have equal inclinations. This is true independent of the specific locations on the dashed lines. It is necessary to have balanced forces on the assembly so that there is no rotation and so the assembly stays at the nominal location with respect to the shoulders.

Assumptions:

$$F_{T1} = F_{T2} = F_T$$

$$F_{B1} = F_{B2} = F_B$$

$$F_{TORSO} = F_{CF} = F$$

$$\Sigma F_x : F_T \cos\theta - F_T \cos\theta + F_B \cos\phi - F_B \cos\phi = 0 \quad (2.1)$$

$\Rightarrow$ The angles are arbitrary.

$$\Sigma M_A : -\alpha F_T \sin\theta + k F_T \cos\theta + \beta F_B \sin\phi - h F_B \cos\phi = 0 \quad (2.2)$$

Assuming $\theta = \phi$,

$$\sin\theta(\beta F_B - \alpha F_T) + \cos\theta(k F_T - h F_B) = 0 \quad (2.3)$$

$$\theta = \frac{k}{\alpha} = \frac{h}{\beta} \quad (2.4)$$

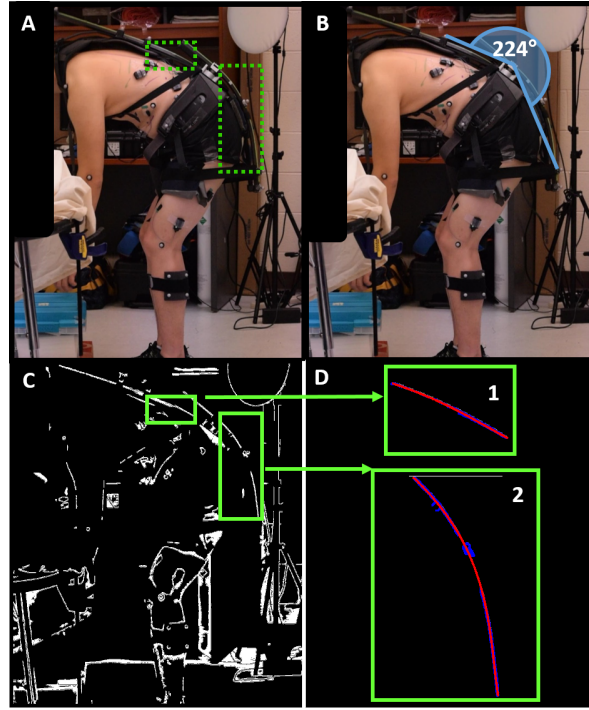


Figure 2.4: Video was processed for determining the energy in the carbon fiber according to body angle through image processing. A is the original image. B shows the effective body angle (back slider to hip assembly to leg slider, γ), while as C and D show the image processing and fit curves.

Regardless of forces' values, the moments will balance.

2.4 Results

The exoskeleton uses the unique properties of carbon fiber beams to apply a restoring moment to the wearer. In order to quantify the energetic return, the angle of the exoskeleton was compared to the curvature of the carbon fiber. In this section, the energetic return and insights into one main component of the exoskeleton, the sliders, are provided. Finally, the EMG results are examined and compared to previous exoskeletons.

2.4.1 Exoskeleton Energetic Analysis

Human subject experiments were performed with Virginia Tech's Institutional Review Board permission under research protocol IRB# 17-127. Video was taken during biomechanics testing. Each subject started from a standing position, bent down to pick up a box, and returned to a standing position. Frames of the descent were extracted and processed through custom MATLAB (Mathworks, Natick, MA, USA) code resulting in ~ 10 data points per lift. Figure 2.4C shows an example of an extracted image. Due to the exoskeleton covering normal anatomical markers commonly used to determine trunk angle, we used the sliders as reference. Effective body angle was measured from the back slider to the hip assembly to the leg sliders. This provided a dependable and repeatable way to measure γ (visible in Figure 2.4B). Post-frame extraction, the carbon fiber shape was identified and extracted from the image (Figure 2.4C). A third-order polynomial was used to approximate the carbon fiber shape (red line in Figure 2.4D). This shape was then resampled and used to numerically calculate the energetic return following Eqns. 2.5- 2.8.

$$U = \frac{1}{2} \int_0^L \frac{M^2}{EI} dx \quad (2.5)$$

$$\text{where } M(x) = EI\kappa \quad (2.6)$$

$$\kappa = \frac{d}{dx}\theta \quad (2.7)$$

$$\theta = \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) \quad (2.8)$$

Two subjects performing stoop and squat lifting conditions were studied. The wearer starts from a standing position ($\sim 188^\circ$), and then moves towards the ground until the box is picked up (~ 230 - 245°). As the angle increases, the carbon fiber increases its bend and thus the potential energy increases. The results of the energetic analysis are in Figure 2.5. The

energy in the carbon fiber increases as the effective body angle increases. Interestingly, the leg carbon fiber serves as the main producer of energy with values surpassing half a Joule consistently. The trunk carbon fiber, on the other hand, does not surpass 0.3 J per beam. The trunk has 42 carbon fiber beams, and the legs have 28 carbon fiber beams for a total of 70 beams. With almost twice as much carbon fiber on the trunk, the carbon fiber there still contributes to the overall energy, albeit minimally.

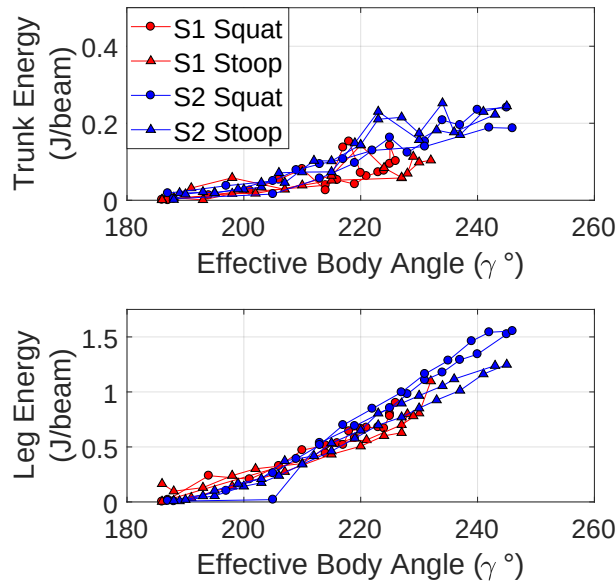


Figure 2.5: Two subjects performed two stoop and two squat lifts. Their images were used to find the amount of energy stored in the carbon fiber beams throughout a lift. The legend in the trunk energy plot also applies to the leg energy plot. Angle is measured from the back slider to the hip assembly to the leg slider (shown in Figure 2.4B).

At the maximum angle, Subject 1 has the energetic potential of 35.1 Joules with 87.6% of the energy being supplied from the leg carbon fiber. Subject 2 has the energetic potential of 52.8 Joules with 80.8% of the energy being supplied by the leg carbon fiber. When comparing the same effective body angle, both subjects experienced an increase in energy for squat lifts of 20% compared to stoop lifting. The increase in energy for squat lifting is due to the necessity of increased knee flexion during a squat lift. With the leg carbon

fiber contributing most of the energy, any change in knee flexion is effective in changing the overall energy.

The results of energy extracted from images confirms our expectations. As the person bends, the bend in the carbon fiber increases, which in turn causes the carbon fiber to have a higher amount of potential energy. With a maximum of 35-53 Joules of energetic return, we are offsetting 50% of the torso's weight. The difference between our expected value (100 J) and results (50 J) is most likely due to the lack of curvature in the trunk. The leg carbon fiber is contributing $\sim 80\%$ of the energy; if the trunk carbon fiber contributed an equivalent amount of energy to the leg carbon fiber (~ 1 Joule/beam), the energetic return would be much closer to 100 J.

2.4.2 Slider Movement

Sliders along the back and legs were incorporated to account for the length change of the distance from the hip assembly (Figure 2.2D) to the back and legs since the center of carbon fiber rotation is not aligned with the spine or the center of the hip rotation. This assumption was challenged by observing the movement of the sliders with motion capture techniques (8 camera system, Qualisys, Sweden). If no sliding is required, then the back and leg assemblies could be dramatically simplified.

