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Improved Backpacking Load Carriage System

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A Major Qualifying Project submitted to the Faculty of *Worcester Polytechnic Institute* in partial fulfillment of requirements for the Degree of Bachelor Science

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Authorship

All members of this team contributed equally to the success of this project.

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Abstract

This project developed a novel load carriage system with an active suspension and pivoting hip belt for recreational backpackers. The design was validated with a controlled study of 5 male subjects. Quantitative and qualitative results were gathered to compare the experimental backpack to a commercial backpack. The results showed that the design did not meet the performance specifications for reducing oscillating load, ground reaction forces, and compression and shear at the lumbosacral joint. However, the design did meet the specification for reducing fatigue, showing a 6% VO_{2max} ± 4% decrease. The design also induced the desired amount of forward lean, between 12 and 30 degrees. Overall, this project was a proof of concept of a small form factor oscillating load backpack that, with improvements to the suspension, could achieve even greater functionality.

Chapter 1: Introduction

On the quest for a happier and healthier lifestyle, hiking has become a popular activity for those seeking its wide range of physical and mental health benefits. In 2015 upwards of 38 million American adults hiked [1]. Backpackers, sometimes called section or thru-hikers, are a subset of hikers who hike for days or weeks at a time and cover long distances each day with around 15-30 pounds in their packs. Several studies show that nearly one-third of backpackers experience load carriage-induced injuries while performing this activity. Technological advancements in the hiking industry continue to grow in efforts to maximize a backpacker's capability and minimize their risk of injury.

Load carriage-induced injuries experienced by backpackers can be broken down into two main categories: paresthesia of the limbs and musculoskeletal injuries. Paresthesia results in a “pins and needles” sensation that goes away once the cause, usually sustained pressure, is relieved [2]. In one study of Appalachian Trail backpackers who had hiked at least 7 consecutive days on the trail, 34% reported experiencing paresthesia [3]. Beyond paresthesia, there are several papers indicating that recreational backpackers experience a variety of musculoskeletal injuries. Backpack load carriage has mainly been linked to musculoskeletal injuries of the lower limbs and back. The most common areas of injury for the lower limbs are the knee and ankle [4-6]. In a study of 75 thru-hikers and 80 section hikers of the Long Trail in Vermont, 46% of thru-hikers experienced musculoskeletal injuries that caused them to lose on average of about half a day of backpacking; the incidence in section hikers was 37.5% but those individuals were sidelined for an average of 1.17 days [5]. The findings in these studies indicate that musculoskeletal injuries are more common when backpackers are exposed to load carriage for an extended period of time.

The total costs of treating back pain annually in the US in 2012 were estimated at between $100 and $110 billion [7]. While not all cases are due to backpack load carriage, back pain is a serious problem in industrialized countries, both in terms of the prevalence and the cost of treating it. The combination of the high prevalence of back pain and the cost of treating it, coupled with the fact that backpacking can increase the incidence of such injuries, provides a compelling case for why an improved backpack system is needed.

The large number of load carriage induced injuries among backpackers justifies the need for a novel load carriage system that allows the wearer to expend less energy than with current commercially available backpacks. The main objective of the proposed design was to construct a pack that would reduce injury and decrease fatigue for backpackers taking on multiple day treks with heavy loads, up to 30% of their bodyweight. Carrying the smallest amount of weight while still carrying necessities allows backpackers to retain more energy and reduce their risk of heavy load carriage injury. Inspiration from populations who have developed unique methods of carrying heavy loads such as the US military, porters in Nepal, and women in Africa have been incorporated to achieve the design objectives. A more recent development of a suspended-load system, which has been shown to significantly reduce the effects of loading on the user’s body, served as the foundation of the final design. This suspended-load system works by allowing the bulk of the backpack load to move out of phase with the body during motion. In addition, design features such as a pivoting hip belt and extended frame were incorporated to improve performance. As a result, a load carriage system was designed to reduce the risk associated with heavy load carriage injuries and reduce the wearer’s energy expenditure.

Testing of the design was necessary to determine the effects of the load carriage system on the body during use. Human gait analysis is important for understanding how carrying load affects the human body. Motion capture was performed with multiple subjects that have had prior backpacking experience to test the design under simulated hiking conditions. Corresponding force data was then used to analyze the effect the new design produced based on multiple mathematical models that were identified from previous research. The lumbosacral joint was a primary focus during analysis representative of musculoskeletal back injuries, as this is the region most associated with back pain. Physiological parameters were also used to gage the user’s degree of fatigue. Many found studies of fatigue and load carriage use oxygen consumption as a quantitative measure of fatigue. For this reason, models relating heart rate, walking speed, grade, and terrain to oxygen consumption and/or metabolic energy cost were explored.

A comparison study was conducted to determine the efficacy of the backpack design. Subjects that participated in the experiment wore both a commercially available backpack and the prototype pack. Compressive and shear forces calculated at the lumbosacral joint, along with heart rate measurements and qualitative survey answers from the subjects to assess fatigue were used in the comparison of the packs. Data and results gathered during testing can be used for future developments in backpack design improvements to decrease energy expenditure and reduce associated injuries.

Chapter 2: Literature Review

2.1 Importance of the Field

Despite high participation, few statistics exist about the average hiker demographic. Fortunately, many outdoor organizations within the US collect data annually of hikers who use popular trails. The Appalachian Trail, one of the most commonly traveled long distance trails, is a 2,190-mile trail running from Maine to Georgia. The Appalachian Trail Conservancy reported that out of all backpackers that have completed the trail, most them were men with only 25% women. Backpackers of the Appalachian Trail reported an average age range within their 20s, noting more specifically that section hikers reported an older age range with a median of 40 [8]. The Long Trail in Vermont, while much shorter than the Appalachian Trail, marking at 291 miles is another popular long distance trail for backpackers. Similarly to the Appalachian Trail, men make up a majority of the demographic with a 76% presence. The average age of The Long Trail hikers was also 40 years old [5].

In addition to small scale reports generated by organizations who maintain long distance trails, the USDA Forest Service published a summary report on visitor use of US National Forests. This report includes all visitors of US National Forests between 2008 and 2012. Of these visitors, 64% were men and over 95% were white. Most the visitors were also reported to be between 30 and 59 years of age. Of all the US National Forest visitors, those who defined themselves as hikers only made up 42% [9]. While these statistics do not clearly display the demographic of an "average hiker," it is evident there are more men than women who reportedly hike. While there is a widespread range of ages among hikers in the US, there is some evidence that the age of the backpacker population is often dependent on the length of the trail. For example, longer backpacking trails like the Appalachian Trail are completed by a younger population and shorter trails like the Long Trail have a higher median age.

While there is evidence to suggest that many Americans hike, the need for a new load carriage system is not necessarily as prevalent among the entire hiker population. To better understand why an improved system is needed it is necessary to understand the effects, of carrying a heavy load over a long distance and period of time, on a backpacker's body. Investigating the natural movement of the human body without carrying a load, the specific types of injuries caused by load carriage, and the cost of treating those injuries are critical factors in designing and reasoning for an improved load carriage system.

2.2 Larger Problem Area

2.2.1 Economic Burden of Load Carriage Induced Injuries

Although this project is targeting recreational backpackers, load carriage induced injuries are common among other populations as well. In particular, backpack-induced paresthesia, also known as BPP or "rucksack palsy," is a common issue in the military in the US and abroad. Some US soldiers become decommissioned for up to two years due to BPP [10, 11]. Lower back pain, blisters, knee pain, and stress fractures have also been reported as common injuries experienced by backpackers and military personnel alike as a result of load carriage [12]. While these injuries do not always lead to a soldier being taken off duty, one study reported that only 2% of the 54% of soldiers with proclaimed back pain returned to active duty. This same study also revealed that replacing one of these injured soldiers can come at a high cost as much as $1 million [13]. While not all back pain cases can be attributed to backpack load carriage, the prevalence of this injury and the cost for treating it is of high concern. In the US, the total costs of treating back pain annually as of 2012 were estimated between $100 and $110 billion [7]. These costs are due to direct treatments, such as therapy and pharmaceuticals, as well as indirect costs, such as time missed from work. Indirect costs are particularly troubling as a recent WHO study revealed back pain as the leading cause of activity limitation, work absenteeism, and loss of productivity in industrialized countries [14]. The high prevalence of back pain and the cost of treating it, coupled with the activity of backpacking attributing to the incidence of such injuries, provide a compelling case for why an improved backpack system is needed.

2.2.2 Market Analysis

Even if there is a medical need established for an improved backpack system, it is important to investigate whether there is a market for such a device. According to a report by the Outdoor Industry Association, Americans spend an average of $12.2 million each year on trail gear, including backpacks and hiking shoes [15]. Additionally, the outdoor recreation economy is a $646 billion industry and has grown 5% annually from 2005 to 2011 in the US despite an overall economic recession [15]. This information indicates that there is clear financial capacity and continued desire for new and improved outdoor gear.

2.3 Load Carriage Effects on Gait

2.3.1 The Human Gait Cycle

Gait is the technical term for the way a human walks. The human gait cycle is described as the patterned sequence of leg propulsion to create forward movement of the body; defined as the interval between contact with the ground of the same foot [16]. All aspects of movement in the lower limbs, trunk, and upper limbs to progress the body's center of mass in the forward direction are encompassed in the gait cycle.

There are two sets of terminology used to describe the different phases of the gait cycle: classic terms and new gait terms. A full sequential image of the gait cycle that uses both sets of terminology is seen below in Figure 1 [17]. In referencing the new gait terms, the cycle can be categorized into eight separate phases. Of these eight phases, there are two overarching phases that include the stance phase, when the observed foot is in contact with the ground, and the swing phase, describing when the observed foot is not in contact with the ground. For a normal gait pattern, the stance phase accounts for 58-61% of the gait cycle, while the swing phase varies between 39-42%. The double support time total (stance time- swing time) consists of about 16-22% of the total gait cycle [18].

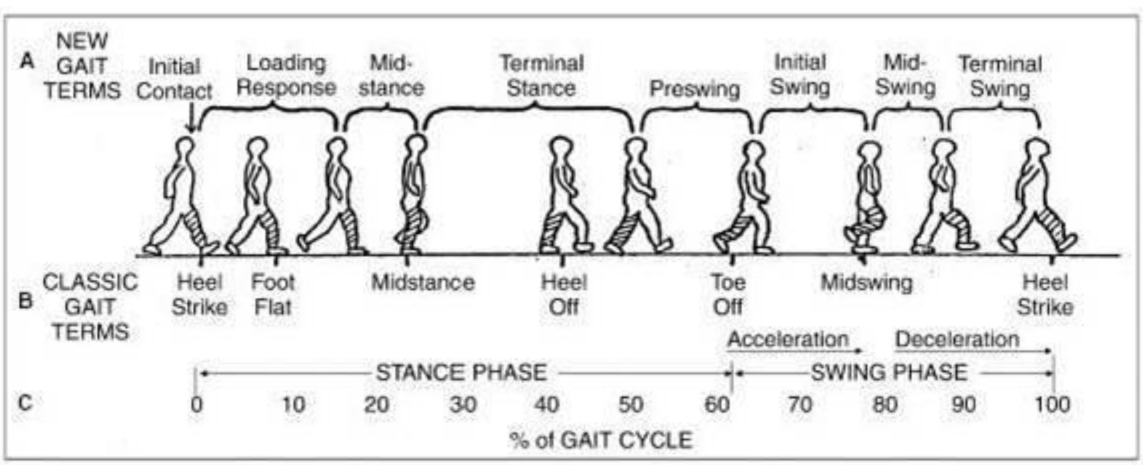

Figure 1: The gait cycle [16]

In Figure 1, the observed foot/limb motion is represented by the dashed lines [19]. The initial contact refers to the start of a new gait cycle in which the observed foot first contacts the ground. The initial contact ideally refers to the heel of the foot, so the lower limb is positioned to act in a rocking motion moving forward. Following the initial contact there is the initial loading response, which occurs until the opposite foot is lifted. The mid-stance phase follows, noting the single support period of the observed foot. This phase starts as soon as the opposite foot is lifted and ends when the person's body weight is aligned over the forefoot of the observed leg. In referring to the inverse pendulum theory, where the body's center of mass (COM) is representative of the weight of a pendulum [20], this mid-stance position would place the body's COM at the "top" of the pendulum. Following the mid-stance comes the terminal stance phase, which ends the single support phase. Ideally this can be observed with the heel rise of the initial contact foot, and the phase continues through until the opposite foot strikes the ground again. During the terminal stance phase, the person's body weight is shifted ahead of the forefoot. The pre-swing phase follows and is the final part of the stance phase, positioning the observed limb to swing. This phase initiates with the opposite foot contacting the ground and concludes with the toe-off of the observed foot. The main objective of the pre-swing phase is the transfer of weight to the opposite limb.

After this weight transfer, when the observed foot is lifted off of the ground, the initial swing phase has started. This phase encompasses the advancement of the initial contact foot from its trailing position, and continues until it is positioned relatively opposite of the stance foot. Important visual cues include clearance of the swinging foot from the floor. The mid-swing phase of the cycle follows, and occurs until the swinging limb is forward and the corresponding tibia is in a vertical position. In respect to joints on the swinging limb, the hip and knee flexion angles are ideally equal. The terminal swing phase represents the final part of the gait cycle in which the swinging limb advances past the thigh and the knee is maximally extended. Deceleration of the swinging limb occurs and the body prepares for stance as the cycle terminates when the foot strikes the floor. This commences the initial contact of the succeeding gait cycle, and the process ideally repeats itself consistently [16].

2.3.2 Normal Gait Parameters

Common terminology when discussing gait include cadence, stride length, step length, velocity, stance, and swing time. A person's stride is defined by two consecutive initial contacts of the same foot and its length is defined as the distance between the two initial contact points. Stride length is dependent on factors such as a person's height, weight, age, and sex [17]. A person's step length on the other hand is defined by the distance from initial contact on opposing limbs [15]. Cadence is defined by the number of steps taken per minute, and is representative of the speed of the gait cycle [15, 17]. Stance and swing time are representative of the amount of time a person is in the stance phase or swing phase of the gait cycle. Evidence of human gait study show that as the cadence and velocity of walking is increased, both stance and swing times decrease, accounting for the fact that the gait cycle is occurring at a more rapid pace. It was specifically observed that men's stance time decreases 3.5 times as rapidly as swing time [17]. This evidence shows more time being propelled as a larger force is applied.

A person's velocity is dependent upon the relationship between stride length and cadence. Stride length and cadence have their own inter-dependence. As cadence and walking velocity increases, stride length increases up to a certain threshold. Multiple studies have shown that between cadences of 80 to 120 steps/minute, a linear relationship exists between cadence and stride length such that they vary as the square of velocity. This means that alterations of cadence and stride length both contribute to the increase in velocity. A graph found in a University of Waterloo Press, Figure 2, shows this relationship described between cadence and step length [17].

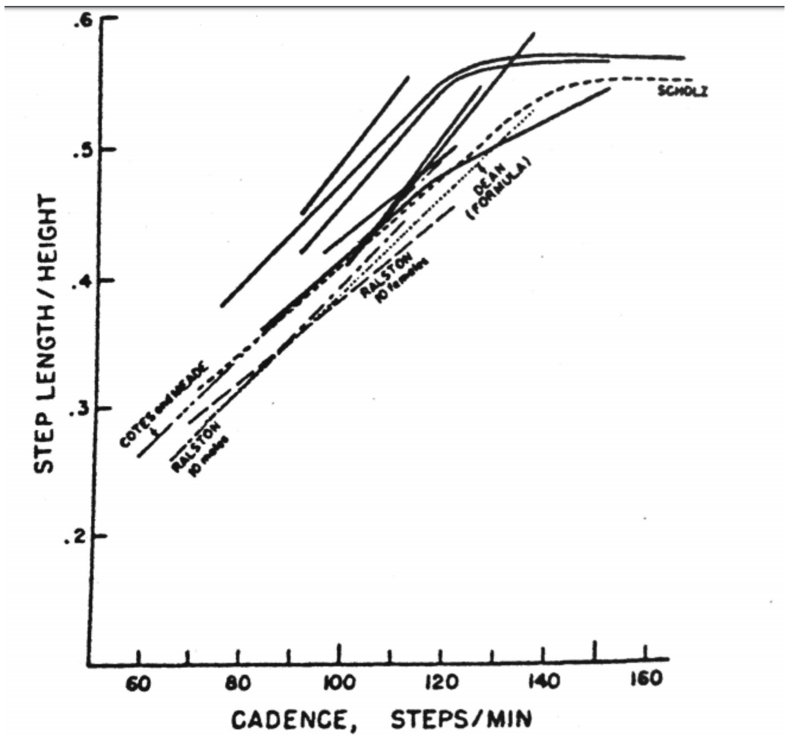

Figure 2: Plot of step length as a function of cadence [17]

The different plots on the graph show a compilation of various testing results from multiple sources. All data trends show this relationship roughly linear up to a cadence of about 120 steps/minute. After this point step length remains relatively consistent. While not shown on the graph, only cadence and velocity will further increase. A Waterloo Gait Laboratory study confirms this through testing of 53 trials that found an overall cadence range of 80-130 steps per minute with a high linear correlation between velocity and cadence proving this dependency [17].