Ten male subjects (height: 180.4 ± 6.24 cm, weight: 81 ± 5.3 kg) wore the exoskeleton and retro reflective markers on the sliders while lifting. Custom MATLAB code found the average maximal sliding amount during a trial (4-6 lifts) based on the marker trajectories. The results are in Figure 2.6. The lines in Figure 2.6 show the average trend between sliding and height; for trunk sliding, there is a positive correlation, but for leg sliding, there is a negative correlation. The R^2 values, or strength of the correlation, however, eliminate any

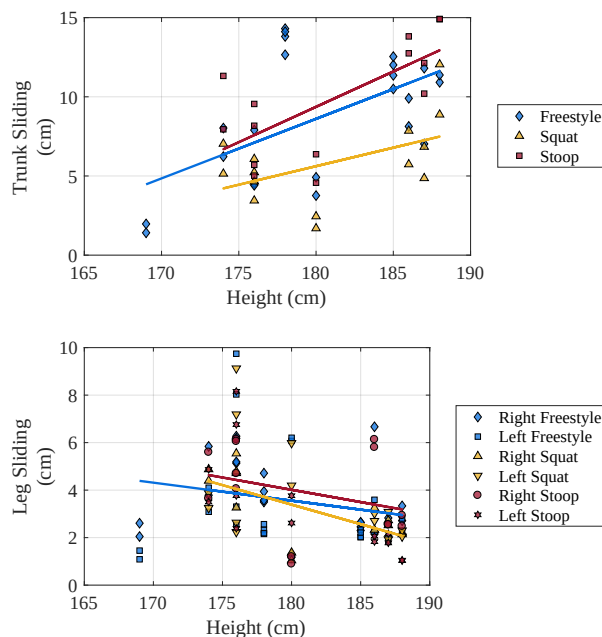


Figure 2.6: The amount of movement for the sliders plotted against the subject's weight. Trend lines represent the linear approximation of the lift condition.

possibility of a predicting the amount of sliding based on height. Excluding the freestyle condition in trunk sliding and the squat condition in the leg sliding, the R^2 values are below 0.15, indicating a lack of correlation. The two excluded cases have values of 0.45 and 0.35 respectively. Similar results were obtained when compared to the subject's weight. We can conclude that there is not a relationship between the amount of sliding and the height of the subject. Most likely, this is due to the variation in the subject's lifting style rather than variation in body type.

If we compare the conditions within subjects, sliding behavior is more predictable. On average, the trunk slider moves more than twice as much as the leg sliders. Additionally, squat lifting has lower trunk sliding values than the stoop lifting. We would expect squat lifting to have higher slide amounts for the legs, but not the trunk in comparison to stoop lifting due to the lifting techniques' requirements with legs or torso bending. Squat lifting

did not cause an increase in leg sliding compared to stoop lifting contrary to our expectations; trunk sliding did follow our expectations with reductions in squat lifting compared to stoop lifting.

The results show that the amount of slider movement is not predictable with our test group (52 trials), and the question remains as to whether sliding is necessary. Soft interfaces could potentially account for sliding that may be needed through loose connections or stretchy features. Adding such features could easily account for up to 5 centimeters of sliding, or the legs' slide amount, and not significantly detract from the energetic return due to the thigh cuff webbing construct. The trunk is more difficult with sliding amounts surpassing 10 cm regularly. Optimal fit is adverse to looseness in the exoskeleton, and thus allowing 10 cm of "looseness" could greatly detract from the energetic return.

When energetic return is considered, the trunk carbon fiber already has a low contribution to the energetic return due to lack of curvature. With this in mind, removing the back slider becomes a more appealing option. Permanent attachment could simplify the design and decrease the weight of the exoskeleton. Another potential benefit is that if sliding is removed, the trunk carbon fiber could have an increased curvature due to the increased pulling force of the torso, though this could have adverse effects in relation to spinal compression. Another issue with permanently determining the location of the back assembly and the thigh cuff webbing is length changes from subject to subject; no person will have the same proportions or height, therefore, the back assembly and the thigh cuff webbing should be adjustable to the subject (as previously discussed in Section 2.3.4). Adjustments to the location of the points of contact for the back assembly and the leg webbing would not be necessary during the lift, but rather during an initial fitting for the wearer.

2.4.3 Biomechanics Testing

To determine the benefits of wearing the exoskeleton, biomechanical testing was performed. Ten male subjects were consented. The study was performed with approval from the Virginia Tech Institutional Review Board (IRB# 17-127). Gender was not an exclusion criteria, however, all volunteers were male. Other studies have precedence for male-only subject pools [20, 57]. None of the subjects reported a history of low-back pain or surgeries within the past 6 months. Each subject wore surface electromyography electrodes (Delsys Inc., Boston, MA), on the left and right of both the thoracic erector spinae and the lumbar erector spinae. Two lifting loads were imposed at 0% and 20% of the subject's body weight (BW). The subjects then performed four symmetrical freestyle lifts with the exoskeleton (EXO condition) and without the exoskeleton (No-EXO condition). Raw EMG signals first had the mean value subtracted. After going through a bandpass filter (20-450 Hz, [32, 58]), the signal underwent full wave rectification. Finally, a moving root mean squared method (250 ms window) was applied to the EMG data. There was no statistically significant difference between the right and left muscles within the same loading and exoskeleton conditions, therefore values presented in Table 2.5 are averages of the left and right muscles together.

Muscle	Weight Lifted (% BW)	Avg. Reduction (EXO vs. No-EXO)
LES	0	-39.7% * †
LES	20	-35.9% * †
TES	0	-31.8% * †
TES	20	-21.4% * †

Table 2.5: Muscle Activity Reductions during Freestyle Lifting. Asterisk (*) signifies that there is statistical significance between the EXO and no-EXO lifting condition ($p < 0.0005$). The † represents statistical significance between the weight lifted condition ($p < 0.01$).

Our results show that during freestyle lifting of 0 and 20% body weight (on average 16.2 kg box) had reductions in the peak EMG values of 31.8% and 21.4% in the thoracic erector spinae and 35.9% and 39.7% in the lumbar erector spinae (Table 2.5). For comparison, during dynamic lifting conditions, the PLAD reported a maximum of 24.7% reductions without adversely effecting other muscles [29]. Other exoskeletons such as the BNDR and Laevo had reductions ranging from 10 to 15% for dynamic lifting conditions [28, 37]. The most recent passive back exoskeleton, the biomechanically assistive garment reduced the peak EMG of the erector spinae muscles by 19% and 23% for 12.7 and 24 kg lifts respectively [15].

Statistics

Paired t-tests were performed for each muscle (LES and TES) to determine statistical significance between EXO and No-EXO lifting conditions (similar to [15]). Both of the muscles had statistical significance for the with and without exoskeleton condition ($p < 0.0002$). Single variable ANOVA analysis between the 0% and 20% lifting conditions was performed as well. Both the LES and TE had statistically significant differences with p-values of 0.00635 and 0.00017 respectively.

2.5 Conclusion

An exoskeleton with a novel elastic mechanism, flexible carbon fiber beams, was presented in this paper. The carbon fiber beams bend with the person, and build up energy as curvature increases. Overall exoskeleton performance was demonstrated through beam energy calculations and electromyography; it was calculated that the carbon fiber beams provided up to 52 J of energy. The exoskeleton proved effective in reducing muscle activity. While

lifting 20% body weight, the exoskeleton, on average, reduced the muscle activity in the LES and TES by 35.9% and 21.4% respectively. For the loading condition with 0% body weight, the LES and TES on average had reductions of 39.7% and 31.8%, respectively.

Components of the exoskeleton, elastic mechanisms and sliders, were critically assessed. Mass and volume of elastic mechanisms were found for providing 100 J of energy, the amount of energy estimated to fully alleviate the torso mass. Hysteresis and fatigue life data were compiled and assessed for feasibility in an exoskeleton use case. The sliders on the exoskeleton proved to not have predictable movement based on height or weight of the subject.

The exoskeleton presented here reduces the muscle activity and clearly applies a restoring moment to the body, which leads us to assume that the lumbar spinal compression is decreased, which in turn reduces the risk of injury [59, 60]. Additional investigation into the comprehensive biomechanical effects is necessary to quantify the benefits of the exoskeleton. Beyond that, more studies are needed to determine long-term effects of wearing an assistive device for the back [6, 26, 37]. Understanding muscle pattern or muscle atrophy while wearing an exoskeleton remain a concern and require clinical trials to ensure that the exoskeleton has no detrimental effects. Another factor to investigate is in relation to adoption rates for exoskeleton wear. In order to fully progress from lab to industry, the factors that influence a manual material handler to wear an exoskeleton could prove to be invaluable information.

Chapter 3

Future Steps

3.1 Future Biomechanical Studies

There are some limitations in the results presented in Chapter 2. The first is a more comprehensive comparison of the muscular activity reduction. While the results of the lumbar erector spinae and thoracic erector spinae are compelling, demonstrating the absence of changes in their antagonistic counterparts will only strengthen our claim to the exoskeleton providing assistance. As mentioned in Section 2.5, further testing is necessary for determining the total body effects of the exoskeleton. Finding the kinematic differences of lifting with and without the exoskeleton, if they exist, need to be determined. Lifting style of the wearer should not be inhibited by the exoskeleton, nor should the style be exaggerated by the exoskeleton; both outcomes could be detrimental to goal of decreasing the risk of low back disorders and pain.

Another total body metric that could support our initial findings of assisted lifting is metabolic testing. Metabolic testing could demonstrate how well the exoskeleton is assisting the muscles that are not easily measured with surface electromyography, and give a better whole-body perspective.

Performing clinical trials for long term effects has yet to occur, although commonly discussed [6, 37]. Long-term wear could be damaging to the stability of the core muscles and

affect the muscle activation pattern, all of which could lead to more injuries. A “best-use” case needs to be established so as to simultaneously decrease the risk of low back pain and muscle weakness.

3.2 Mechanical Changes

Excluding biomechanical factors, further investigation would be beneficial before the exoskeleton was used in industrial settings. Safety concerns related to the exoskeleton still need to be investigated. The chance of tripping or falling with an exoskeleton on remains to be studied. Depending on the use case, the environment could also be conflicting to the benefit of the exoskeleton. The use of a safety harness with an exoskeleton is not widely accepted, although one commercial exoskeleton claims a safety harness can be worn with the exoskeleton [34].

Future work on the exoskeleton design could address the lack of trunk curvature. If the carbon fiber on the trunk obtains a higher curvature, then the energetic return will be greatly increased and the muscle reductions even greater. One possibility is that carbon fiber is eliminated from the trunk completely. With minimal sliding, the connection to the chest from the hip belt could be merely a connection, potentially an exclusively soft connection. To make up for the energetic difference of removing the trunk CF, more carbon fiber could be added to the legs. The solution to the lack of sliding and low trunk energy is still to be determined.

3.3 Applications

The goal of the exoskeleton presented here is to relieve the low back muscles during lifting tasks. As discussed in 2.1, manual material handlers fit the user profile for exoskeleton use. Various industries have MMHs such as package fulfillment, retail stocking, and distribution centers; with over 2 million workers categorized as MMH, hardly any company goes untouched by the issues of manually handling materials. After the work discussed in Section 3.1 and 3.2, the exoskeleton presented here could be integrated into the daily routine of MMHs. Workers would experience less fatigue, less pain, and less risk of injury.

Excluding manual material handlers, many people could benefit from exoskeleton use. The option to wear an exoskeleton could be open to persons performing lifting tasks at home. Wearing an exoskeleton when packing boxes, moving out, or even performing childcare could have lasting benefits to the person using the exoskeleton.

Wearable devices will become more ubiquitous as research progresses from laboratory-proven technologies to commercially available products. Eventually, we will achieve a time when devices will fully protect the body, and people will experience a better, pain-free world.

Chapter 4

Conclusions

The exoskeleton presented here is flexible, lightweight, and effective. Carbon fiber has low hysteresis, high energetic return due to high flexibility, and the potential for a long cycle life. Implementing carbon fiber into exoskeletal designs has very few drawbacks compared to other methods for storing energy. The wide spread of energetic return for two subjects (36-53 J) leads us to believe that while the exoskeleton will provide assistance to the wearer, the degree of assistance will greatly depend on the wearer's own lifting dynamics. The electromyography results, however, show statistical significance between the with and without exoskeleton conditions and an average of 30-37% reduction in the LES and 21-31% reduction in the TES muscle activity. Overall, the exoskeleton, while effective in reducing the erector spinae muscle activity, has features that could be improved and further studied. Until exoskeletons are worn like a second skin, there will be numerous aspects to improve upon.

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Appendices

Appendix A

Material Data

Table A.1: Material Properties of Exoskeleton Carbon Fiber[\[3\]](#)

Metric Carbon Fiber (T770/Bisphenol Epoxy vinyl Ester)	
Fiber Volume	60 %
Tensile Strength	1.72 GPa
Tensile Modulus	134 GPa
Ultimate Elongation	1.20 %
Glass Transition Temp. 160 deg C	
Resin Type	Bisphenol Epoxy Vinyl Ester

Table A.2: Suppliers and part numbers of the materials used in Figure 2.1.

Mechanism	Color Code	Manufacturer	Part No.
Composites			
Carbon Fiber	Dark Green (PL)	CST Sales	T770L2
Carbon Fiber	Light Green	CST Sales	T770L2
Fiber Glass (Garolite)	Dark Green	McMaster	8557K41
Gas Springs (low to high mass)			
Gas Spring	Dark Blue Triangle	Dadco	C.180.025 (RD)
Gas Spring	Dark Blue Triangle	Dadco	C.180.038 (BU)
Gas Spring	Dark Blue Triangle	Dadco	C.250.025 (YW)
Gas Spring	Dark Blue Triangle	McMaster	6626K54
Gas Spring	Dark Blue Triangle	Dadco	C.180.080 (GR)
Gas Spring	Dark Blue Triangle	Dadco	L.500.013
Gas Spring	Dark Blue Triangle	Dadco	L.750.006
Gas Spring	Dark Blue Triangle	Dadco	L.300.013
Gas Spring	Dark Blue Triangle	McMaster	9502T1
Gas Spring	Light Blue Triangle	McMaster	6626K54
Gas Spring	Light Blue Triangle	McMaster	4175T5
Gas Spring	Light Blue Triangle	Dadco	Custom
Coil Springs			
Compression Spring	Magenta Triangle	McMaster	9648K12
Die Spring	Magenta Triangle	McMaster	9722K55
Torsion Spring	Magenta Triangle	McMaster	9271K706
Torsion Spring	Magenta Triangle	McMaster	9287K118
Rubber			
Natural Gum Rubber	Orange and Yellow Squares	McMaster	6856K14
Other			
Titanium	Black Diamond	McMaster	Grade 5

Appendix B

Trends in Fit

Table B.1: R^2 Values for the Slider Movement vs. Weight

Slider	Lift Condition	R^2
Trunk	Freestyle	0.352
Trunk	Squat	0.116
Trunk	Stoop	0.019
Right Leg	Freestyle	0.006
Right Leg	Squat	0.108
Right Leg	Stoop	0.000
Left Leg	Freestyle	0.136
Left Leg	Squat	0.021
Left Leg	Stoop	0.001

Table B.2: R^2 Values for the Slider Movement vs. Height

Slider	Lift Condition	R^2
Trunk	Freestyle	0.309
Trunk	Squat	0.250
Trunk	Stoop	0.493
Right Leg	Freestyle	0.076
Right Leg	Squat	0.435
Right Leg	Stoop	0.100
Left Leg	Freestyle	0.028
Left Leg	Squat	0.234
Left Leg	Stoop	0.527

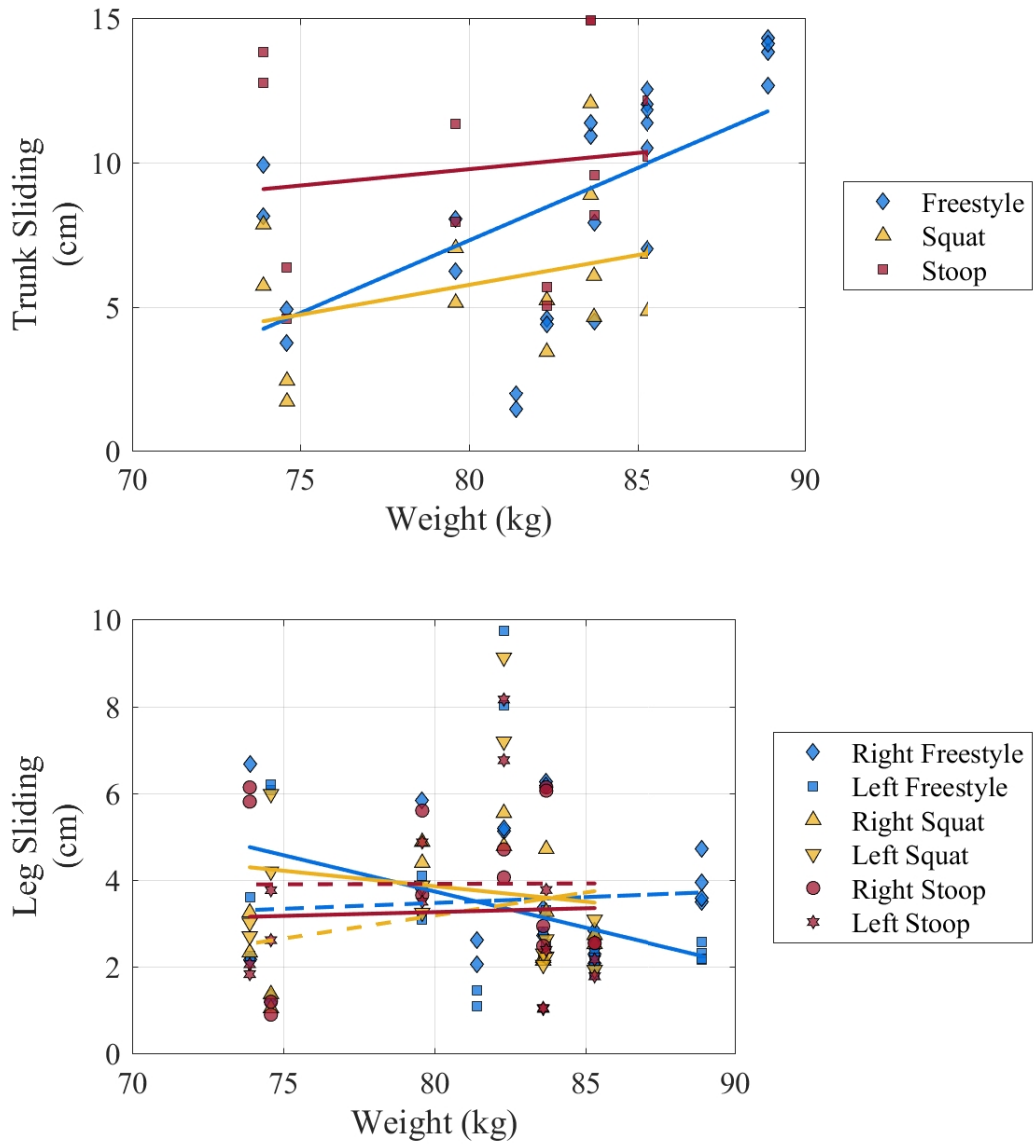


Figure B.1: The slider on the trunk (top graph) was tracked and measured for maximum distance traveled during a lift. Each leg slider (bottom) was also tracked. There is no correlation between the amount of sliding and the weight of the subject.