The amount of force someone applies to the ground as they walk has an effect on the gait parameters previously discussed. Gait studies measure ground reaction force (GRF) to quantifiably gauge the relationship between different gait parameters. GRF during the gait cycle is referred to as the force exerted from the ground acting back on the body. The Waterloo Gait Laboratory has recorded data showing the relationship for the components of ground reaction forces throughout a gait cycle at different cadences. In this study, natural cadence was characterized as 106 ±6 steps per minute, while slow and fast cadence was defined as 20 less than and 20 more than natural cadence respectively. The graphs shown in Figure 3 display the ground reaction force of an observed foot during one full gait cycle at slow and fast cadences [21].

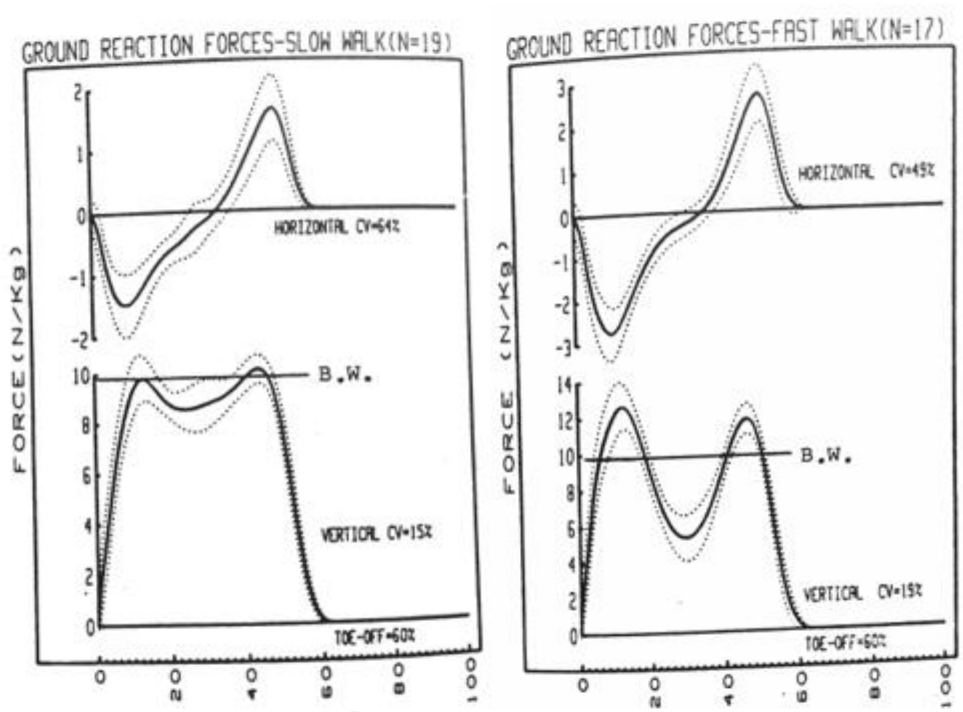

Figure 3: Plot of ground reactions force during % of gait cycle [21]

The horizontal component represents the shear forces measured on the surface of the force plate and the vertical component represents the body's acceleration due to gravity [21]. Initial contact, typically heel strike, is seen as the first spike of the vertical component, paired with a respective negative shear force. The second spike of the vertical component represents the foot preparing for propelling the body forward and a respective positive shear force is present. While the general shape of this graph should remain consistent, the magnitudes of the forces are directly related to the person’s cadence. Understanding the force profiles during the human gait cycle is beneficial to interpreting the interrelationships between gait parameters, and how the presence of an added load to the body alters normal human gait.

2.3.3 Effects of Loading on Gait Parameters

The gait parameters previously discussed are variously affected by the introduction of an external load. Many studies have been conducted to compare the differences in these parameters between loaded and unloaded gaits. Naturally the body has to adjust and counterbalance the introduced load to maintain posture for effective movement forward.

In a study of male soldiers carrying loads from 6.5-27.2% of their body weight there was a significant increase in step length and cadence as an act of compensation compared to no load. The average cadence of the soldiers' self-selected speed during testing was 95.6 ± 7 steps/minute under no loading and increased to 98.3 ± 5.4 steps/minute under the maximum load. The results of this finding falls under the step length, cadence, and velocity relationships explained previously [19]. Based on the Waterloo University study, the soldier's cadence falling in between the 80-120 range would explain the increase in velocity. While ground reaction forces were not measured in this study, hypothesizing normal human gait behavior, the increase in pack load would result in increased ground reaction forces, also confirming the direct relationship between GRF and cadence. While increasing cadence is necessary for load carriage, it also increases the probability of injury.

Forward lean of the trunk is a common method of accommodating heavy loads and has been reported by many studies [19]. This phenomenon occurs naturally to adjust the body's COM so that it is located over the support foot or feet. Under load, forward lean is used to minimize energy expenditure. Allowing for an induced forward lean at the optimal angle is desirable for a load carriage system to achieve these two critical goals. Multiple studies have varying conclusions regarding the relationship of forward lean. Of the group of soldiers tested under varying loads, those carrying 16% BW and greater resulted in a significant increase in forward lean while those carrying lighter loads of 3-10% BW resulted in only a slight increase in forward lean [22]. Another study of rucksack carrying subjects, with loads of up to 34kg, observed insignificant changes in forward lean [19]. While another backpack study found that carrying loads of 15-30% BW increased loading at the lumbosacral joint and associated this with increased forward lean, almost no alterations in stride length and cadence were observed [23]. These variations in forward lean under loading conditions may be attributed to a wide range of factors such as the normal gait of subjects being tested, the positioning of the load on the body, and the conditions in which they were being tested in. While an induced forward lean is a natural method for minimizing energy expenditure, this positioning of the trunk over long periods of time may lead to significant muscular pain and lower back injury.

Understanding the differences between normal and loaded gait parameters is beneficial to the design of an effective load carriage system. Design elements that take advantage of natural gait changes to minimize energy expenditure and reduce the incidence of injuries can and should be utilized.

2.3.4 Load carriage induced injuries

Injuries from backpack style load carriage typically manifest in one of two ways for recreational backpackers: paresthesia of the limbs or musculoskeletal injuries.

2.3.4.1 Paresthesia

Paresthesia is defined as a neurological disorder that results in burning or tingling sensations, numbness, and decreased touch and pain sensitivity; it is not associated with decreases in motor function [24]. Paresthesia is also not associated with a painful feeling, but rather a “pins and needles” sensation that goes away once the cause, usually a sustained pressure, is relieved [3]. In one study of Appalachian Trail backpackers who had hiked at least 7 consecutive days on the trail, 34% reported experiencing paresthesia [24]. A follow-up questionnaire given to backpackers in this 34% indicated that the paresthesia was resolved for 98% of these backpackers by the time of the follow up. Based on this study, the primary factors involved in predicting the occurrence of paresthesia were distance and duration of a trip; other factors such as pack weight, body weight, and hiking shoe type were largely insignificant.

Another cross-sectional study of long distance backpackers who had all hiked more than 500 miles on either the Appalachian Trail of Pacific Crest Trail, however, specifically linked pack weight with the incidence of paresthesia and found that at weights of 10-20 lbs, 35% of backpackers experienced paresthesia, at weights of 21-30 lbs, 50% of backpackers experienced paresthesia, and at weights greater than 31 lbs, 69% of backpackers experienced paresthesia [2]. This study also showed that footwear rigidity contributed to an increased incidence of paresthesia, but only when examined independently of pack weight; this indicates that there is a confounding relationship between pack weight and footwear rigidity [2]. Although paresthesia is not life-threatening, backpackers represent a higher risk group for the development of paresthesia due to the specific load distributions that they experience from the compression of straps, waist belts, and boots during hiking [24]. If the incidence of paresthesia in backpackers can be reduced by an improved load carriage system, backpacking may become more accessible to a larger population.

2.3.4.2 Musculoskeletal Injuries

There are several papers indicating that recreational backpackers experience a variety of musculoskeletal injuries beyond paresthesia. Backpack load carriage has mainly been linked to musculoskeletal injuries of the lower limbs and back. The most common areas of injury for the lower limbs are the knee and ankle [4-6]. In a study of 75 thru-hikers and 80 section hikers of the Long Trail in Vermont, 46% of thru-hikers experienced musculoskeletal injuries that caused them to lose on average of about half a day of backpacking; the incidence in section hikers was 37.5% but those individuals were sidelined for an average of 1.17 days [5]. This indicates that injuries are common when the individual is exposed to extended load carriage. A different study also found that backpackers experienced musculoskeletal injuries as a result of carrying a backpack, but the incidence was fairly low at about 2% [24]. The reason for this low incidence was that this study only looked at acute injuries which are more commonly caused by falls and are not necessarily influenced by pack weight. Additionally, while the participants in this study were experienced hikers they were not necessarily engaged in long distance hiking during this study. Thus, the evidence is mixed as to what role pack weight and weight distribution play in causing musculoskeletal injuries in backpackers. However, with more people engaging in outdoor activities such as backpacking, there will be increased exposure to the stresses of load carriage at a higher frequency, and thus a higher risk for developing various musculoskeletal injuries.

In relation to lower limb injuries, Lloyd and Cooke have shown that the vertical GRF increases proportionally with load; thus, it can be inferred that joint contact forces also increase with increasing load [25]. While this may be true, increased vertical GRFs have not been directly linked to actual injuries of the knees or ankles. Carrying loads at 40% body weight (BW) has been shown to greatly increase muscle activity of the gastrocnemius and vastus lateralis, which increases fatigue and can lead to a higher risk of lower limb injury in women [26]. Multiple studies have also shown that load carriage via a backpack increases ankle and knee flexion, and generally associate this with a compensation mechanism to reduce joint loading [27-29]. While ankle and knee injuries in backpackers are common, research shows that the body compensates for the additional loading, indicating that the injuries are only an indirect result of the loading. The only lower limb injury conclusively linked to backpack loading is blister development on the feet as a result of increased horizontal braking forces induced by the additional loading [30]. This is not a musculoskeletal injury, but is an issue that can reduce a hiker's enjoyment and, in some cases, prevent them from being able to hike.

The other common musculoskeletal injury associated with backpack loading is back pain as a result of increased spinal loading. Multiple studies have shown a direct link between load carriage and increased spinal loading and curvature [23, 27, 31-34]. Goh found that under a load of 15% BW there was a 26% increase in the load at the lumbosacral joint. He also found that when the load was increased to 30% BW, the joint force increased by another 29.5% [23]. These increases are on top of the spinal loading created by walking with no load, which is about 1.5-2.2 times BW [23]. Another study has shown that load carriage can affect back health much earlier than previously thought, indicating that the issues experienced by long distance backpackers may also be popular in short distance backpacking [34]. This agrees with studies that have shown a strong link between the daily carrying of backpacks by school children and altered posture and gait [35]. Loading forces in the spine are mainly compressive, but also contain a shear component that has been shown to have a more significant influence over the development of back pain [23]. The body has two mechanisms to alleviate these large forces: changing spine curvature and increasing forward lean. Front packs have been shown to increase spinal kyphosis, a condition where the spine curves concavely primarily in the thoracic region, see Figure 4 [27]. Conversely, regular backpacks have been shown to induce spinal lordosis, a condition where the lumbar spine curves convexly; this works to shift the body's center of mass more anteriorly to account for the added back load [34]. Both conditions increase torsion and shear in the spinal discs, which have been shown to cause damage to the discs [34]. Further, increased compression and shear forces in the spine have been linked to the development of back pain [32]. The other mechanism for reducing spinal loading is to increase

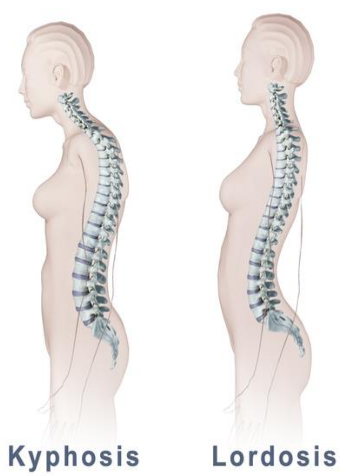

Figure 4: Diagram illustrating kyphosis and lordosis [73]

forward lean. As forward lean increases, the COM of the combined body and load shifts to be more centered over the lower limbs, alleviating some shear forces in the spine [28]. At loads of 27-30% BW, forward lean was found to be between 10 and 12 degrees [22, 23]. Additionally, increasing forward lean has other benefits such as decreasing thrust forces and increasing forward movement [30]. It is also associated with the tumpline method of load carriage which, as discussed later, has been shown to be energy efficient [36, 37]. Despite its benefits, excessive forward lean can cause fatigue of the hamstrings and semispinalis muscles as these must activate to keep the trunk stable [28].

2.3.5 Load Carriage in Rural Cultures

Load carriage methods have evolved throughout history to accommodate different types of loads, body types, economies, and geographies. From porters in Nepal and women in Africa to soldiers in the US military, humans have pushed the boundaries of their bodies to find the most effective methods for carrying heavy loads.

Due to the diverse geography of Nepal, natives have had to rely on human power as the primary method of load carriage. A porter, or one who is employed to carry loads for others, is a popular occupation for both men and women throughout Nepal [38]. Depending on the environment, porters use a variety of carrying methods to transport heavy loads. Kaneda, Yamauchi, et al. described the methods of load carriage used in different areas of Nepal, revealing that the four most common methods, illustrated in below, were on the top of the head, via handcart, with baskets hung across the shoulders, and on the back using a tumpline [39].

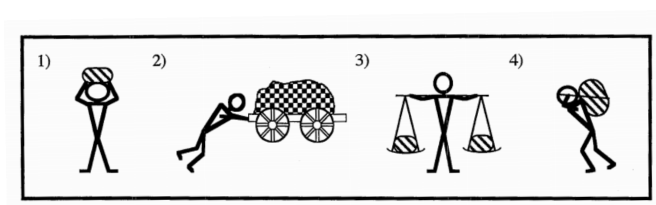

Figure 5: Illustration of the four most common methods of haulage in Nepal. 1) Top of the head 2) hand cart 3) yoke 4) tumpline [40]

Among those, the use of the tumpline, or sling with a strap on the forehead [40], was seen the most and was associated with mountainous regions. The tumpline method is regarded as the most energy efficient among the methods observed and is of high interest to those studying the effect of heavy loads on human gait and physiology. In this context, energy efficient refers to a reduction in oxygen consumption during the load carrying activity when compared to other methods of load carrying. Via this method, male porters have been documented as able to carry over 100% of their body weight, while female porters can carry over 80% of their body weight [41]. This method includes the use of the tumpline, or namlo, that links the forehead to a basket,

Figure 6: Example of a Nepalese porter using the tumpline method of carriage

or doko, which is supported by the back and that is intermittently rested on a T-shaped stick called a tokma [42]. Nepalese porters do not typically rely on other tools or aids for this method, and oftentimes walk fully loaded in simple shoes or even barefoot. While the tumpline appears to be the dominant form of load carriage by porters in Nepal, the head-supported load system is also used in parts of Nepal, as well as parts of Africa.

The Kikuyu and Luo women of Africa use the head-supported load method as their main technique for carrying heavy loads. It has been observed that these women carry loads up to 70% of their body weight, entirely balanced on the top of their heads [18]. A modification to this technique is the use of a strap across the forehead to carry equally large loads, which is seen in women of the Kikuyu tribe [18]. One of the biggest mysteries of the head-loading technique is these women’s ability to carry heavy loads without an increased rate of energy consumption. Several gait studies of these two tribes show that this load carrying method induces a gait change that increases energy efficiency.

The energy efficiency of these women was quantified by measuring oxygen consumption and heart rate as they walked with a range of loads on a treadmill. Such testing revealed that the women could carry up to 20% of their own body weight before requiring additional exertion [18]. This phenomenon was explained using the inverse pendulum model of the human gait. In this model, the COM of the body can be represented by the motion of the pendulum ball, with the two legs representing the two stiff wires that the ball is attached to. Forward movement is then maintained as the energy of the ball is transferred from one wire to the other, or the body's COM is transferred from one leg to the other. Although this model is useful, it does not take the knees into account and the knees have been shown to be critically important in gait modifications under load. However, in this case these women walk with a more upright posture and with less weight than the porters in Nepal and thus have less significant knee flexion. By modulating the pendulum, the women in these tribes are able to maximize the efficiency of this load transfer. On average, about 65% of energy is transferred during forward walking movement. Research has shown that these specific groups of African women transfer at least 80% of their energy while using their specific load carrying gait method [43]. Another test performed by Cavagna and Heglund found that the loss of potential energy was primarily during the transition from the single stance to the double stance phase of gait [44]. During this transition, the leg muscles are contracting to resist the fall instead of fully converting the potential energy to increase speed. African women are able to convert more of their potential energy into motion by shortening this transition phase while carrying a load. Ultimately, while this load carriage method is energy efficient, it is not fully understood on a biomechanical level and is more of a body-compensation method than backpack design feature.