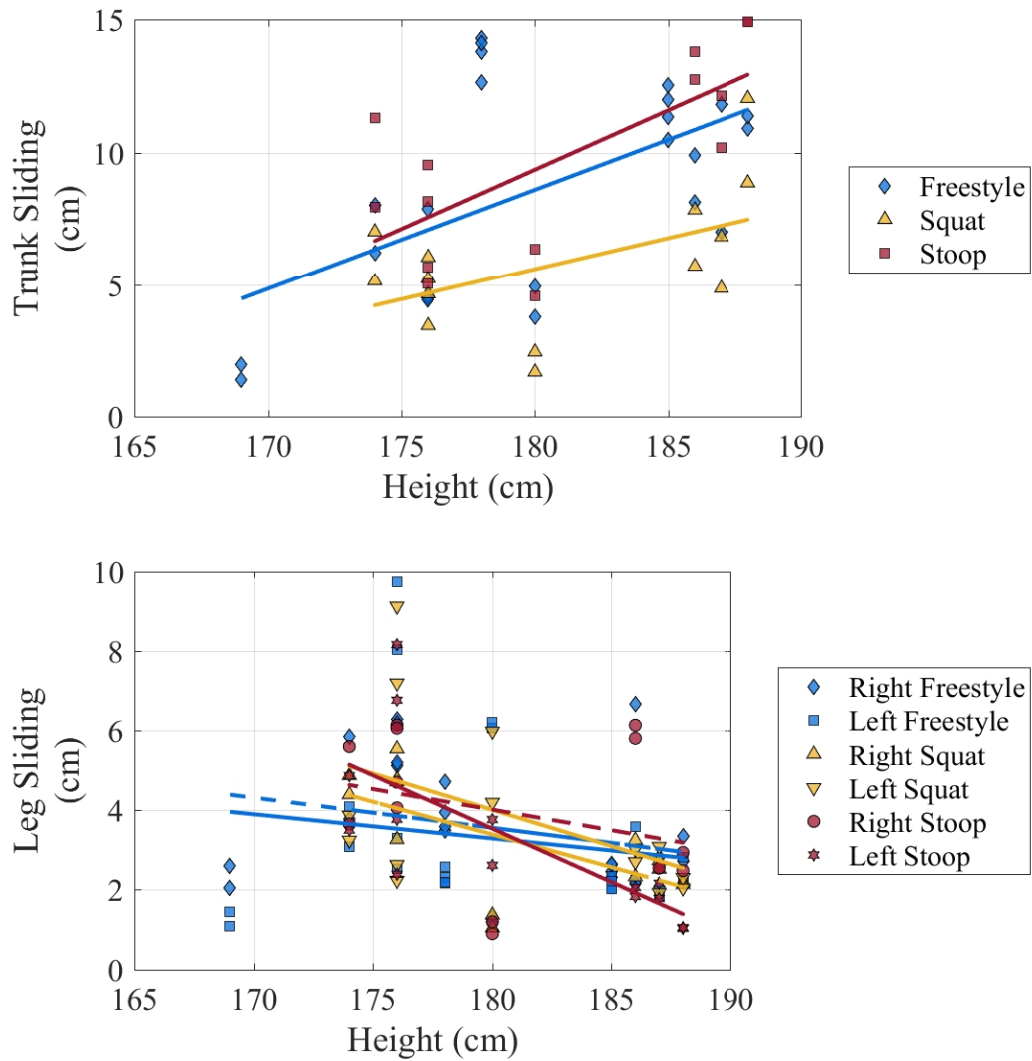


Figure B.2: The slider on the trunk (top graph) was tracked and measured for maximum distance traveled during a lift. Each leg slider (bottom) was also tracked. There is no correlation between the amount of sliding and the height of the subject.