The porters’ method of load carriage allows them to transport loads that are on average 30% BW heavier than the loads carried by the African women at comparable metabolic rates. In comparing load versus speed versus energy cost, the porters achieve their energy efficiency advantage through walking more slowly for longer hours; they typically walk for 15 seconds and then rest for 45 seconds. While both of these load carriage methods show fairly large increases in overall energy efficiency, the biomechanical mechanisms causing these changes are not fully understood [41].

2.4 Gap in Current Research

Although there is clear link between load carriage and back pain in industrialized countries, the relationship in less developed countries is obscure. This is primarily due to a lack of gait studies with large sample sizes in these countries. Sarkar et. al. have shown high incidences (79%) of back pain in manual material handlers in Calcutta, India [33]; this was supported by the work of Williams et. Al., who revealed that India had the highest incidence of intense back pain among the countries surveyed in a 2015 WHO study on back pain [14]. Knee pain has also been shown to be a problem in rural Tibet according to one study by Hoy et. al. [45]. Although this handful of studies have shown high incidences of back pain, most studies have shown back pain to be far less prevalent in less developed countries [46]. Notably, there are almost no studies looking at the long-term health of porters in Nepal. This is particularly important because multiple studies have shown that porters carry large loads very energy efficiently [36, 37]. It is possible that this increase is achieved at the expense of increasing skeletal loading and back injuries, though there are no existing studies that are able to conclusively state this.

Few studies have investigated the biomechanical effects of backpacks as a whole. Most studies take a specific feature of a design and investigate the biomechanical effects of that feature. While this research is useful for finding what designs and features are beneficial in specific scenarios, it is less useful in determining the effects of integrated backpack systems. Such systems could include many of the features discussed in Section 2.6. Specifically, Foissac discusses that the experiments and models used to evaluate suspended load backpacks have only been validated on flat surfaces [47]. This does not necessarily mean that those types of packs will not work on uneven or inclined terrain but that the benefits are unknown for these scenarios. The importance of studying integrated backpack systems is that while some features may be beneficial in isolation, when combined they may have confounding effects that lead to less than desirable performance.

2.5 Analytical Models and Assumptions

Three areas of the project required modelling: the design of the backpack, assessment of user fatigue when wearing the backpack, and the skeletal loading created by the backpack. The models used for these parts are described briefly below and in more detail in sections 5.1 and 5.7.the skeletal loading created by the backpack. The models used for these parts are described briefly below and in more detail in sections 5.1 and 5.7.

2.5.1 Backpack Design Models

All backpacks have suspensions which consist of a shoulder and hip harness and an array of strapping. Recently experimental packs have been designed with elastic elements in the suspension and these have shown a lot of potential at reducing loading on the body. Therefore, a vibration based suspension model is needed. Such a model was experimentally developed by Foissac et. al. and expanded upon and optimized by Hoover and Meguid [48, 49]. Essentially this model treats the backpack and person as a two-part spring-damper system, as seen in Figure 7.

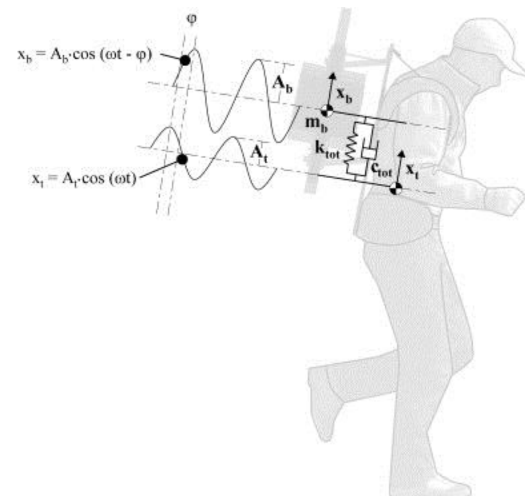

Figure 7: Model of suspended-load backpack mounted to a person. x_t and x_b, A_t and A_b are, respectively, the vertical displacements and the amplitude of the vertical displacements of the trunk and the backpack, ω and φ the walking frequency and phase angle. k_{tot} and c_{tot} are the stiffness and the damping coefficient of the entire system

Figure 7 shows the backpack model with a person and illustrates how the torso and pack load oscillate out of phase with each other. It is desirable to have the pack load and torso oscillate about 90 degrees out of phase with each other to minimize the contribution of the load created by the moving mass of the backpack [48]. This model can be used to select the correct stiffness for the spring element and damping coefficient for the damper element when designing the backpack.

Although this model is useful, it does have some limitations. The primary assumption is that the stiffness and damping coefficients are assumed to be constant; however, this is only valid as long as there are no excessive accelerations and deflections of the pack [49]. Through experimentation, this model has been shown to be most accurate when the walking speed is in the 3-6km/h range, with the best accuracy at 5km/h [49]. A full description of this model and the equations derived from it are shown in Section 5.1.

2.5.2 Energy Expenditure Models

The best way to assess user fatigue is to measure oxygen consumption during exercise. This is a common practice in studies of load carriage as the body requires oxygen to do work and thus a measure of oxygen consumption is also a measure of work to a certain degree. Bot and Hollander conducted a study where participants performed a number of non-steady state exercises and established a mathematical relationship between heart rate and VO_{2max}, or the maximum oxygen consumption [53]. This is useful as measuring oxygen consumption directly, while the best method, is often expensive and thus using proxies such as heart rate is more practical.

2.5.3 Force Analysis Models

One of the primary goals of this project is to design a backpack to minimize loading on the body. As such, all external forces applied to the body need to be accounted for and then translated into internal joint contact forces. Based on the work of Foissac et. al. the optimum method to measure the force applied by the moving backpack is to use an accelerometer attached to the backpack. To measure the overall ground reaction force, standard force plates provide the most robust data. The only issue with using force plates is that they force the study to be conducted in the lab in conditions that fail to accurately simulate a real hiking environment. There are other systems that can inserted into a shoe to capture more dynamic data but any system with the accuracy of a force plate is prohibitively expensive.

In terms of analyzing the force data once captured, the ideal method would be to use a full musculoskeletal modeling software such as OpenSim. OpenSim can create full body models of the human musculoskeletal system, run simulations of various motions, and perform static and dynamic analyses of these motions [50]. A full body model is created by modifying a generic built-in model to incorporate specific motions and scale the model to individual subjects. An example of a full body model with a rough backpack object undergoing a walking motion is shown in Figure 8. To incorporate specific motions, OpenSim requires marker data from experimental measurements where motion capture was performed. This marker data specifies the locations of limb segments in three-dimensional space and their positions relative to each other by measuring the angle between segments. By calculating these angles iteratively over the time interval of testing, a simulation of the motion can be generated. In addition to the kinematic data from the motion capture, it is necessary to include information on all external forces on the person; in this project, those would be the ground reaction forces and the forces from the backpack itself. Due to the relatively slow nature of backpacking and the fact that this project is primarily interested in reducing maximal loads at the lumbosacral joint, static positions can be analyzed as opposed to dynamic motions. The benefit of this approach is that it significantly reduces computation time. Free body diagrams used by this method are shown in Section 5.7.

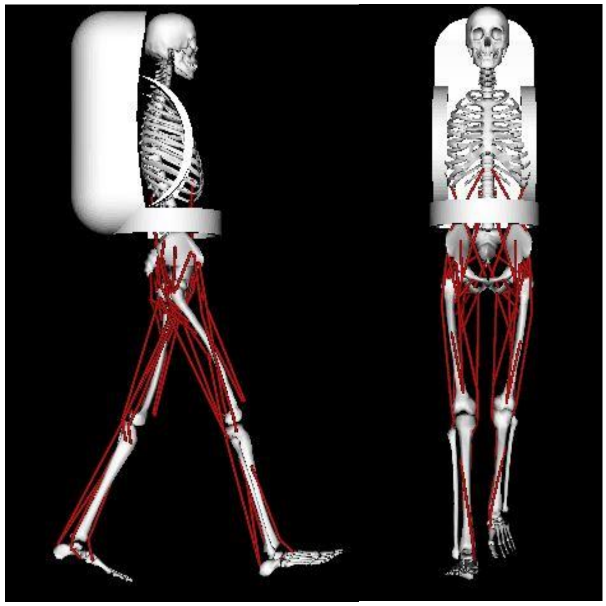

Figure 8: (Left) Side view of a full body OpenSim model with a backpack during a gait simulation. (Right) Front view of that same model.

2.6 State of the Art

2.6.1 Military Load Carriage

As of 2014, there were upwards of 27 million active armed forces in the world [51]. With limited access to transportation, many service members must rely on their bodies to haul heavy supplies and equipment. A typical US soldier carries a minimum of 27 kilograms of gear, including protective gear, weapons, and survival supplies; however, carried weight can be much higher depending on the soldier's role and mission [52]. Some of the largest loads carried by US Army members in Light Infantry Positions reach 76 kilograms, nearly 92% of the average US male soldier's body weight [52].

There are currently two methods of load carrying available to US soldiers. The first, All-Purpose Lightweight Individual-Carrying Equipment (ALICE), was introduced in 1973. The ALICE pack utilizes an external frame to hold the pack away from the body. ALICE has been succeeded by a Modular Lightweight Load-Carrying Equipment (MOLLE) pack, which was introduced after a series of studies on the functionality of ALICE in the early 2000s. This improved pack utilizes an external frame and a load bearing vest. In addition to improving carrying functionality with customizable packs, MOLLE utilizes improved padding and strap adjustments that allow for better load distribution.

Figure 9: (Left) ALICE pack [72]. (Right) MOLLE pack [71]

2.6.2 Advancements in Recreational Backpacks

Various mechanisms and features of backpacks and other haulage systems have been developed to reduce the negative biomechanical effects of load carriage. The most important finding from the literature review on backpack design is that decreasing pack weight is not the "magic bullet" solution to reducing musculoskeletal injuries [4]. This finding is critically important because it indicates the need for specific features and mechanisms in backpacks to transfer loads off of injury prone areas regardless of total pack weight. Furthermore, this is important because pack weight depends on the individual, the type of trip they are taking, and the gear they are bringing. These factors are largely independent of the type of carriage method, indicating that a new load carriage system must be designed to reduce injuries in backpackers without depending on controlling one of these factors.

Before investigating specific features of backpacks, it is important to address the effects of general backpack design and load placement on the incidence of injuries and the loading of joints. The optimal load position has been shown to be either on the high back or the low back, as opposed to the mid-back. Placing loads high on the back is shown to be better for limiting forward lean and decreasing foot injuries, but is a less stable configuration for uneven terrain [53]. In general, it is best to carry the load as close to the body's COM as possible; however, shifting the COM of the pack posteriorly has been shown to decrease the thrust force at toe-off and increase forward lean, which decreases overall joint loading and improves forward movement [30]. Further, distributing the load evenly on the torso, such as with a front pack or double pack, can reduce the horizontal braking force by 10% and thus reduce the incidence of blisters [30]. Non-traditional backpacks such as front or double packs have also been shown to induce a posture similar to an unloaded posture [27]. Wearers of double packs were shown to be more energy efficient [37] and experienced a decrease in both propulsive and braking forces [25]. With these general design guidelines in mind, it is important to look at specific features of backpacks and their effects on loading and injury prevention.

The first feature found to decrease injury and loading is not found in the traditional backpack, but rather something employed by the mountain porters of Nepal. The patuka, a piece of cloth that is wrapped tightly around the abdomen of Nepalese porters, see Figure 10, has been shown to increase intraabdominal pressure and reduce spinal loading [54]. Although the patuka is not something currently used in backpacks, a similar approach could potentially be implemented to achieve the same results. The closest feature to a patuka in modern backpacks is the hip belt. Hip belts in modern backpacking backpacks, see Figure 11, have been shown to reduce EMG activity of the trapezius muscle [53] and transfer up to 30% of the load to the pelvis [55]. They have also been shown to allow for more transverse plane rotation and increased stability between the pelvis and thorax, with these effects being most significant at loads greater than 40% BW [56]. The hip belt in combination with a frame can reduce the incidence of backpack induced palsy [53]. Recently, hip belts have become part of an integrated frame system designed to even more effectively transfer load to the pelvis. One of the other features of this frame system are lateral stiffness rods, which are rods running along sides of the backpack parallel to the main axis and connecting to the hip belt, see Figure 11[57]. They can transfer up to 14% of the vertical load to the hips from the shoulders and back and can reduce forward lean by increasing the extensor moment about the medio-lateral axis of the L3-L4 joint [55]. Another feature of this system is load-lifter straps. These straps can bring the pack load closer to the torso and higher up the back [55].

Figure 10: Nepalese porter wearing a white patuka

Figure 11: Osprey Volt 60L backpack showing features such as a hip belt, load lifter straps, and lateral stiffness rods.

These improvements in backpack design have been shown to be effective at transferring loads to different regions, but none of these innovations have attempted to actually reduce the total vertical load applied by the ground to the body. This is important for two reasons: first, reducing the total load will decrease almost all joint loads and second, the benefits of the current innovations have been shown to be less effective when trunk flexion exceeds 30 degrees [55]. Such an extreme forward lean can occur when backpackers carry loads greater than 30% BW, and so any reduction in total load would be beneficial. The primary mechanism for reducing total vertical load is to reduce the magnitude of the oscillating load created by the load inside the pack accelerating up and down during the gait cycle. There is always going to be a static load from the pack that cannot be alleviated, but there is also a dynamic load that can increase the total vertical load if the oscillation is in phase with the gait cycle [47-49]. To reduce the oscillating load, multiple prototype backpacks have been created with suspension systems that mount the load to a mobile carriage connected to a regular backpack frame, see Figure 12; this configuration allows the load to move relative to the pack frame [47-49]. Such systems have been shown to reduce the oscillating load by up to 80% [49] and reduce the peak vertical GRF by 33% [48]. These packs have also been shown to be most effective at speeds of 3 to 6 kilometers per hour and large loads in excess of 25% BW [49]. This is promising because these are conditions more likely to be encountered by experienced backpackers. By taking advantage of some of these features and designs, it is possible to create a new backpack that more effectively reduces skeletal loading and thus prevents injuries.

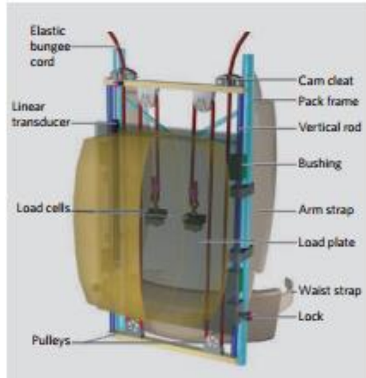

Figure 12: An example of a suspended load backpack, this one uses surgical tubing to suspend the load [48]

2.7 Limitations of Existing Systems

The current haulage methods employed by individuals in rural areas, specifically porters in Nepal and women in Africa, have several drawbacks. While porters are regarded as having an energy efficient method to carry large loads greater than 100% BW, they are often limited to walking slowly for hours; this is not a realistic feature of recreational backpacking, as backpackers often aim to hike 15 to 25 miles per day, depending on the terrain and other environmental factors. In addition, a porter's typical cycle of walking for 15 seconds and resting for 45 seconds, observed in a study on the energetics of load carrying of porters [41], is not feasible for backpackers on long-distance trails. On a similar note, the head-supported haulage method employed by tribal women in Africa is effective because of the pendulum-like gait mechanism that they use; however, this is limited to flat and even terrain, and may not be applicable to graded terrain.

The load carriage utilized in the US military and international militaries still cause complications and injuries despite continual advancements in the underlying technologies. A survey conducted among those who served in the Australian Army Corps found that 34% of respondents had sustained at least one injury due to load carriage in the past year. Most load carriage injuries were sustained in the bones and joints of the lower limbs [30]. In addition to musculoskeletal injuries, blisters, rucksack palsy, and local discomfort are common among soldiers [12]. Current military carrying methods are not alone in causing injury; some of the experimental load carriage methods being evaluated by various militaries are known to fatigue the wearers. In particular, double packs are successful in distributing loads more evenly, but limit the wearer's mobility and increase fatigue due to poor heat dissipation and air flow [58].

Despite advancements made in modern backpacking equipment to more evenly distribute loads, injuries are still prevalent. One of the most common is paresthesia, affecting 34% of surveyed backpackers [24]. Thus far, the incidence of paresthesia has not been reduced by new backpack technologies and thus new features may be necessary. Additionally, as discussed above in section 2.6, the advancements of modern backpacks have been shown to be less effective when forward lean exceeds 30 degrees.