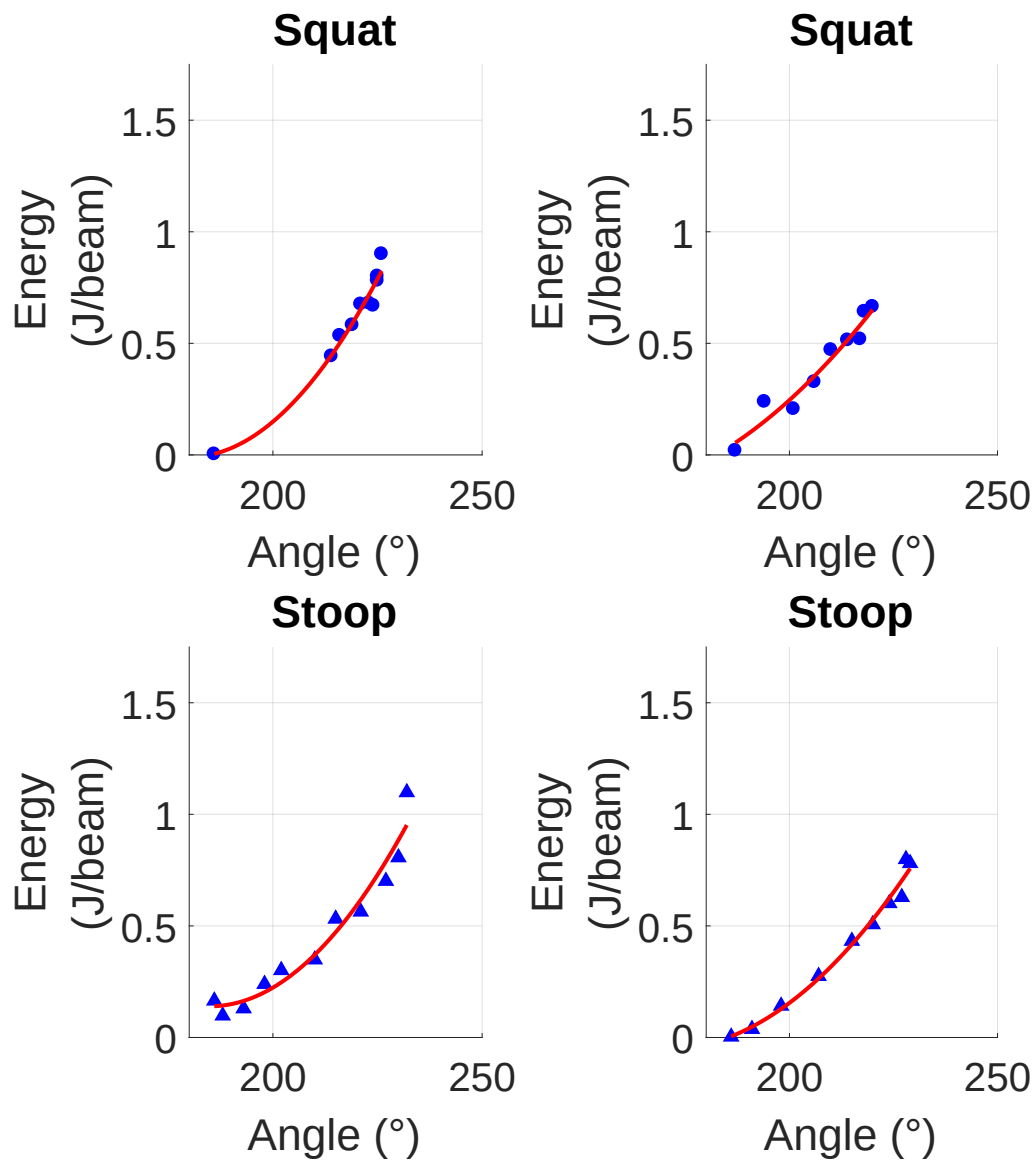


Figure B.3: Subject 1 performed four lifts

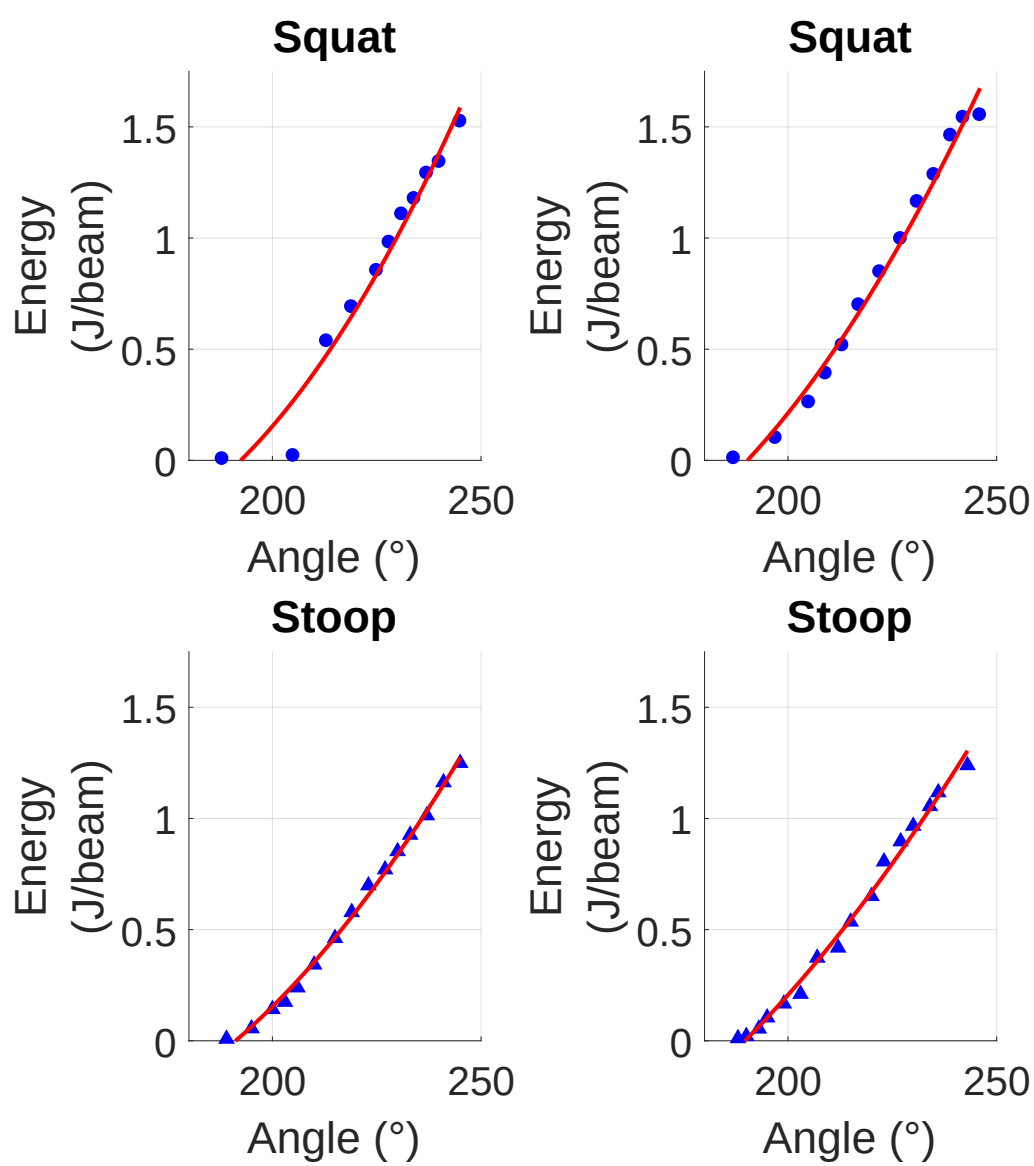


Figure B.4: Subject 2 performed four lifts

Table B.3: R^2 Values for Image Processed Lifting

Subject	Lift Condition	R^2
S1	Squat	0.971
S1	Squat	0.947
S1	Stoop	0.950
S1	Stoop	0.984
S2	Squat	0.989
S2	Squat	0.967
S2	Stoop	0.997
S2	Stoop	0.992

Appendix C

Comfort Survey

In this appendix, the reader may see each subjects response to a comfort survey given after experimentation. The scores ranged from 0 to 10 with 0 being no discomfort, 2 as fairly comfortable, 5 is moderate discomfort, 8 defined as very uncomfortable and 10 as extreme discomfort. The highest score reported occurs in Table [C.1](#) for subject 5 with a score of 5 or moderate discomfort on the right thigh. The average across all subjects, however, was less than 1.6 for all body parts and sides, which is better than “Fairly Comfortable” according to our established scale.

Table C.1: Comfort Survey (Right Front of Body)

Sub- ject	Neck	Shoul- der	Upper Arm	Elbow	Fore- arm	Groin	Wrist	Hand	Thigh	Knee	Lower Leg	Ankle or foot
S1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	2	0	0	0
S4	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	5	0	0	0
S6	0	0	0	0	0	0	0	0	3	0	0	0
S7	0	2	0	0	0	3	0	0	2	0	0	0
S8	0	0	0	0	0	0	0	0	3	2	0	0
S9	0	0	0	0	0	0	0	0	0	0	0	0
S10	0	0	0	0	0	2	0	0	4	0	0	0
S11	0	0	0	0	0	0	0	0	0	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0	0
S14	0	0	0	0	0	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	2	0	0	0
S16	0	0	0	0	0	0	0	0	0	2	0	0

Table C.2: Comfort Survey (Left Front of Body)

Sub -ject	Upper Back	Shoul- der	Upper Arm	Elbow	Fore- arm	Mid-to -lower Chest	Wrist	Hand	Thigh	Knee	Lower Leg	Ankle or Foot
S1	0	0	0	0	0	0	0	0	4	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	2	0	0	0
S4	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	4	0	0	0
S6	0	0	0	0	0	0	0	0	3	0	0	0
S7	0	2	0	0	0	0	0	0	2	0	0	0
S8	0	0	0	0	0	0	0	0	3	2	0	0
S9	0	0	0	0	0	0	0	0	0	0	0	0
S10	0	0	0	0	0	0	0	0	4	0	0	0
S11	0	0	0	0	0	0	0	0	1	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	0	0	0	0
S14	0	0	0	0	0	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	2	0	0	0
S16	0	0	0	0	0	0	0	0	0	2	0	0

Table C.3: Comfort Survey (Right Back of Body)

Sub- ject	Neck	Shoul- der	Upper Arm	Elbow	Fore- arm	Mid-to-Lower Back	Wrist	Hand	Thigh	Knee	Lower Leg	Ankle or foot
S1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0	0	0
S4	1	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	2	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	1
S9	0	0	0	0	0	5	0	0	3	0	0	0
S10	0	0	0	0	0	1	0	0	0	0	0	0
S11	0	0	0	0	0	0	0	0	0	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	3	2	2	0	0
S14	0	0	0	0	0	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	2	0	0

Table C.4: Comfort Survey (Left Back of Body)

Sub -ject	Upper Back	Shoul- der	Upper Arm	Elbow	Fore- arm	Butt- ocks	Wrist	Hand	Thigh	Knee Leg	Lower or Foot	Ankle
S1	0	0	0	0	0	1	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0	2	0	0	0
S8	0	0	0	0	0	0	0	0	0	2	0	1
S9	0	0	0	0	0	0	0	0	3	0	0	0
S10	0	0	0	0	0	0	0	0	0	0	0	0
S11	0	0	0	0	0	0	0	0	1	0	0	0
S12	0	0	0	0	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0	2	2	4	0
S14	0	0	0	0	0	0	0	0	0	0	0	0
S15	0	0	0	0	0	0	0	0	0	0	0	0
S16	0	0	0	0	0	0	0	0	0	2	0	0

Appendix D

Hysteresis

The following figures are the results from conducting loading and unloading of various materials. The changes in the area under the curves was compared to calculate the hysteresis values shown in [D.1](#).

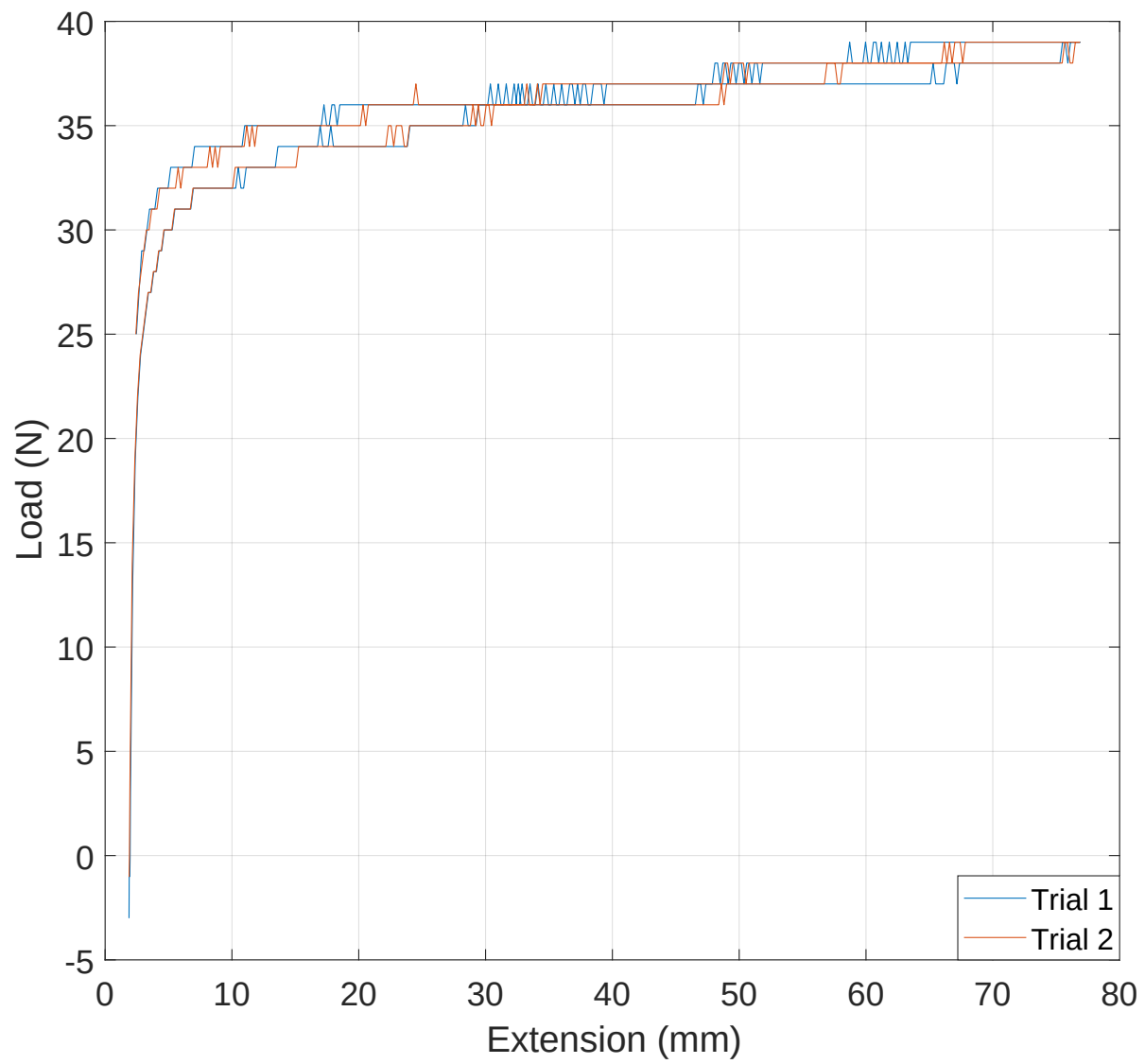


Figure D.1: Two trials of carbon fiber enduring compression.