Chapter 3: Project Strategy

3.1 Initial Client Statement

The goal of this project is to develop a novel load carriage system for recreational backpackers that takes design influence from rural cultures and the technological advancements of modern backpacks.

3.2 Technical Design Requirements

3.2.1 Design Objectives

With the client statement in mind, there are many requirements and features that are necessary to design an improved load carriage system. The following design objectives were selected to fulfill the initial client statement:

1. **Lightweight:** An improved load carriage system must be less than or equal to the weight of commercially available options for backpacks.
2. **Adjustable:** The load carriage system must be adjustable to adapt to the wide range of backpackers and varying load ranges. Additionally, design features may have dependencies on walking speed and thus those features will need to be variable.
3. **Durable**: The material selected must be durable and endure weather, as backpackers hike long distances in all weather.
4. **Optimize load distribution:** It is imperative that an improved load carriage design optimizes load distribution to different parts of the body to minimize injury and fatigue.

3.2.2 Performance Specifications

With the design specifications defined, it is necessary to determine exactly how the backpack will perform. To accomplish this task, a series of performance specifications were determined, and are outlined below in Table 1. The parameters were chosen based on studies discussed in Chapter 2; the various methods of measuring each parameter were also based on these studies. To quantify the desired effect of the backpack on each parameter, values were generally based on results from previous studies on existing backpack systems. In cases where a quantifiable value could not be measured reliably, the parameter was evaluated qualitatively by comparing its value between different test conditions. Table 1 includes the performance specifications chosen for this project, for a full breakdown of all specifications considered, see Appendix A.

Table 1: Final performance specifications

Parameter	Specification
Posture	Increase forward lean to between 10 and 30 degrees
Compression and shear at the lumbosacral joint	Reduce by 60%
Oscillating Load	Reduce by 80%
Total Vertical GRF	Reduce by 33%
Fatigue	Decreased compared to commercial backpack

As discussed in Chapter 2, the body compensates for additional loads by altering the gait cycle. Therefore, it is necessary to measure some additional parameters to conclusively link any improved user performance to the backpack itself. These parameters are expected to change because of gait compensation and not necessarily due to the design of the backpack; thus, they are mostly incorporated to serve as comparisons between conditions. Since these parameters are not actively influenced by the backpack design they are not included as performance specifications but are outlined in Appendix B.

3.2.3 Constraints

In addition to various design requirements and specifications, there are a number of constraints to consider in order to meet expectations set by backpacks currently on the market.

1. **Unrestricted mobility**: An improved load carriage system must not inhibit any mobility so backpackers will not be held back by their packs.
2. **Support 30% of body weight**: Backpackers can carry up to 30% of their body weight depending upon the length of their hikes and the weather and terrain they will endure.
3. **Interior volume:** The interior volume of the carriage system must be comparable to commercial backpacks, because backpackers are not likely to sacrifice volume. Interior volume is important to ensuring a pack can hold all the necessary supplies.
4. **Maintain features that are commonplace among commercial backpacks:** The improved carriage system must maintain common features such as water bottle holders, easily accessible pockets, and external strapping for adjustments and mounting of gear. These features, although seemingly small, play a significant role in the functionality of a pack.

The aforementioned constraints are important to accommodate in the final design to satisfy the client's needs of an improved carriage system without sacrificing important features.

3.3 Experimental Design Requirements

To accurately determine the performance of the backpack, data must be collected from a controlled experiment. The following experimental design outlines the methods and materials required to properly collect data on the improved backpack and a standard backpacking pack. Overall, data was collected from two separate experiments for each subject. The first experiment was designed to collect precise force data to determine the efficacy of the experimental pack’s load minimization and optimization and was of a short duration. The second experiment was designed to assess subject fatigue and took place over a longer duration

3.3.1 Materials

The materials used to conduct experiment 1 are as follows:

- Plywood ramp
    - Sturdy plywood ramp set at a fixed 8.5-degree angle. The ramp was about 8ft long so that two full toe-off events can be captured

- Force Plates
    - Standard AMTI force plate borrowed from the WPI BME department
- Accelerometer
    - Accelerometers are required to monitor the oscillating load of the pack.
- Cameras & tripods
    - Two video camcorders were rented from the WPI ATC and set up to create a motion capture system.
- Motion Capture Markers
    - Colored ping pong balls taped to the subject
- Backpacks
    - The custom backpack, a modified Osprey Volt 60L, and a standard Osprey Volt 60L backpack are necessary to collect comparative data.

The materials used to conduct experiment 2 are as follows:

- Treadmill
    - LifeFitness 95Ti Treadmill in the WPI Sports & Recreation Center with an incline of up to 15%.
- Stationary Bike
    - The subjects' maximum heart rate was determined after utilizing LifeFitness 95c Lifecycle Bike available in the Sports & Recreation Center.
- Heart rate monitor
    - Heart rate must be taken to accurately estimate exhaustion. The FitBit Surge was used as well as the built-in monitors on the bike and treadmill.
- Video camera and tripod
    - Video camcorder was rented from the WPI ATC and set up

3.3.2 Methods

3.3.2.1 Subject Selection

Because the designed backpack was intended for use by experienced backpackers, selection criteria were defined for potential subject participants. All participants were required to be male, between the ages of 20-29 and between 150-200 pounds. Additionally, participants had to have prior backpacking experience. Finally, participants could not have any diagnosed spinal, gait, heart, or lung problems. To participate in the study subjects provided informed consent.

Table 2: Comparison of required sample size vs. actual sample size in load carriage studies

Parameter	Difference	SD	Req. Sample Size	Sample Size References
Oscillating load	82%	6.4%	1	6 [48]
VO_2(fatigue)	3.8%	2%	5	12 [47]
VO_2(fatigue)	6.16%	4.5%	9	6 [48]

VO_2(fatigue)	5%	4.8%	15	9 [25]
L5/S1 Compression	.96BW	.05BW	1	10 [23]
L5/S1 Shear	.18BW	.05BW	2	10 [23]
Forward Lean	6.6deg	1.2	1	10 [22]

To calculate the appropriate sample size for this study, the literature was reviewed to identify the expected means and standard deviations for each of the parameters of interest, see Table 2. Using a comparison of means test with a significance level of 5% and a power of 80%, the desired sample sizes were calculated using equation 1, where the Z's are the critical values assuming a normal distribution, σ is the standard deviation, and d is the expected difference in means:

$$\boldsymbol{n = (Z_{\frac{\alpha}{2}} + Z_{\beta})^2 * 2 * \sigma^2/d^2} \quad \textbf{Equation 1}$$

Based on this information, it appears that a sample size of 10 would be acceptable for measuring the desired parameters and is a common sample size in the literature. The only parameter for which a sample size of 10 may not be well suited is for measuring VO_2. While 10 is the ideal sample size, due to time restrictions, the team sought to test 5 subjects. With this sample size the team could accurately assess the changes in lumbosacral loading and forward lean, and give a fairly accurate assessment of fatigue.

In terms of the sample size needed to provide significant results from qualitative surveys, a review of the literature showed that the lowest sample used was 100 subjects. Due to the time and budget constraints of this project, such a large sample size was impossible and thus the primary focus was collecting quantitative data.

3.3.2.2 Test Setup: Experiment 1

To facilitate data collection, it was necessary to attach motion capture markers, measure subject anthropometry, and set up cameras to capture the movement.

To scale the analytical model used to analyze the subject's gait, it was necessary to measure the length or width of the following body segments on the subject:

1. **Thorax and abdomen:** Measured from the 1st thoracic vertebrae to the sacrum
2. **Head and neck:** Measured from the 1st cervical vertebrae to the ear canal
3. **Forearm and hand:** Measured from the elbow axis to the ulnar styloid
4. **Upper arm:** Measured from the glenohumeral axis to the elbow axis
5. **Foot:** Measured from the lateral malleolus to the head of the second toe
6. **Shank:** Measured from the femoral condyles to the medial malleolus
7. **Thigh:** Measured from the greater trochanter to the femoral condyles
8. **Knee width:** Measured from the lateral to medial femoral condyles
9. **Ankle width:** Measured from the lateral to medial malleoli

Additionally, the subject's height and weight were recorded. The weight was used to determine the appropriate backpack mass. All anthropometric data was recorded in a spreadsheet as laid out in Appendix C.

To perform 2D motion capture, the subject was fitted with 18 markers. Each marker was a ping-pong ball that was marked to designate the center as seen from all angles. The markers were attached to the subject with tape. The locations of the markers were chosen to allow the team to determine accurate joint angles and simplify analysis as much as possible. The marker set is shown visually in Figure 14. The exact anatomical location of each marker is specified in Appendix D.

Motion capture was conducted using two cameras. The cameras were located such that one had an unobstructed view of the left side of the subject and one had an unobstructed view of the right side of the subject. Each camera's field of view was referenced to single global origin to ensure all motion capture measurements were taken in the same coordinate system. This global origin was visually denoted with a separate marker. Such a setup is show in Figure 13. Additionally, in each field of view a scale, in inches, was placed passing through the global origin and running along the corresponding axis. This allowed the marker positions to be converted from pixels to Cartesian coordinates.

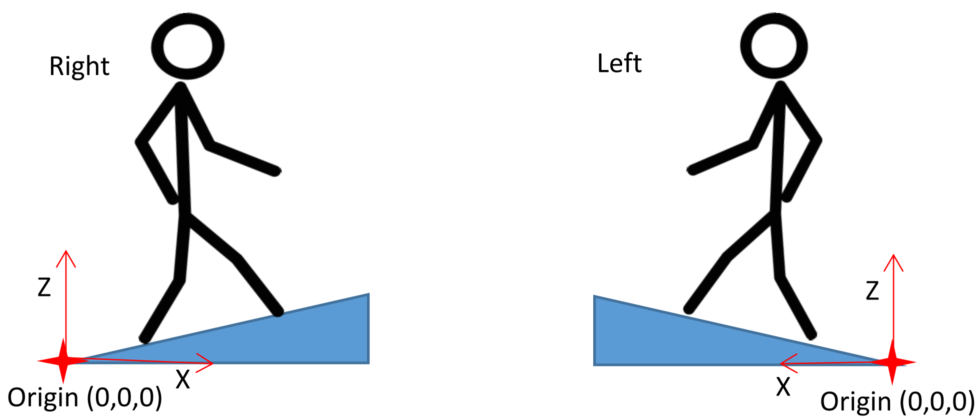

Figure 13: Two camera setup for motion capture data. The ramp will be at a 15% grade, about 8.5 degrees, to match the maximum incline on a treadmill. Lab global origin will be located midway along the width of the ramp at the base.

To accurately measure the vertical motion of the backpack and torso, both the backpack and subject were fit with accelerometers. In both cases, the accelerometers were placed as close to the center of mass of each body as possible.

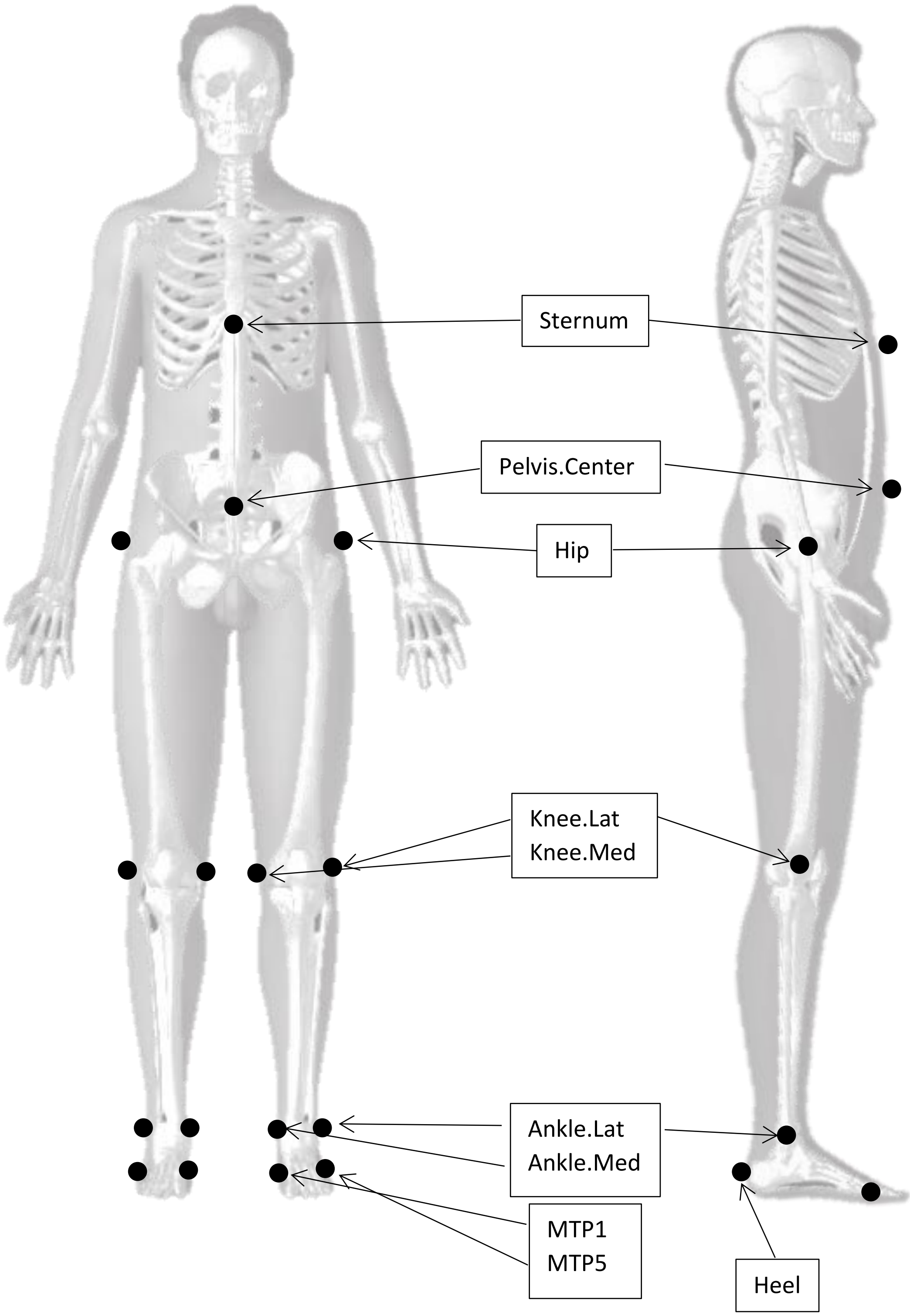

Figure 14: Marker locations

3.3.2.3 Test Setup: Experiment 2

Experiment 2 was designed to assess user fatigue by approximating oxygen expenditure using heart rate. The subject was fit with a heart rate monitor that sent continuous live data to a smartphone. Although no motion capture was performed, a single camera was used to provide additional visual indications of fatigue.

Testing took place in the WPI Rec Center as the use of an exercise bike and treadmill was required. The camera was set up so that the side of the subject was clearly visible when walking on the treadmill.

3.3.2.4 Experimental Procedure: Experiment 1

1. The subject signed the consent form; this consent form covered both experiments.
    a. As per the WPI IRB Application, all subjects must read and sign an Informed Consent Form prior to partaking in any study-related procedures and after being informed of all study logistics. In this stage, any questions about the study will be answered before beginning the experimental procedure.
2. The subject took part in a habituation session.
    a. The subject familiarized themselves with the experimental set-up by walking on the ramp under both test conditions: with a normal hiking backpack and with the testing backpack, each with a load of 30% body weight. During this period, the subject was fitted to each backpack. Adjustments to be made include filling each backpack with the appropriate number of flour bags to make the load 30% body weight and adjusting the torso length, shoulder harness, and hip belt. Additionally, this time was used to adjust the placement of the force plates to allow a natural stride on the ramp. Once the force plates are positioned, their position and orientation in the global coordinate system was recorded. A minimum period of 5 minutes walking on and off the ramp with each backpack was allotted to ensure that subjects were comfortable with each test condition and that all necessary adjustments were made.
3. The team measured and recorded subject parameters.
    a. Subject parameters to be measured are outlined in Chapter 3, Section 3.3.2.2: Test Setup: Experiment 1.
4. The team followed the test setup.
    a. The test setup is outlined in Chapter 3 Section 3.3.2.2: Test Setup: Experiment 1.
5. The team calibrated the force plates.
6. The team verified data collection.
    a. A test run was conducted to verify that data was being sent from the force plates and from each accelerometer to the computer, and that the data was within reason for what is expected.
7. The team verified motion capture.
    a. With all testing parameters set-up, a trial motion capture was conducted to ensure the subject and all markers and scales were visible from each camera.