Table D.1: Hysteresis Results for Each Trial of Tested Mechanisms.

Mechanism	Trial	Hysteresis (%)
Gas Spring (130 Lbf)	1	14.24
	2	15.51
	3	16.92
	4	17.78
	5	18.32
Average		16.56
Gas Spring (240 Lbf)	1	13.58
	2	14.08
	3	14.78
	4	15.30
	5	15.64
Average		14.68
Miniature Gas Spring	1	15.33
	2	13.96
	3	13.80
	4	13.77
	5	13.60
Average		14.09
Average (without 1st trial)		13.78
Carbon Fiber	1	2.24
	2	1.70
Average		1.9723
Natural Gum Rubber (50% Elongation)	1	22.79
	2	6.69
	3	4.21
	4	3.46
	5	3.23
Average		6.98
Average (without 1st trial)		4.34

Table D.2: Hysteresis Results for Each Trial of Tested Mechanisms Continued.
Values that were negative are assumed to be zero due to rounding error, which is represented by 0*.

Mechanism	Trial	Hysteresis
Natural Gum Rubber (50% to 100% Elongation)	1	0*
	2	0*
	3	0*
Average		0*
Natural Gum Rubber (100% Elongation)	1	15.08
	2	5.22
	3	3.86
	4	3.49
Average		6.91
Average (without 1st trial)		4.19

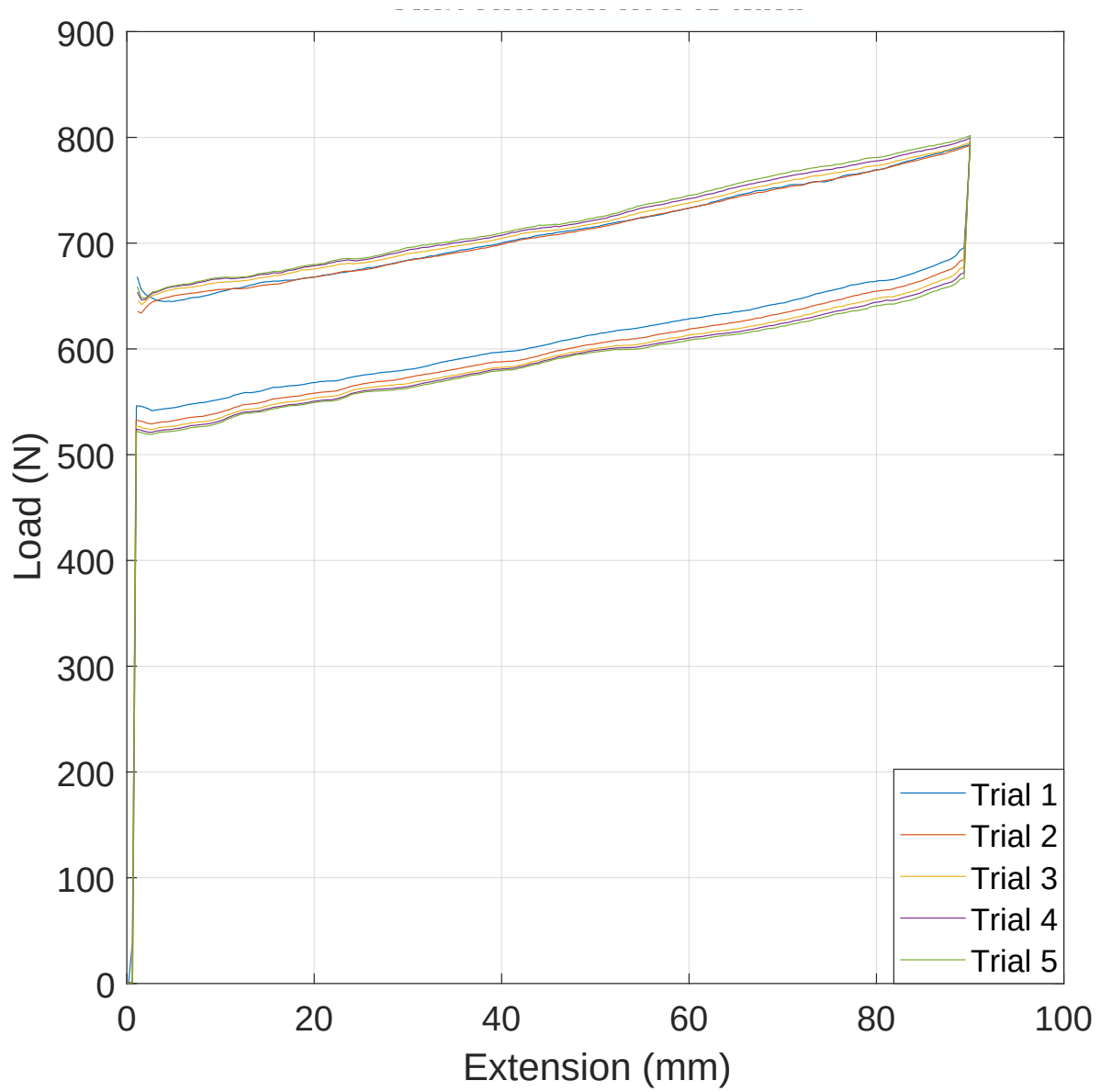


Figure D.2: Gas springs with a compression force of 578 N (130 pounds) endured five trials of compression and release. The spring manufacturer and part number can be found in Table 2.4.

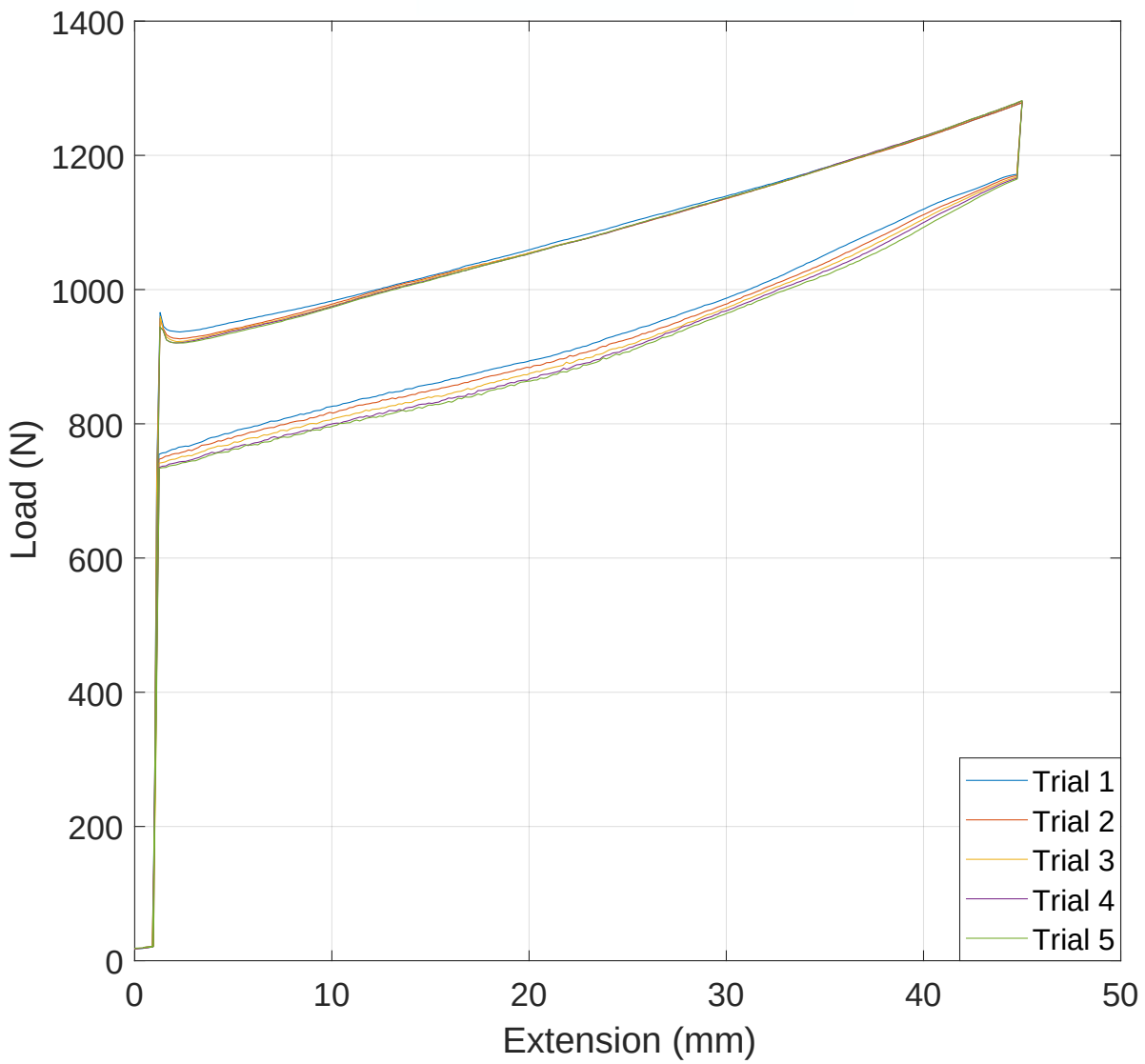


Figure D.3: Gas springs with compression force of 1258 N (240 lbs) endured 5 trials of compression and release. The spring manufacturer and part number can be found in Table 2.4.

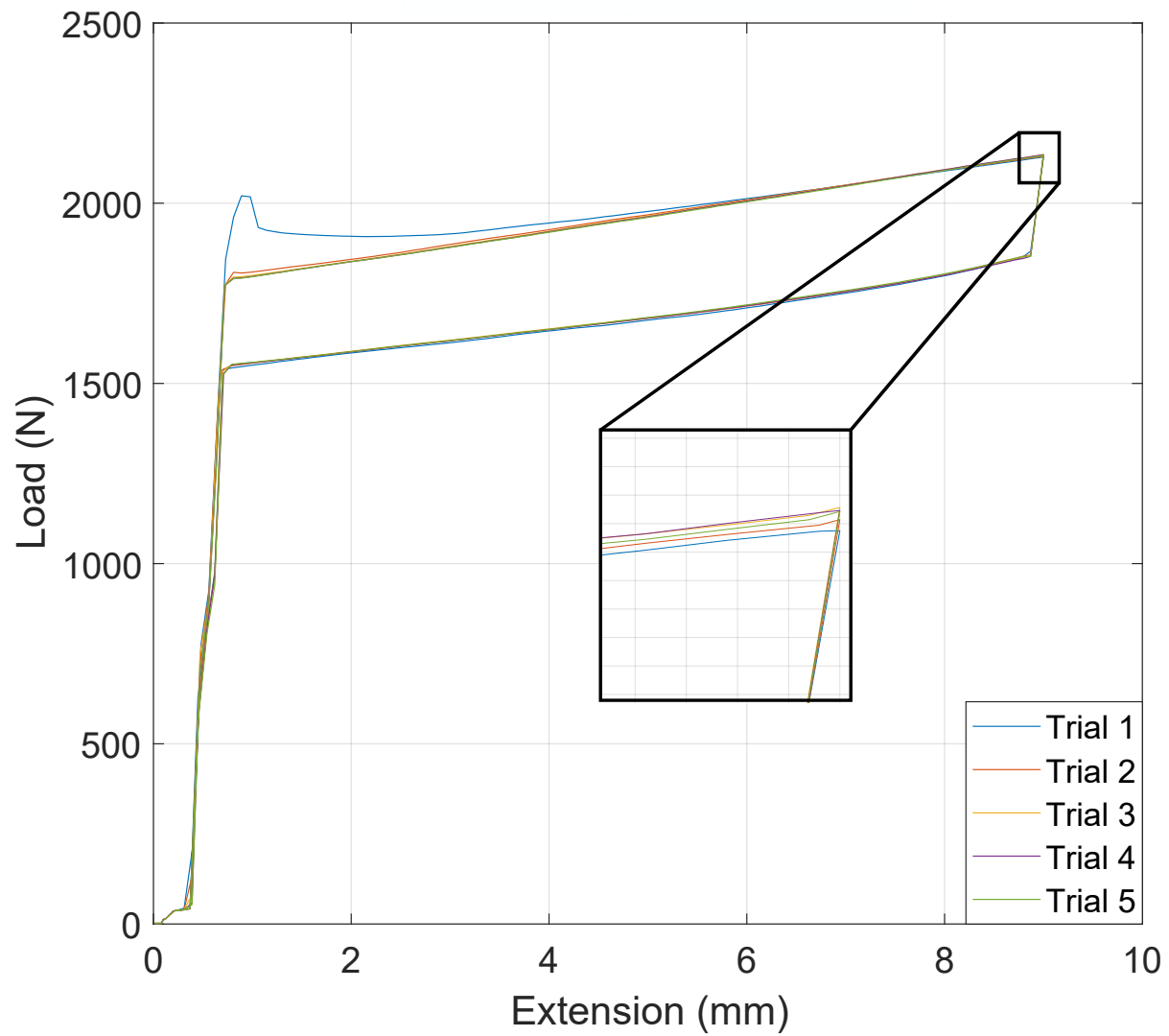


Figure D.4: A gas spring with compression force of 2135 N was loaded and unloaded five times.

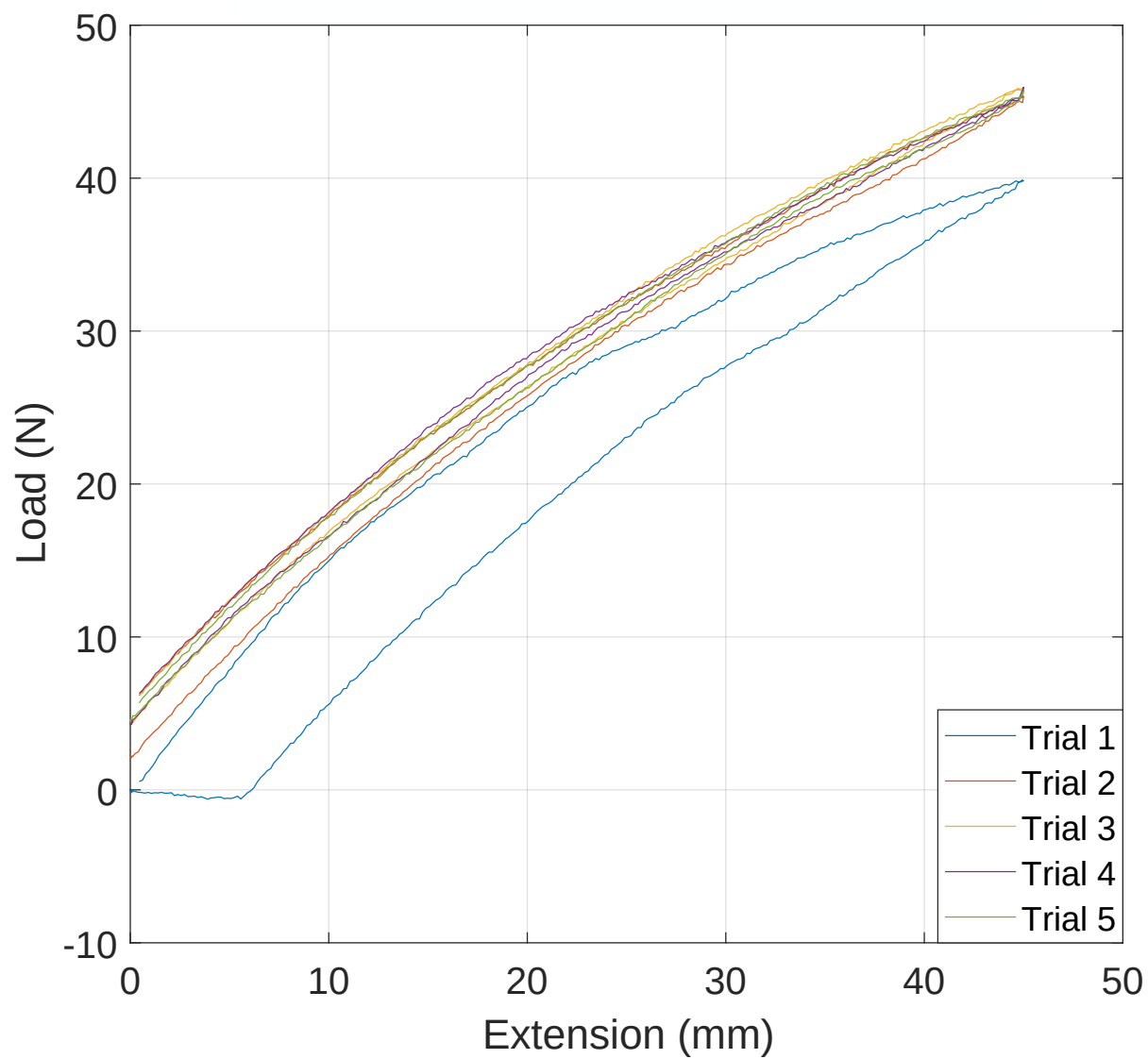


Figure D.5: Natural gum rubber was elongated by 50% of its original length and then returned to its original length.