8. The subject tested condition 1: normal hiking backpack.
    a. Subject was fitted with normal hiking backpack. Backpack strap and belt adjustments made during the habituation session were verified. The subject walked across the ramp, making sure to step on both force plates. This was repeated 3 times so that 3 toe-off events per foot were captured.
9. The subject underwent a period of recovery.
    a. The subject was given a recovery time of at least 5 minutes.
10. The subject tested condition 2: experimental hiking backpack.
    a. Subject was fitted with the experimental hiking backpack. Backpack strap and belt adjustments made during the habituation session were verified. The subject walked across the ramp, making sure to step on both force plates. This was repeated 3 times so that 3 toe-off events per foot were captured.

3.3.2.5 Experimental Procedure: Experiment 2

1. The subject took part in a habituation session.
    a. The subject familiarized themselves with the experimental set-up by walking on the inclined treadmill under both test conditions: with a normal hiking backpack and with the testing backpack, each with a load of 30% body weight. During this period, the adjustments made in Experiment 1 to backpack weight, torso length, shoulder harness, and hip belt were verified for each backpack. A minimum period of 5 minutes on the treadmill with each backpack was allotted to ensure that subjects were comfortable with each test condition and that all necessary adjustments were made.
2. The team recorded the subject's resting heart rate.
3. The team measured and estimated maximum heart rate using the Conconi Stress Test.
    a. The subject was connected to a heart rate monitoring system and rode an exercise bike. During this test the subject completed a 5 minute warm up going at a steady pace at a resistance of 10. The team then recorded the initial heart rate. Next the resistance was increased by 3 units every minute and the subject's heart rate recorded at each minute. This continued until the subject felt they needed to slow down or the team saw a clear plateau in the heart rate. The heart rate data was plotted vs. time and the deflection point in the curve was used as the aerobic threshold of the subject. This threshold is typically 80% of HR_{max} so it can be used to approximate $HR_{max.}$ This can be plugged into Equation 9 to estimate the subject's level of fatigue as a percentage of VO_{2max}.
4. The subject underwent a period of recovery.
    a. The subject was given a recovery time of at least 15 minutes. At the end of this period, the heart rate was recorded; if the heart rate had not returned to HR_{rest} recorded at the beginning of the study, 5 minute increments were added onto the recovery time until HR_{rest} was achieved.
5. The team followed the test setup.

   a. The test setup is outlined in Chapter 3 Section 3.3.2.2: Test Setup: Experiment 2.
6. The subject tested condition 1: normal hiking backpack.
   a. Subject was fitted with the normal hiking backpack. Backpack strap and belt adjustments made during the habituation session were verified. Subject then walked for 20 minutes on the inclined treadmill at the specified test speed of 3mph.
7. The subject underwent a period of recovery.
   a. The subject was given a recovery time of at least 15 minutes. At the end of this period, the heart rate was recorded; if the heart rate had not returned to HR_{rest} recorded at the beginning of the study, 5 minute increments were added onto the recovery time until HR_{rest} was achieved.
   b. During this recovery time the subject completed the first half of a qualitative questionnaire.
8. The subject tested condition 2: experimental hiking backpack.
   a. Subject was fitted with the experimental hiking backpack. Backpack strap and belt adjustments made during the habituation session were verified. Subject then walked for 20 minutes on the inclined treadmill at the specified test speed of 3mph.
9. The subject completed a post-test survey.
   a. The second half of the qualitative survey was completed by the subject comparing comfort levels between the two test conditions, as well as taking input on observed differences between the two backpacks.

3.4 Standards and Regulations

3.4.1 Design of Prototype

The design requirements had to comply with the Consumer Product Safety Act, as this backpack was designed for use by recreational backpackers. Within this act, it is noted that all design requirements are expressed in terms of performance requirements and that they are marked with clear and adequate warnings or instructions to minimize risk of injury associated with product use. CAD models designed complied with ANSI standards, and material testing for the construction of the prototype complied with ASTM standards. Any fasteners and pack accessories were designed to be compatible with standard industry components.

3.4.2 Design of Experimental Subject Testing

To conduct backpack testing on human subjects, approval from the Institutional Review Board (IRB) was granted to evaluate the effects of our design. Subjects went through an initial screening process and were disqualified if they exhibited any of several conditions. Non-significant risks were posed during performance testing, all markers were attached externally to the body, and subjects were exposed to simulated conditions they would encounter during backpacking expeditions. The success of the design performance specifications was based off the performance testing and a qualitative questionnaire. Tests were performed in the WPI

Recreational Center utilizing exercise equipment, including a treadmill at various speeds and inclined positions, as well as a lab room in Goddard Hall utilizing a set of camcorders and tripods.

3.5 Revised Client Statement

After analyzing the available literature and developing a list of achievable design and performance specifications, the client statement was revised to reflect these changes. The revised goal of the project is as follows: to develop a backpack for recreational backpackers to carry 30% body weight more efficiently than commercially available backpacks. In this context, efficiently means reducing spinal loading, back pain, and fatigue. The target population for this backpack was male backpackers.

3.6 Project Management Approach

In monitoring progress and advancement towards completion, the team broke the project down into major milestones associated with activities that need to be achieved, along with their expected dates. A work breakdown structure, seen in Figure 15, was created to group each milestone with what actions needed to be achieved. The structure was broken down into initial research, development of prototype and experimental design, creation of prototype and experimental procedures, evaluation of design through testing and data analysis, and ensuring completion of deliverables.

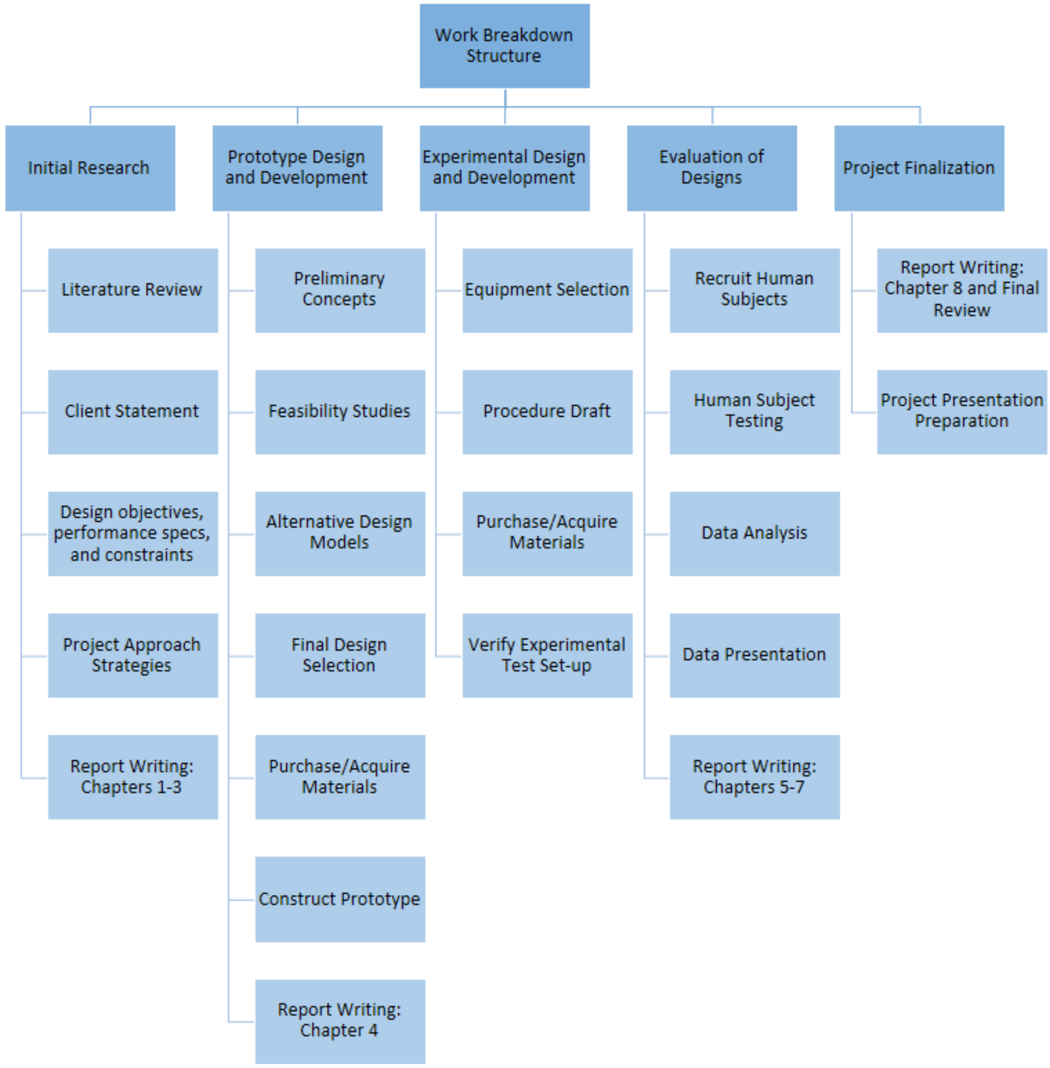

Figure 15: Work-breakdown structure

3.6.1 Gantt Chart

To manage the project milestones given time and financial constraints, Microsoft Excel was utilized to keep track of finances and maintain a Gantt chart to progress the project forward. The team divided the work breakdown structure into expected dates of completion based on WPI's term schedule.

In A-term, all applicable background research and literature review was completed to develop a client statement as well as objectives, constraints, and performance specifications of the design. Final report Chapters 1-3 were written and project approach strategies were established.

A bulk of the physical labor in drafting designs, testing alternatives, manufacturing the final prototype, and verifying the experimental design procedures occurred in B-term. The design process was documented and written as Chapter 4 in the final report. Once the prototype was manufactured and the experimental design set-ups were completed, subject testing was first carried out by the team themselves. This testing served as an iterative process of revision for both the prototype and experimental procedure in preparation for human subject testing.

The final prototype design was evaluated through execution of human subject testing in C-term. Data analysis was performed to determine success of design. Success of the new load carriage system was determined through evaluating performance specifications and outperforming an existing pack the design was compared to. The final report consisting of Chapters 5 through 8 was written and submitted for review. Final edits of the paper were completed and the eCDR was submitted within the first two weeks of D-term. Upon submission, the final poster was created as preparation for the final presentation.

3.6.2 Budget

With each team member allotted $250, the total budget for the project came to $1,000. The budget was broken down into two main components: prototype construction and testing components needed. Approximately $500 was allocated to the prototype construction that involved buying an existing pack to build off of, along with materials such as fabric, fasteners, and elastic and rigid components to support the new design. The other $500 was allocated to buying materials for subject testing that involved force sensors and motion capture equipment. Ultimately, no money was spent purchasing load cells or other equipment for testing, as this was all borrowed.

A list of all materials used kept track of how much was spent, where the material was purchased or borrowed from, the date it was purchased or borrowed, and the person who bought the material for reimbursement purposes. Materials intended to be borrowed through different resources on campus were still considered in the budget to show the full span of materials needed to construct and test the prototype. Table 3 below outlines the cost for all raw materials purchased, however not all the raw materials ordered were used for the prototype.

Table 3: Budget

Items	Place of Purchase	Cost
Backpack	Osprey	$ 108.90
Hip Belt	REI	$ 20.79
Elastic components	McMaster Carr	$ 18.67
Fasteners, washers, springs, aluminum rods	McMaster Carr	$ 157.69
Velcro	Home Depot	$ 10.06
Grommet	Amazon	$ 8.72
Fabric, thread, needle	Joann Fabrics	$ 20.00
Spring scale	Amazon	$ 9.99
	Total cost for all raw materials	**$ 354.82**

Chapter 4: Design Process

The design process of the prototype was initiated by analyzing the performance specifications to determine the set of needs the design should address. Alternative designs were evaluated based on the results of surveying a focus group, comparing various functional means, and determining feasibility when combining conceptual designs. The decision making factors that went into final design selection included a configuration to minimize loading and accomplish optimal load distribution, material properties to achieve durability, stability, and comfort of the pack, appropriate cost of materials to construct a design that can be comparable to others on the market, and achievable manufacturability of the design.

4.1 Needs Analysis

A needs analysis was executed to evaluate the performance specifications in comparison with one another. Based on findings from the literature review, the team ranked six design needs in order of which would best meet the project goal. The team then conducted an online survey of 9 experienced backpackers where respondents were asked to rank the six design needs in order of perceived importance. The respondents were given the option to suggest additional features or needs as part of the survey as well. Table 4 below shows these needs ranked in order of importance based on both the team's review and the survey results.

Table 4: Needs analysis comparison

Rank	Design Team	Focus Group
1	Reduce Vertical Load	Optimize Load Distribution
2	Reduce Fatigue	Reduce Fatigue
3	Optimize Load Distribution	Durable
4	Durable	Lightweight
5	Adjustable	Adjustable
6	Lightweight	Reduce Vertical Load

The following needs also suggested by the survey respondents include: easy to repair, flexible hip belt, hydration sleeve, external gear tie-downs, and maximize air flow. The hydration sleeve, flexibility of the hip belt, and gear tie-downs were already considered as part of the constraints listed in Section 3.2.3. Maximizing air flow was considered as a means of reducing fatigue and ease of repair was considered as a means of making the pack durable.

Based on the survey results, the needs were prioritized into three main functions:

1. **Minimize Loading:** This encompasses reducing the vertical loads on the entire body as a unit and on specific body parts. Optimal load distribution was also included in this category because most of the pack load should be transferred to the lower limbs through the pelvis and loading the backpacker’s shoulders or back should be avoided.

2. **Reduce Fatigue:** Fatigue is generally recognized as a measure of how tired the backpacker is after extended physical activity. It is affected by such factors as external loading, heat dissipation, airflow, and fitness level. While these are all physical

phenomena, they can manifest in one of two ways: physical or mental fatigue. Physical fatigue refers to the effectiveness of physiological processes while mental fatigue refers to how the backpacker perceives they are performing. Often it is mental fatigue that limits performance. By minimizing the loads on the body and minimizing contact of the pack and physical and mental fatigue can ideally be reduced.

3. **Durability:** Backpackers take their equipment to rugged environments where it is exposed to physical abrasion, cyclical loading, large temperature changes, precipitation, and extended exposure to sunlight. Therefore, pack components and materials must be durable, weather resistant, and easily repairable.

Making the pack adjustable and lightweight were determined to be less important than the needs listed above and therefore given a lower priority during the design process. A Functions-Means table, seen below in Table 5, proposed a variety of options to accomplish the higher priority needs defined above.

Table 5: Functions and Means Table

Function	Means				
Minimize Loading	Create load suspension system	Add counterweights to the front of the pack	Add hip belt extension	Add a shoulder strap tumpline	Re-route shoulder straps
Reduce Fatigue	Use breathable fabrics	Minimize loading	Use a pivoting hip belt	Support spine with patuka-like device	Include space between contact surfaces and main pack body
Durability	Use UV, water, temperature, corrosion, and wear resistant materials	Minimize moving components			

4.2 Conceptual Designs

Conceptual designs were developed to accomplish the means listed in Table 5. Aspects of each design were further researched to align their purpose in the design to the needs defined.

4.2.1 Suspension System

The goal of a suspension system is to minimize the amount of loading on the body by reducing the force created by the load moving vertically during walking. Figure 16 gives an overview of the suspension.

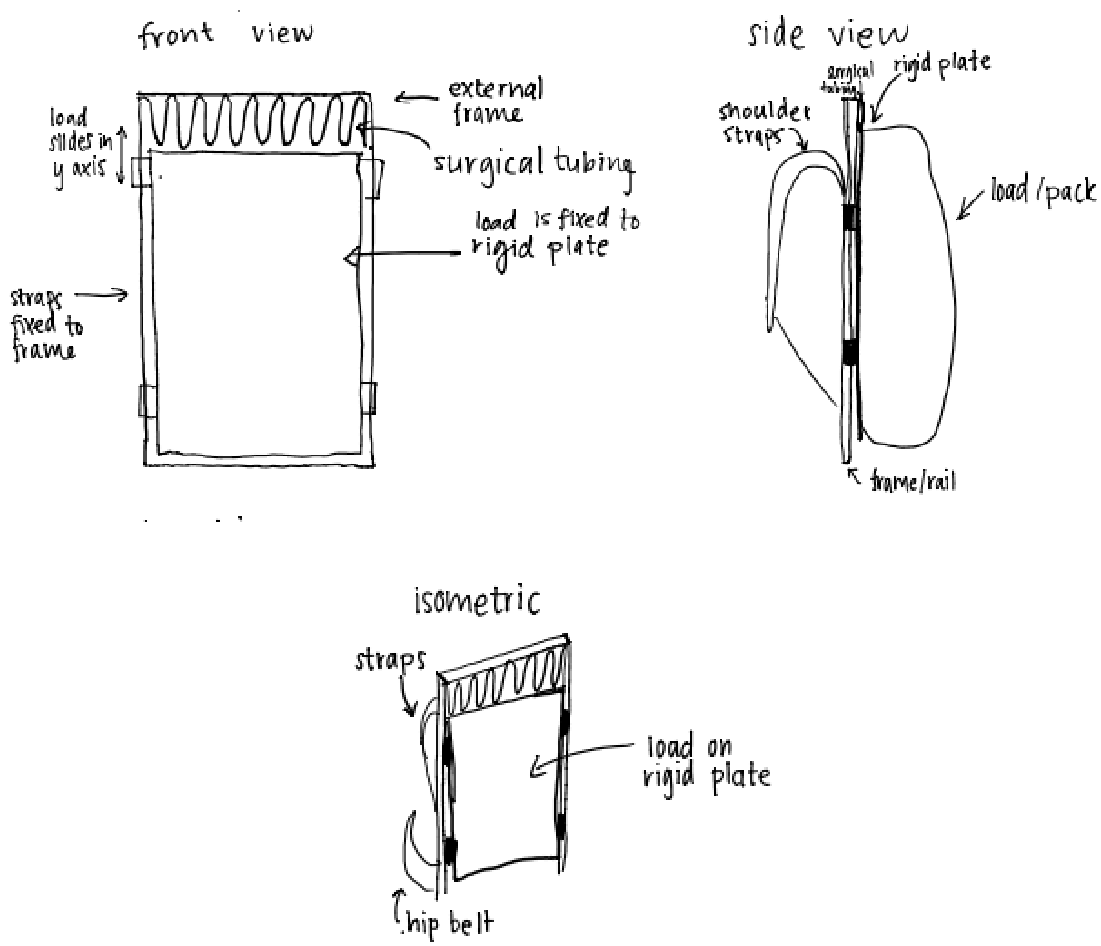

Figure 16: Suspension

- *Advantages*
    - From research, this design reduces oscillating load by 82% and total vertical GRF by 33% [49]
    - Most effective at high speeds, ~3mph, and heavy loads, >25%BW [49]
    - Provides shock absorption
    - May be able to be incorporated with a flexible frame to make the pack contour to the body more
- *Disadvantages*
    - Moving parts may be less durable

4.2.2 Counterweight

The goal of a double pack design is to have weight distributed in both the front and back of the body. This will distribute weight more evenly around hips, orient the loading more vertically downwards, minimize shoulder load, and minimize the disruption of natural posture and movement of the body.

Figure 17: Commercially available Aarn double pack [61]

- *Advantages*
    - Smaller increase in forward lean [59, 60]
    - Closer to normal posture providing better convex spine curvature in the thoracic region [61]
    - Greater range of trunk motion of trunk in early phases of gait cycle [59]
    - Decrease in ground reaction forces [59]
    - Smaller displacement in COM/smaller differences in unloaded gait patterns [59]
    - Improved energy efficiency [59]
- *Disadvantages*
    - Increase fatigue [59]
    - Increased discomfort in neck and hip [60]
    - Limited field of vision in front of the body [60]
    - Burdensome to put on and remove [60]
    - Ventilation and heat exchange problems in the front of the pack [60]

4.2.3 Extended Hip Belt

The goal of an extended hip belt would be to transfer load distribution to the hips of the backpacker. It performs a similar role to the lateral stiffness rods in existing backpacks.

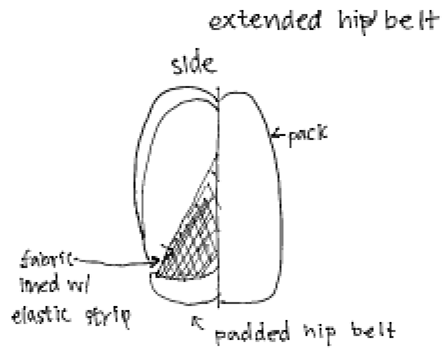

Figure 18: Extended hip belt

- *Advantages:*
  - Lateral stiffness rods can transfer 14% of vertical load to hips from shoulders/back [55]
  - Transferring the load lower on the back provides more stability and increase forward lean which decreases thrust force at toe-off [62, 63]
  - Having weight posteriorly increases forward lean and improves forward movement [30]
- *Disadvantages:*
  - May not be adjustable enough
  - May decrease air flow and heat dissipation

4.2.4 Tumpline

The goal of the tumpline feature would be to transfer all of the weight that the shoulders bear to a point on the backpacker's head.

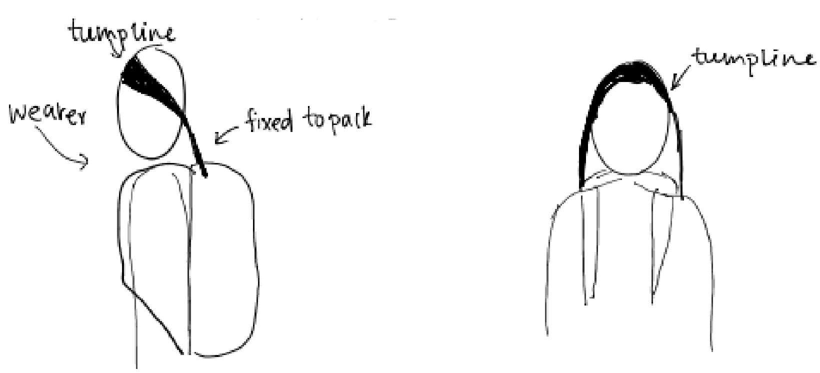

Figure 19: Tumpline

- *Advantages:*
  - Energy efficient [36, 37]
  - Associated with forward learn, which reduces spinal loading

        - Alleviates pressure on shoulders and hips through suspension of the pack load to the top of the head [64]
        - Minimizes exertion of abdominal and spinal muscles [54]
        - Counter moment of force created that should reduce the shear force on the lower back [65]
    - *Disadvantages:*
        - Requires practice to perfect its use effectively (Patagonia)
        - Can cause injury if not used properly
        - Increases loads at cervical and lumbar vertebrae [39]

4.2.5 Patuka

The goal of a patuka would be to reduce spinal loading of the backpacker.

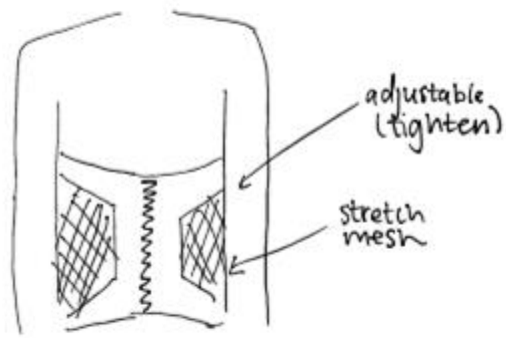

Figure 20: Patuka

- *Advantages:*
    - Increase intra-abdominal pressure and reduce spinal loading
        - Comparable to hip belt in modern backpacks that have been shown to reduce EMG activity of trapezius muscles and transfer up to 30% of the load to the pelvis [55]
    - Minimize back pain [54]
- *Disadvantages:*
    - Discomfort and unfamiliar to user
    - Decreases air flow and heat dissipation[66]

4.2.6 Strap Rerouting

The goal of strap rerouting explored a design found that pulls straps down the center of the torso and into a single buckle mechanism for quick release that also attaches to the hip belt.

Figure 21: Concept art of the Coxa Carry single strap shoulder harness [67]

- *Advantages:*
  - Possible increase in load transference to the hips
  - Increase arm mobility
  - Quick release of buckle
- *Disadvantages:*
  - Comfort of buckle in the midsection.
  - Lack of sufficient evidence showing effectiveness [67]

4.2.7 Pivoting Hip Belt

The goal of a pivoting hip belt would be to enhance backpacker comfort and accommodate pelvic tilt and rotation.

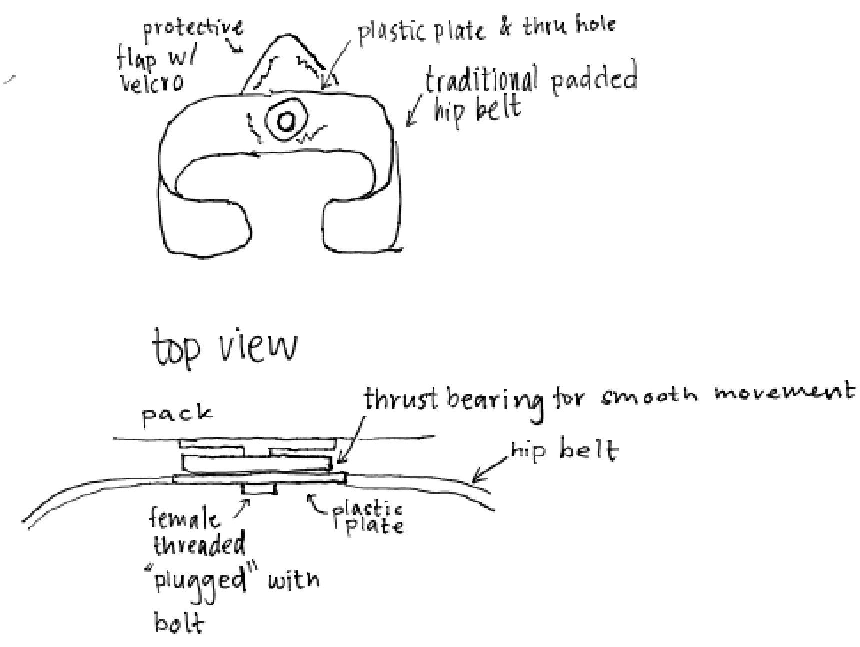

Figure 22: Pivoting hip belt

- *Advantages:*
    - Static hip belts provide more stability between torso and pelvis
        - Allow more transverse plane rotation [56]
    - Qualitatively increases comfort, especially on rough terrain
    - Allows for frontal plane rotation
- *Disadvantages:*
    - Moving parts
    - Maybe less durable
    - Single contact point between backpack and hip belt

4.3 Conceptual Design Comparison

After compiling evidence into advantages and disadvantages for each conceptual design, a ranking system was used to analyze how each design contributed to the identified needs. Each conceptual design was given either a "1" if it accomplished the need or a “2 if it either hindered the means of accomplishing the need or if the effect was unclear. Then, based on the averaged rank of importance calculated in Table 4, a weight factor was applied to the conceptual design's rank. Physical and mental fatigue were split up and categorized with their own weights to clear up confusion from the focus group questions and also to recognize the different effects they contribute. Forward lean of 10-30 degrees allows for maximum energy efficiency, induced forward lean was also added to the list of needs. These two additional needs were given weight factors based on the literature review. The breakdown matrix of this ranking process can be seen in Table 6: Design Matrix.

Table 6: Design Matrix

	Weight Factor	Suspended Load	Counterweight	Extended Hip Belt	Tumpline	Patuka	Pivoting Hip Belt	Strap Rerouting
Reduce Physical Fatigue	1	1	1	1	1	1	2	2
Optimize Distribution	2	4	2	2	2	4	2	4
Induce Forward Lean	2	4	4	2	2	4	4	4
Reduce Verticle Load	3	3	6	6	6	6	6	6
Durable	4	8	8	8	8	8	8	8
Adjustable	5	10	10	10	10	10	5	10
Reduce Mental Fatigue	5	5	10	10	10	10	5	10
Lightweight	6	12	12	12	12	12	12	12
Total Rank Score		**47**	**53**	**51**	**51**	**55**	**44**	**56**

For example, when analyzing how the suspended load feature contributed to the lightweight need, it originally received a 2 because the added components increasing the pack weight. That rank of 2 was then multiplied by the weight factor of 6, resulting in the suspended load design to receive a rank of 12 in the lightweight category. All of the rank scores were added together for each design component, and the lowest rank score represented the highest priority design component that was pursued in the design process. The weighted rank results were as follows:

1. Pivoting Hip Belt
2. Suspended Load
3. Extended Hip Belt (Tie)
4. Tumpline (Tie)
5. Counter Weight
6. Patuka
7. Strap Rerouting

Based on these comparative results, the pivoting hip belt, suspended load system, and extended hip belt were the three main features that were incorporated into alternative designs. The feasibility of incorporating the remaining design features was discussed. Based on either their conflict with features already chosen or insufficient knowledge about how the feature would accomplish the overall pack goal, they were no longer incorporated into the design process moving forward.

4.4 Alternative Designs

4.4.1 Frame

To stay within a reasonable price range and still achieve the desired material properties, two types of aluminum alloys were explored. 6061 Aluminum Alloy is a commonly used material chosen for its higher corrosion resistance and weldability amongst other options. The approximate yield strength of 6061 is 35,000psi. 7075 Aluminum Alloy was also considered as an option due to its desirable high strength to provide support for the suspended load system. The approximate yield strength of 7075 is 62,000psi.

The shape of the frame had to be bent in a way that fully accommodated the placement of the suspended load system, provide enough support the oscillating load, and fit within the parameters of attaching to the back of the user. The desired maximum bending stress the frame should be able to experience was calculated to be 17,500 psi. The bending stress was used to determine how far forward the frame would be bent to attach into the hip belt, see Appendix E for full calculations [68]. Two different shapes were modeled, varying in the bend of the side of the frame, dependent on the aluminum alloy.

Figure 23: (Left) 7075 frame with more pronounced prongs at the end. (Right) 6061 frame with less pronounced prongs at the end

4.4.2 Suspended Load System

The suspension system consists of the frame, a load plate, and elastic elements connecting the two. The frame is what attaches to the shoulder harness and hip belt and ultimately to the person. The load plate is what the backpack itself attaches to and thus is where the load attaches. The load plate slides vertically on the frame via small fabric loops and the elastic elements control its movement.

4.4.2.1 Elastic Elements

It was important to consider how heavy the load would be and how far the load could move when determining what type of tubing or bungee cord to use. Surgical tubing, bungee cord, and rubber cord were all considered. Rubber cord was chosen because of the inexpensive price, the variety of sizes, and its durability and weather resistance.

4.4.2.2 Load Plate

To keep the weight of the pack as low as possible, the load plate needed to be constructed from a lightweight but strong material. The load plate needed to hold approximately 50 pounds, depending on the subject. Several materials were considered, such as aluminum and HDPE, but ultimately HDPE was selected for its manufacturability and stiffness. HDPE is also currently used in most commercial backpacks as part of the internal frame.

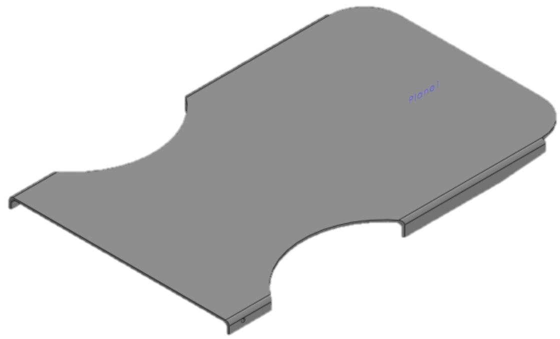

Figure 24: Load plate design

4.4.3 Pivoting Hip Belt

To create a pivoting hip belt, an existing hip belt attachment was selected to be modified with washers, screws, and an attachment piece. It was decided to use an existing hip belt because the hip belt is not the innovation, the pivoting function is.

4.5 Final Design Selection

Since this project primarily focused on elements of the backpack frame and suspension, the team did not see it necessary to build an entire backpack from scratch. Instead, the team decided to purchase a commercially available backpack and remove its frame and harnesses so that what remained was the fabric sack making up the main compartment and the top hatch. Additionally, the team decided to purchase a commercially available replacement hip belt and use that to design the pivoting hip belt.

The backpack chosen was the Osprey Volt/Viva 60L as it matched the size and model of a backpack already owned by a team member. This meant that when conducting the comparative testing many of the other variables such as padding, gear attachments, and pockets were constant. For the hip belt the team purchased the REI Cresttrail 70 replacement hip belt as this belt was a continuous unit with a semi-rigid mounting region. The backpack and hip belt are shown in Figure 25.

Figure 25: (Left) Osprey Volt/Viva 60L. (Right) REI Crestrail 70 replacement hip belt

The following parts were removed from the Osprey pack: aluminum wire frame, HDPE interior frame, hip belt, shoulder harness, and all foam padding on the back. The foam padding and shoulder harness were saved to be repurposed on the new pack.

The overall final design consisted of an aluminum frame around the perimeter of the pack, an HDPE load plate which moved vertically on the frame, and a pivoting hip belt. The frame and the load plate were attached with elastic cord of the appropriate stiffness to achieve the desired suspension characteristics. As opposed to a single elastic cord attaching the two, it was chosen to use multiple cords to increase pack stability and better distribute the load on the frame. This final design can be seen in Figure 26, as some of the components are flexible pieces, they are not modelled but simply sketched on.