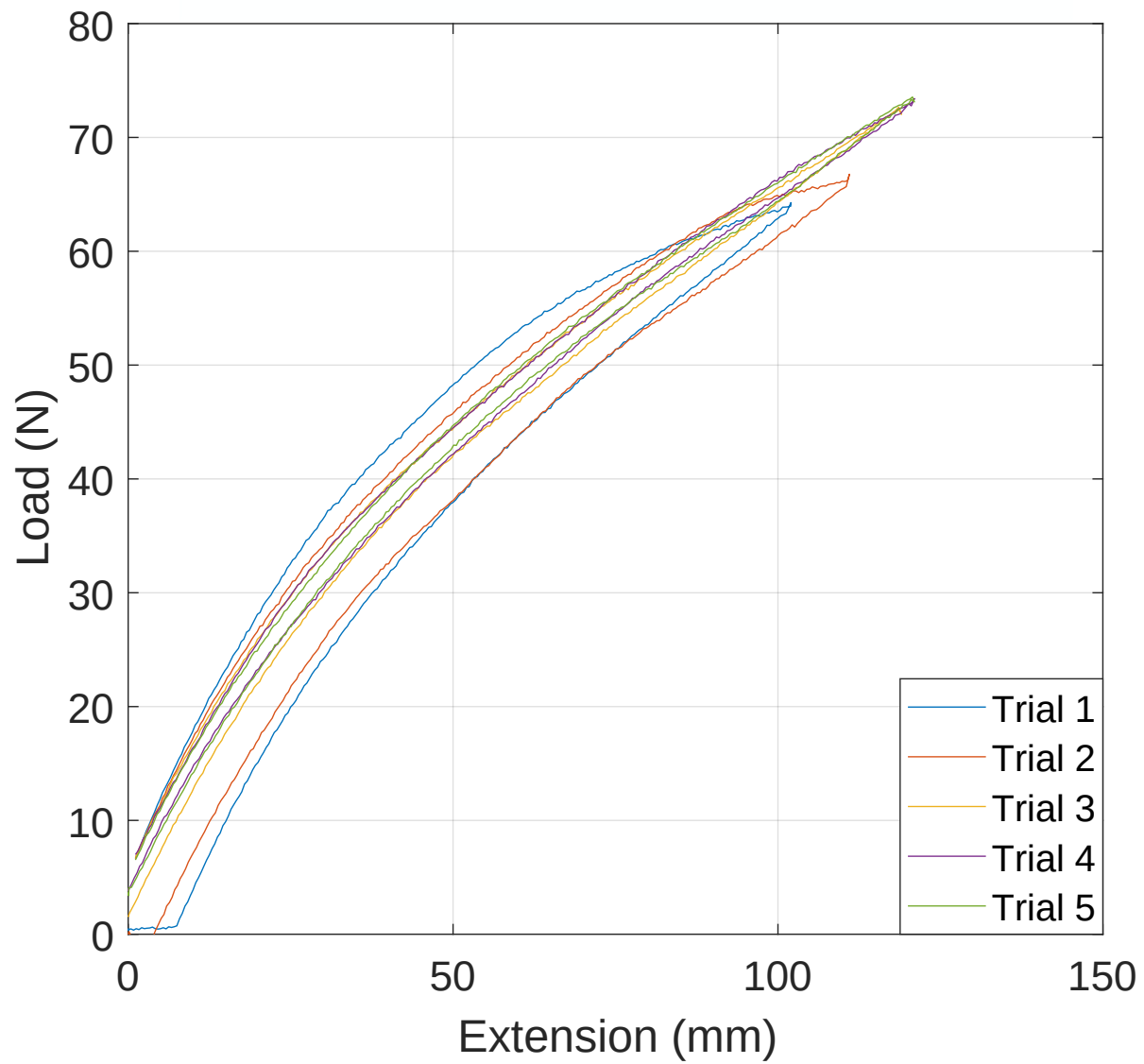


Figure D.6: Natural gum rubber was elongated by 100% of its original length and then returned to its original length.

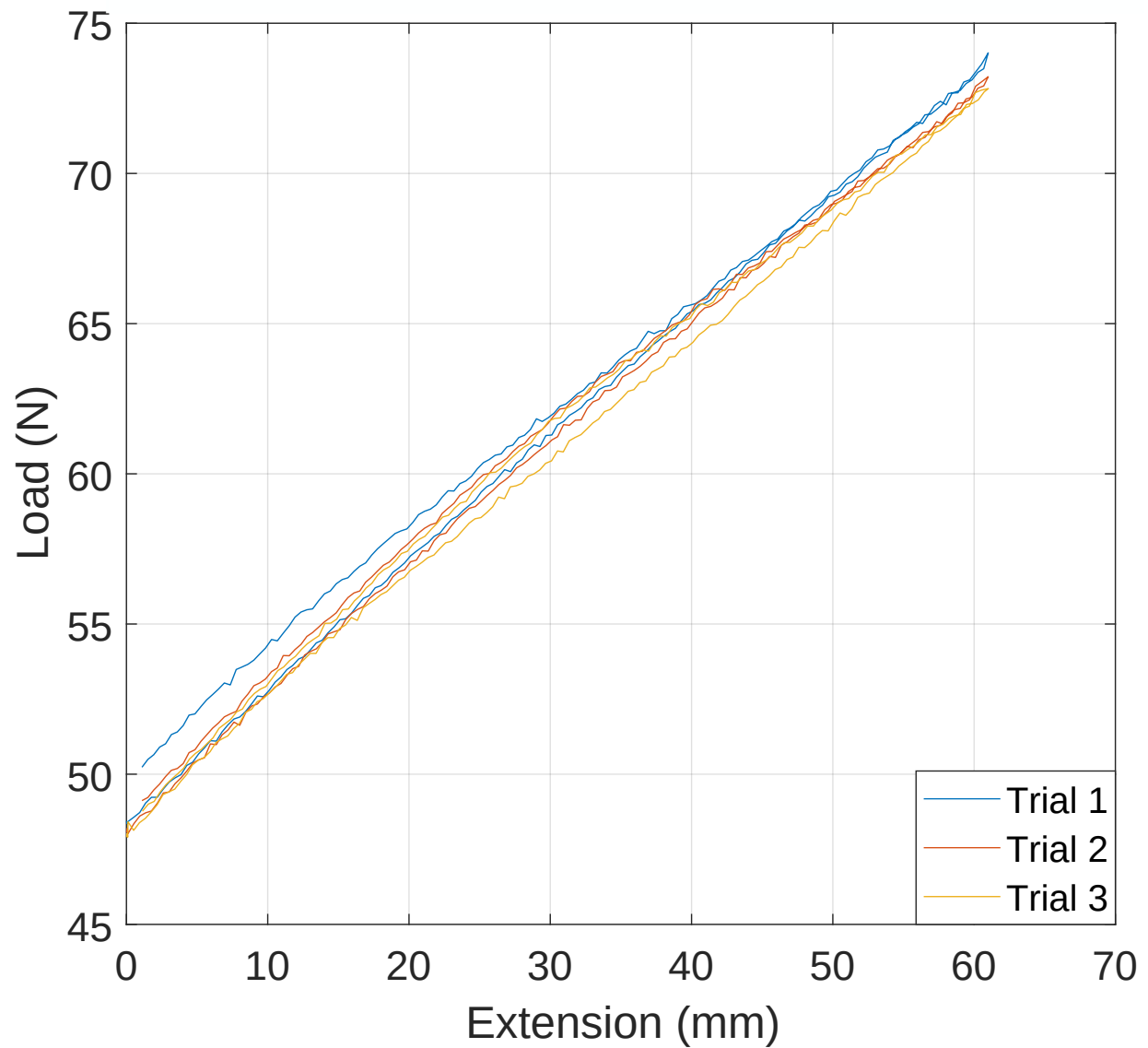


Figure D.7: Natural gum rubber was elongated by 50% of its original length before the test began. Then, the NGR sample was elongated another 50% for a total of 100% elongation and returned to the original 50% elongation amount.

Appendix E

IRB 17-127 Approval Letters



Office of Research Compliance
 Institutional Review Board
 North End Center, Suite 4120, Virginia Tech
 300 Turner Street NW
 Blacksburg, Virginia 24061
 540/231-4606 Fax 540/231-0959
 email irb@vt.edu
 website <http://www.irb.vt.edu>

MEMORANDUM

DATE: April 4, 2017 

TO: Alan Thomas Asbeck, Sarah Emily Beauchamp, Mohammad Mehdi Alemi

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Evaluation of a passive, flexible exoskeleton

IRB NUMBER: 17-127

Effective April 3, 2017, the Virginia Tech Institutional Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at: <http://www.irb.vt.edu/pages/responsibilities.htm>

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Expedited, under 45 CFR 46.110 category(ies) 4,6,7**
 Protocol Approval Date: **April 3, 2017**
 Protocol Expiration Date: **April 2, 2018**
 Continuing Review Due Date*: **March 19, 2018**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

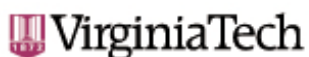
Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

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Figure E.1: Approval Letter in 2017 for conducting experiments with human subjects and the exoskeleton.



Office of Research Compliance
 Institutional Review Board
 North End Center, Suite 4120, Virginia Tech
 300 Turner Street NW
 Blacksburg, Virginia 24061
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Figure E.2: Continued approval granted in 2018.