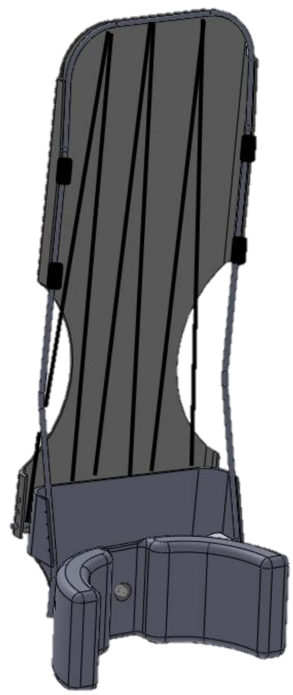

Figure 26: Final design with suspension and pivoting hip belt. Fabric loops attaching the load plate and frame and elastic cords are sketched on.

4.5.1 Frame

The aluminum alloy to construct the frame out of was ultimately determined by both manufacturability and the desire to have the frame extend as far out at the ends as possible. Therefore, 7075 was the ideal choice because of its strength but it is less bendable than 6061. With supporting evidence of bendability of 6061, a method was created using a manual pipe bender. After an appropriate method was decided upon for achieving the desired bends with a piece of 6061 rod, the 7075 rod was ultimately worked into the desired shape. Due to the success of the manufacturing method and its high strength capacity, the 7075-aluminum rod was chosen for construction of the frame for the final prototype.

4.5.2 Suspended Load System

The first step in building the prototype backpack was to determine the appropriate stiffness and damping coefficients for the suspension. As described in section 2.5.1, this was done using the model developed by Foissac et. al. and optimized by Hoover and Meguid. The full model is described below as well as the results of applying the model to this project.

Table 7: Name and description of variables used in analytical models

Variable	Description
m_b	Mass of the backpack [kg]
ω	Step angular frequency [rad/s]
φ	Phase angle [rad]
k_b	Stiffness of the pack itself [N/m]
k_{tot}	Total stiffness calculated during the while-walking experimentation [N/m]
c_b	Damping coefficient of the pack itself [Ns/m]
c_{tot}	Total damping coefficient (pack + pack/body interface) [Ns/m]
A_t	Amplitude of the vertical movement of the trunk [m]
g	Gravitational acceleration [m/s^2]
S	Height of person [m]
l_0	Leg length of person [m]

4.5.2.1 Walking model with backpack load

The first part of the model deals with establishing the frequency of walking and the vertical motion of the torso when walking. These are later used to determine the pack stiffness and damping as well as the total excursion of the backpack relative to the person. To approximate the walking motion with a backpack, the inverted pendulum model can be used with parameters such as leg length, height, and walking speed. Although this model does not accurately predict torso and leg motion in all scenarios, it has been shown to be accurate when investigating walking under load on level surfaces [49]. Grieve and Gear have shown that the walking frequency of an individual can be related to the walking speed and height by the

$$\boldsymbol{\omega = \frac{4\pi * 64.8\left(\frac{v}{S}\right)^{0.57}}{60}} \qquad \textbf{Equation 2}$$

The motion of the torso can be determined expanding the inverted pendulum model and adding corrections for pelvic rotation, pelvic tilt, knee flexion, ankle position, foot length, and walking base [61]. Using Equation 3, the vertical amplitude of oscillation of the torso can be approximated.

$$A_t = \frac{l_0}{2}\left(1 - \sqrt{1 - \left[\frac{0.963v}{l_0 * 2 * 1.504 * \left(\frac{v}{l_0}\right)^{0.57}}\right]^2}\right) - 0.0157 l_0 \qquad \text{Equation 3}$$

4.5.2.2 Determining the desired stiffness and damping

To determine the optimum stiffness and damping, Hoover and Meguid defined the performance stiffness as the pack stiffness for which a change in damping would not change the oscillating load [49]. At stiffness values below the performance stiffness, the oscillating load is reduced; additionally, if the stiffness is below the performance stiffness, a reduction in damping will also reduce the oscillating load [49]. Therefore, when choosing an elastic material to build the pack, its stiffness, k_b, should be less than or equal to the performance stiffness solved for in Equation 4. Due to the linear dependence of stiffness on pack mass, a commercially viable suspended-load backpack would likely need to have variable stiffness. A k_b of 1,000N/m and a c_b of 100 Ns/m can theoretically reduce the oscillating load by up to 80% when the pack mass is 18.5kg, the subject is 1.78m tall, and the walking speed is about 5km/h [49]. Hoover and Meguid also determined that the maximum phase shift at about 95 degrees, found by Equation 5, occurs at the performance stiffness [49].

$$k_{performance} = \frac{1}{2} m_b \omega^2 \geq k_b \qquad \text{Equation 4}$$

$$\varphi_{max} = \operatorname{atan}\left(\frac{m_b c_b \omega}{{c_b}^2 - \frac{1}{2}{m_b}^2 \omega^2}\right) \qquad \text{Equation 5}$$

By choosing the pack stiffness to be at or below the performance stiffness and aiming to achieve a 90-degree phase shift, it is possible to calculate the corresponding damping coefficient for this scenario using equation 6.

$$c_b = \frac{m_b \omega \pm \sqrt{m_b^2 \omega^2 - 2 m_b^2 \omega^2 \tan^3(\varphi)}}{2\tan(\varphi)} \qquad \text{Equation 6}$$

As this project targets hikers in the weight range of 150-200 lbs, a range of stiffness values were calculated corresponding to these weights. Heights were estimated at each weight using a body mass index, BMI, table, the pack weight was selected at 30% of the total body weight, and the walking speed was chosen to be 5 km/h, or 3mph. Additionally, as discussed in section 2.5.1 the phase angle was chosen as 90 degrees. The results of this analysis are shown in Figure 27.

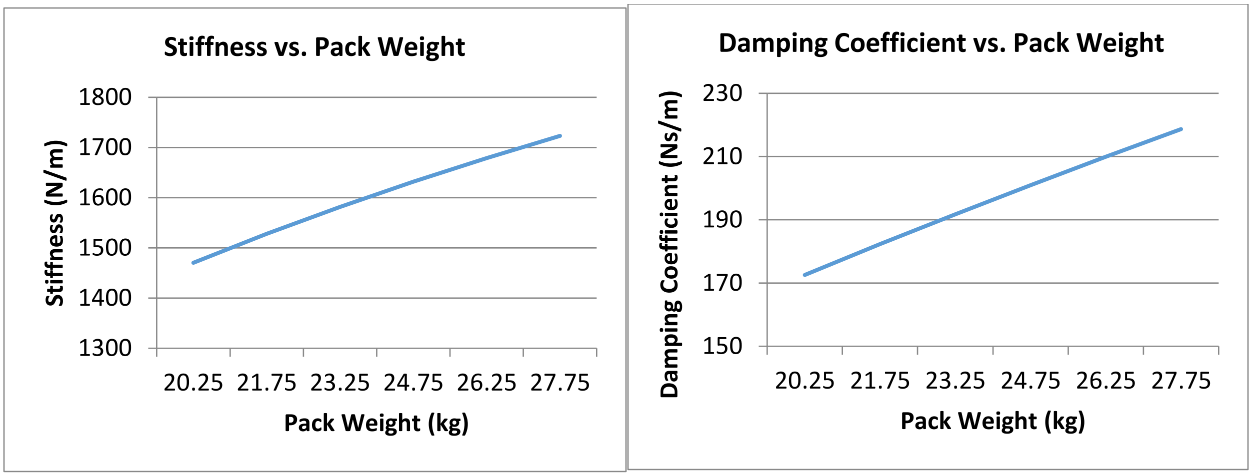

Figure 27: Desired stiffness and damping as functions of pack weight for total body weights in the range 150-200lbs.

Equations 2 through 6 allow the designer to perfectly optimize a suspension backpack, but in reality there are physical limitations to the pack that can cause sub-optimal minimization. The primary limitation is that the load can only undergo so much motion relative to the pack frame; this relative movement must be less than the total torso length of the pack. This relative movement is calculated using the following equation:

$$|x_t - x_b| = \sqrt{A_t^{\ 2} - 2A_tA_b cos(\varphi) + A_b^{\ 2}} \qquad \text{Equation 7}$$

Using the calculated stiffness and damping coefficients, the maximum excursion of the load was predicted and is shown in Table 8.

Table 8: Maximum excursion of the suspension

Stiffness (N/m)	Damping (Ns/m)	Suspension Excursion (in)
1470	173	0.77
1528	182	0.76
1582	192	0.75
1632	201	0.74
1679	210	0.72
1723	219	0.71

4.5.2.3 Elastic component configuration

In selecting the elastic component of the suspension, it was necessary to choose something light, flexible, and weather resistant. For these reasons, EPDM-rubber elastic cord was chosen as the material. Since this elastic cord does not have a constant linear stiffness like a spring, the stiffness properties were verified using an Instron tensile testing machine. As discussed earlier, the suspension has more than one elastic cord to better distribute the load to the frame. Placing multiple cords in parallel results in a total stiffness that is the sum of the individual stiffnesses.

Samples of 5/16" cord of varying lengths were inserted into an Instron tensile testing machine and stretched at a rate of 100mm/min while the force applied was measured. This testing revealed a linear relationship between initial length and stiffness with stiffnesses ranging from below the desired stiffness to far above it. The relationship between cord length, stiffness, and number of cords is described by Equation 8 which is derived from the generalized Hooke's Law. In this equation, *k* is the total suspension stiffness calculated above, *E* is the elastic modulus, *A* is the cross-sectional area of the cord, *n* is the number of elastic cords used, and *l* is the initial unstretched length.

$$l = \frac{EAn}{k} \qquad \text{Equation 8}$$

Based on Equation 8, as the number of cords is increased the length of each cord increases because longer cords are more flexible. The cord length is constrained by the torso length of the backpack which was chosen to be about 25 in. Thus, in order to have the maximum number of cords while staying in this length range, the maximum number of cords possible is 6 cords. Figure 28, below, shows the relationship between cord length and stiffness.

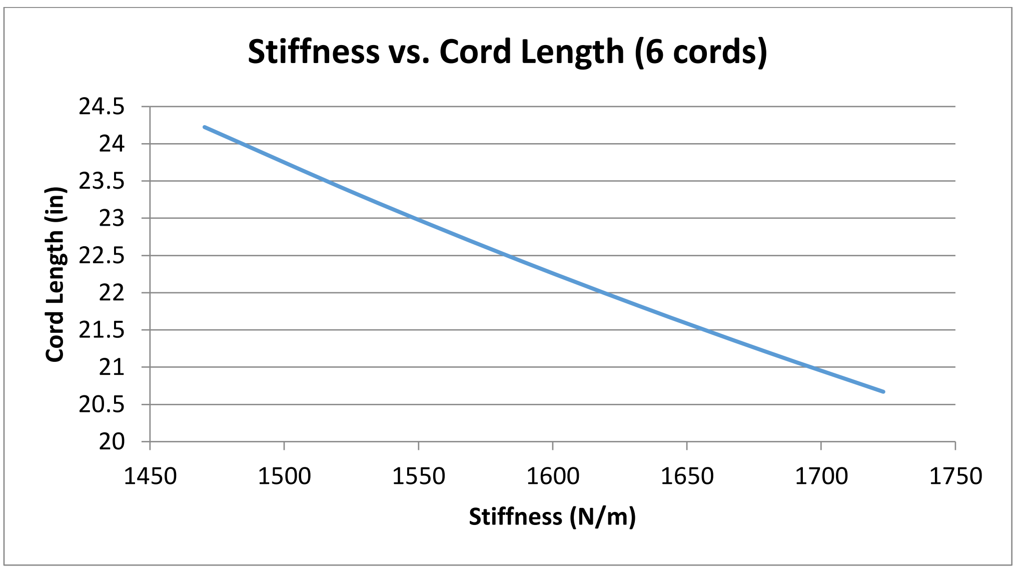

Figure 28: Cord length as a function of stiffness for 6 total cord segments

4.5.3 Pivoting Hip Belt

The final design of the pivoting hip belt feature is shown below in Figure 29. A small cylindrical piece was constructed out of Delrin to be the attachment point of the hip belt and piece of HDPE that connected towards the bottom of the frame. A hole was cut through the hip belt and the inner circular extrusion of the pivoting piece secured the belt to the HDPE portion of the pack. Nylon washers were used to clamp the pivoting unit together and reduce friction.

Figure 29: (Left) Exploded view of the pivoting unit assembly. (Right) Image of the assembled unit.

To transfer the load to the hips, the ends of the frame were connected into two smaller pockets of the hip belt. To allow the hip belt to pivot while maintaining this attachment, the ends of the frame needed to be able to contract in length as the hip belt rotated. To accomplish this springs were attached to the ends of the frame before securing the frame into the hip belt.

4.6 Manufacturing of the Prototype

4.6.1 Load Plate

The load plate, made of HDPE, was manufactured by cutting the 1/8" HDPE with shears and bending portions with applied pressure and heat from a heat gun. The pack was fixed to the load plate using heavy duty Velcro, which holds 5 pounds per square inch. Holes were drilled along the sides of the load plate to accommodate both the fabric loops for attaching the plate to the frame and for the lower mount rod for the elastic cord.

4.6.2 Frame

The frame was manufactured by bending ¼" 7075 Aluminum rods using a manual pipe bender. A jig was created with plywood and 2 x 4s to ensure that the final bent frame was bent to the correct angles. Each individual bend was checked both with a protractor and with the jig.

4.6.3 Pivoting Hip Belt

The pivoting portion of the hip belt was manufactured with a lathe and the holes were threaded with a tap. Small aluminum tubes were cut and crimped so that they would fit within the inner diameter of the springs chosen. The uncrimped end of the tube was then inserted over the end of the frame and a hole was drilled to bolt the spring units to the frame. The fabric pockets of the Osprey pack were repurposed and sewn on to the REI hip belt to allow for a place to insert the frame into the hip belt. Additionally, small nylon strap pieces were sewn around the pockets to constrain the pocket to remain close to the hip belt.

4.6.4 Assembly

With the major components manufactured and assembled, the entire backpack was assembled. First the fabric loops were created by cutting nylon straps and adding grommets. These were bolted to the load plate, two on each side. The lower elastic mount was then inserted and fixed in place using shaft collars. The frame was then inserted into the fabric loops and the repurposed shoulder harness was slid onto the frame. Mesh was then sewn and slid onto the frame below the lower fabric loop to provide a place for the person's back to rest. Some of the foam padding from the Osprey pack was also sewn to this mesh; this padding also contained some Velcro to attach to the shoulder harness. The HDPE piece for mounting the hip belt was then fixed to the frame using tube clamps. The hip belt was attached to the mounting plate with bolts. The EPDM elastic was then attached between the lower elastic mount and the top of the frame. This was done using pairs of tube clamps, one clamp with EPDM cushion clamping the frame and one clamp without cushions clamping the elastic cord. As the whole elastic system was a single piece of cord, the tension of each segment could be adjusted by pulling the cord through the clamps. Once the appropriate tension was achieved, the ends of the cord were secured with hose clamps. Finally, the backpack compartment from the Osprey pack was attached to the load plate with industrial strength Velcro. The final assembled pack can be seen in Figure 30.

Figure 30: Final assembled pack

Chapter 5: Design Verification

This backpack design was tested to evaluate the effect of loading on the body and fatigue. Five male subjects were recruited to participate in an institutionally approved motion capture and fatigue study. Two experiments were conducted on each subject. Experiment 1 consisted of having the subject walk across a wooden ramp instrumented with two AMTI force plates. The subject was marked with 18 markers and video footage was recorded to determine kinematic data and was fitted with single axis accelerometers to measure vertical acceleration. The subject walked across the ramp with both the experimental and control backpacks. Experiment 2 consisted of having the subject walk on an inclined treadmill, at 15% incline, at 3 mph for 20 minutes for each pack to assess fatigue.

Both experiments were designed to assess the backpacks performance in five categories: posture, compression and shear at the lumbosacral joint, vertical ground reaction force, oscillating load, and fatigue.

5.1 Assessing Backpack Design

5.1.1 Evaluating the performance of the suspension

As discussed in Section 4.5.2, the suspension characteristics were determined by choosing the appropriate length and number of cord segments. Due to the complex nature of the entire backpack system, it was useful to validate the stiffness of a suspended-load backpack after it had been constructed. To accomplish this, tensile tests were conducted on segments of elastic cord equal in length to those used in the final suspension configuration. The results of this testing are shown below in Figure 31. In total the actual suspension was about 12-13% stiffer than predicted by the model. For subject testing, a segment length of 18 inches was used which resulted in a total stiffness of 2256 N/m, which was outside the desired range of 1470-1720 N/m. This discrepancy is discussed in more detail in Chapter 7.

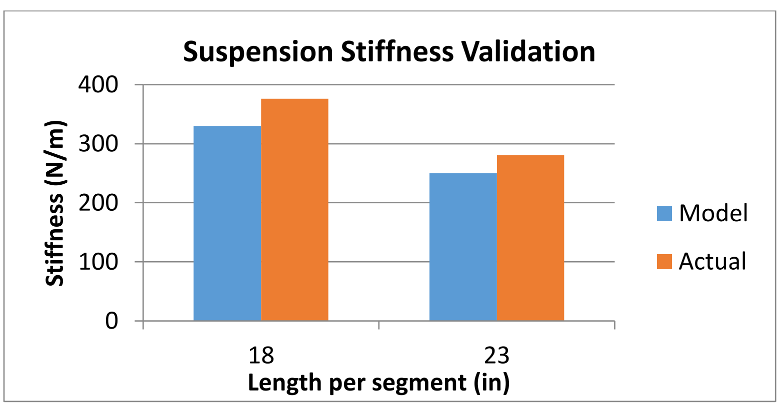

Figure 31: Validation of elastic component of the suspension using an Instron tensile testing machine.

5.1.2 Approximating energy expenditure

Accurately measuring energy expenditure can be a difficult and expensive task, as the most accurate method requires expensive equipment to measured oxygen consumption. An alternative method for measuring energy expenditure approximated oxygen consumption through measurements of heart rate [53]. Based on the following equation, a person's oxygen consumption, as a percent of VO_{2max} (a measure of the maximum volume of oxygen consumed during an activity), can be approximated from Equation 9:

$$\%\boldsymbol{VO_{2max}} = \mathbf{1.49}\%\boldsymbol{HR_{max}} - \mathbf{57.8} \qquad \textbf{Equation 9}$$

5.1.3 Model of the forces at the lumbosacral joint

A free-body diagram is necessary to fully analyze the person/pack system. Figure 32 shows a free body diagram of the spine and lumbosacral. Although some of the weight of the backpack is distributed to the shoulders, it was assumed that the force of the backpack acts primarily as a moment around the L5-S1 joint, as seen in Figure 32. This FBD also assumes that the spine is a straight link undergoing bending and that the head acts in line with the trunk and thus does not create an additional moment. An anthropometric table was consulted to determine the approximate location of the center of mass of the HAT.

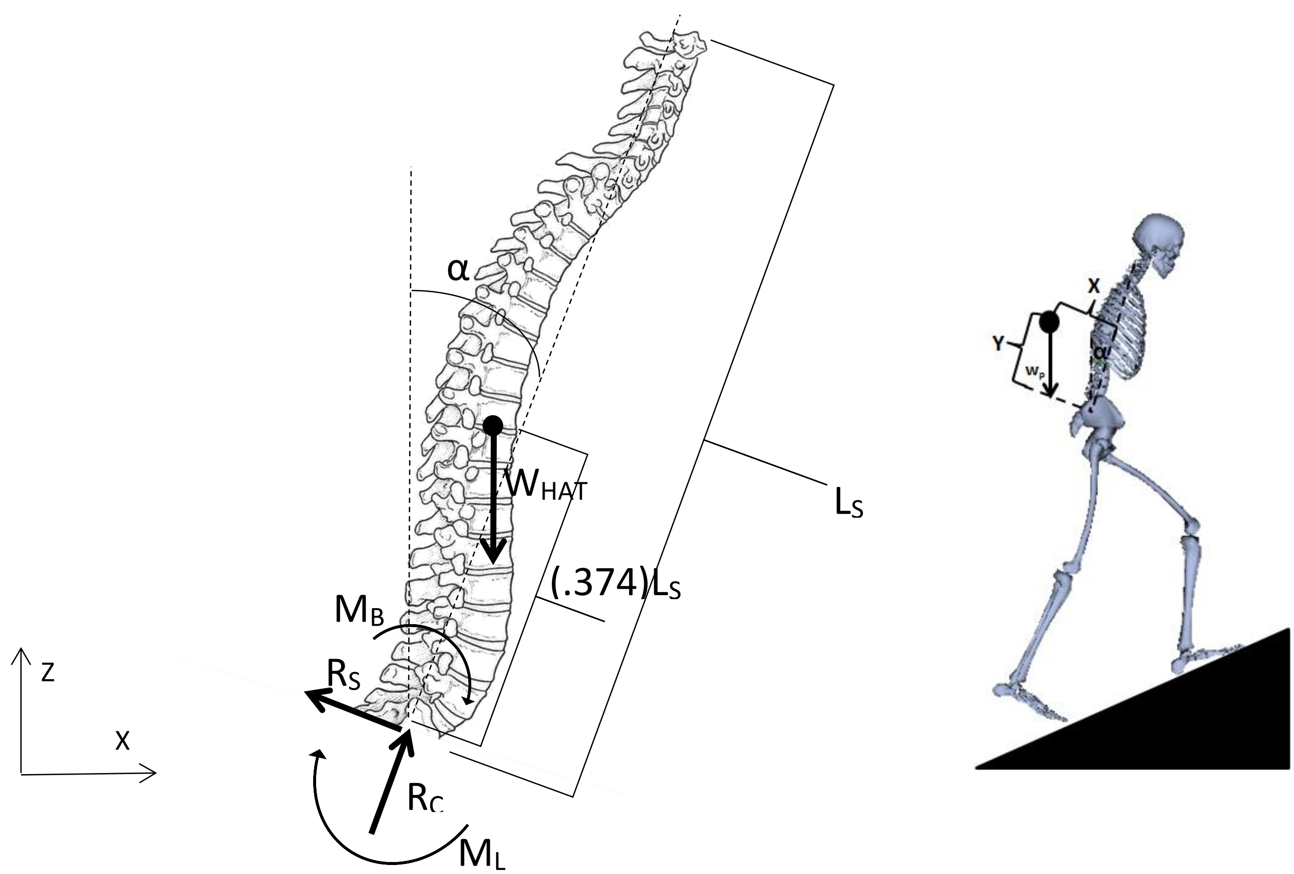

Figure 32: (Left) FBD of the lumbosacral joint. (Right) Diagram of the backpack COM

Table 9: Variables for Spinal FBD

Variable	Description
W_{HAT}	Weight of the head, arms, and trunk
m_b	Mass of backpack
R_C	Reaction force at L5-S1 joint through spinal column
R_S	Reaction force at L5-S1 joint, shear
L_S	Length of spine
α	Angle of forward lean measured from vertical
$(R_C)_z$	$(R_C)\cos(\alpha)$
$(R_C)_x$	$(R_C)\sin(\alpha)$
$(R_S)_z$	$(R_S)\cos(90 - \alpha)$
$(R_S)_x$	$(R_S)\sin(90 - \alpha)$
M_B	Moment from the backpack
M_L	Reaction moment at the lumbosacral joint
a_x	Horizontal acceleration of the HAT
a_z	Vertical acceleration of the HAT
α_{HAT}	Angular acceleration of the HAT
X	Distance off the spine to the HAT CoM
Y	Distance up the spine from the lumbosacral joint to the HAT CoM

The variables and corresponding descriptions of the diagram are detailed above in Table 9. The reaction forces, $\mathbf{R_s}$ and $\mathbf{R_c}$, at the lumbosacral joint are the most important unknowns. During bending, the spinal angle, α, changes based on posture; in the case of the backpack load, it corresponds to the angle of forward lean [69]. According to this model, the area below the L5-S1 joint at the lumbosacral disk is a hinge for the spine. A reaction force from the sacrum acts both through the $\mathbf{R_C}$, and in shear on the L5-S1 joint, $\mathbf{R_S}$. The weight of the head, arms and trunk, $\mathbf{W_{HAT}}$, acts at a distance 37.4% of the spine, up from the L5-S1 joint. The weight of the pack acts on the L5-S1 joint through a moment $\mathbf{M_b}$. The linear and angular accelerations of the HAT are determined through kinematic analysis of motion capture data. From this free body diagram, the equations of dynamic equilibrium can be created and used to solve for the unknown forces. Equation 13 is derived from the geometry provided in the right-hand diagram of Figure 32. In Equation 13, X and Y were determined to be 50% of the thickness of the backpack and 40% of the height of the backpack up from the hip respectively due to the uniform packing of the backpack. Although this was not a perfect method of locating the center of mass, an error of 10% in location for both X and Y only results in a change of 10 Nm for M_{L5}, which is only 1% or less of the actual value of M_{L5}.

$$\sum \boldsymbol{F_z} = \boldsymbol{R_{Cz}} + \boldsymbol{R_{Sz}} - \boldsymbol{W_{HAT}} = \boldsymbol{m_{HAT}a_z} \quad \textbf{Equation 10}$$

$$\sum \boldsymbol{F_X} = \boldsymbol{R_{Cx}} + \boldsymbol{R_{Sx}} = \boldsymbol{m_{HAT}a_x} \quad \textbf{Equation 11}$$

$$\sum \boldsymbol{M_{L5}} = \boldsymbol{M_B} + \boldsymbol{M_L} - [(\mathbf{0.374}\boldsymbol{L_5}\cos(\mathbf{90} - \boldsymbol{\alpha})\,\boldsymbol{W_{HAT}}] = \boldsymbol{I_{HAT}\alpha_{HAT}} \quad \textbf{Equation 12}$$

$$\sum \boldsymbol{M_B} = \boldsymbol{W_B}\,[\boldsymbol{X}\cos(\propto) - \boldsymbol{Y}\sin(\boldsymbol{\alpha})] \quad \textbf{Equation 13}$$

5.3 Results

The data collected for Experiment 1 and Experiment 2 were broken down based on the performance specifications detailed in Table 1 of Section 3.2.2. The performance specifications evaluated by the experiments are posture, compression and shear at the lumbosacral joint, oscillating load, total vertical GRF, and fatigue. Data were gathered to assess how the performance of the experimental backpack compared to that of the control. The results of all five subjects were evaluated separately and averaged to get a holistic comparison between backpacks. Data collection for each parameter was either quantitative, qualitative, or both, and the results for each are presented below.

5.3.1 Total Vertical GRF

Force plate data were gathered at a frequency of 60 Hertz to an accuracy of 1 Newton. The data were used to compare the total vertical ground reaction force in both the Z and X directions, vertical and horizontal, for each subject for both the control and experimental backpack. Table 10 and Table 11 show the peak GRF at the toe-off instance for each subject and a subject comparison via percent difference with statistical analysis. A right-tailed paired t-test was performed to determine statistical significance. The null hypothesis was that the difference would be less than zero and an alpha value of 0.05 was considered significant.

Table 10: Total GRF for each subject

Subject	Control				Experimental			
	Avg. GRFz		Avg. GRFx		Avg. GRFz		Avg. GRFx	
	Left (N)	Right (N)	Left (N)	Right (N)	Left (N)	Right (N)	Left (N)	Right (N)
1	860	970	211	246	867	949	222	243
2	994	1150	244	297	999	1136	184	290
3	998	1072	202	262	1036	1091	235	242
4	838	1085	230	302	876	1003	225	276
5	1047	1169	206	246	1040	1030	189	233

Table 11: Subject comparison and t-tests for total GRF

		In Subject Comparison			
		GRFz Diff (%)		GRFx Diff (%)	
		Left	Right	Left	Right
		-1	2	-5	1
		0	1	25	2
		-4	-2	-17	7
		-4	8	2	9
		1	12	8	5
Paired T-test Statistics (Null Hyp.	**Total Diff Avg.**	-2	4	3	5
	Total Diff SD	2	5	15	3

= u < 0) (a < .05) (Right Tail)	**Total Diff SE**	1	2	7	1
	Total T-Score	-2	2	0	3
	P - Value	**0.924**	**0.079**	**0.366**	**0.014**

5.3.2 Compression and Shear at the Lumbosacral Joint

Motion capture data was used to calculate the compression and shear forces, R_c and R_s respectively, at the lumbosacral joint as per Equations 10-13. The motion capture data was used to determine the forward lean angle, horizontal acceleration of the torso, vertical acceleration of the torso, and angular acceleration of the torso. The procedure for calculating the accelerations can be found in Appendix F. The weight and moment of inertia of the HAT was determined using an anthropometric table [21]. The length of the torso was measured according to Section 3.3.2.2. Table 12 presents the shear and compression for both test conditions and for both left and right toe-off events. Table 13 presents the percent difference between the control and experimental, experimental minus control, and test statistics. A left-tailed paired t-test was performed on the percent difference for shear and compression between the control and experimental. The null hypothesis was that the difference between the control and experimental was positive, indicating that the control performed worse than the experimental. An alpha value of 0.05 was considered significant. In the case of the shear data, the average shear for each subject was calculated only as a magnitude as the direction occasionally switched; the significance of this change in direction is discussed in more detail in Chapter 7. An alpha value of 0.05 was considered significant. In the case of the shear data, the average shear for each subject was calculated only as a magnitude as the direction occasionally switched; the significance of this change in direction is discussed in more detail in Chapter 7.

Table 12: Shear and compression forces for each subject

Subject	Control				Experimental			
	Avg. Shear		Avg. Compression		Avg. Shear		Avg. Compression	
	Left (N)	Right (N)	Left (N)	Right (N)	Left (N)	Right (N)	Left (N)	Right (N)
1	206	328	421	574	143	180	471	652
2	275	329	738	545	399	183	635	737
3	250	117	710	894	88.6	183	479	690
4	154	317	578	353	171	229	487	489
5	264	305	641	1022	362	297	547	648

Table 13: Subject comparison and T-test statistics for shear and compression forces

In Subject Comparison			
Shear Diff (%)		Compression Diff (%)	
Left	Right	Left	Right
-31	-45	12	14
45	-44	-14	35

		-65	56	-33	-23
		11	-28	-16	39
		37	-3	-15	-37
Paired T-test Statistics (Null Hyp. = u > 0) (a < .05) (Left Tail)	**Total Diff Avg.**	0	-13	-13	6
	Total Diff SD	46	42	16	34
	Total Diff SE	21	19	7	15
	Total T-Score	0	-1	-2	0
	P - Value	0.494	0.270	0.071	0.635

5.3.3 Oscillating Load

Single axis accelerometers were used to evaluate the performance of the suspension system in the experimental backpack as compared to the control. Accelerometers were placed on the subject and on each backpack for both testing conditions, and data collected at 60Hz were analyzed for Experiment 1. The data was analyzed according to the procedure outlined in Appendix G. In MATLAB, peaks and valleys were determined as values greater than 25% of the maximum peak; outliers were considered to be any point greater than 1.5 times the interquartile range of the peaks. The number of peaks selected for each trial was determined by visually inspecting the plot of the torso acceleration and identifying peaks, as this acceleration followed a clear sinusoidal pattern.

The acceleration of the person is plotted against the acceleration of the experimental pack, relative to the person, as seen below in Figure 33; the triangles and circles were generated by MATLAB and represent the peaks and valleys, respectively. A left-tailed paired t-test was performed to determine statistical significance. The null hypothesis was that the difference would be positive and an alpha value of 0.05 was considered significant. Table 14 shows the comparison in oscillating load between the experimental and control backpacks.

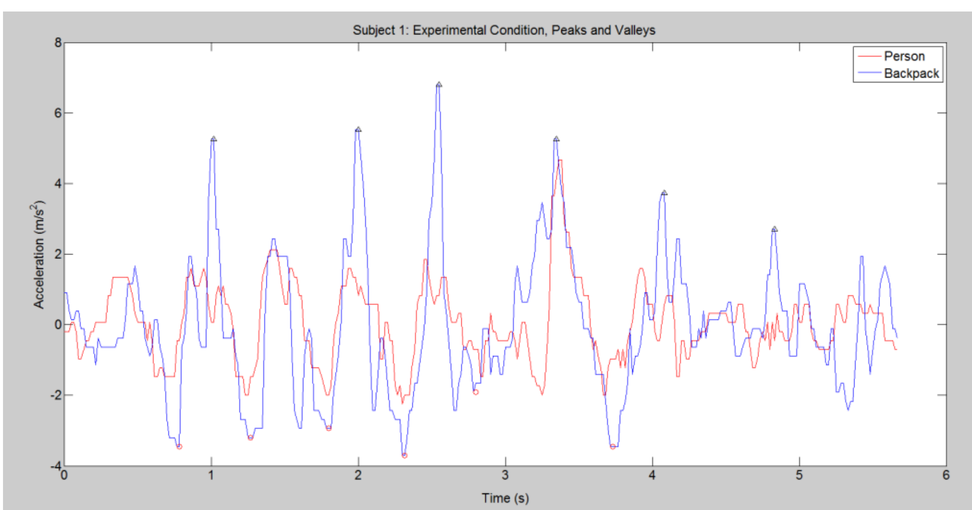

Figure 33: Acceleration Comparison

Table 14: Percent difference comparison of peak and valley accelerations in control vs. experimental

Subject	Control Accel. (m/s^2)		Experimental Accel. (m/s^2)		% Difference	
	Peak	Valley	Peak	Valley	Peak	Valley
1	6.0	-3.8	5.1	-3.1	-14.8	-17.0
2	4.0	-4.7	2.3	-4.6	-41.6	-0.7
3	2.4	-2.4	2.5	-1.6	4.4	-33.3
4	3.3	-2.9	1.8	-4.1	-45.2	41.2
5	4.1	-4.0	4.5	-5.1	9.8	28.2
				Mean	-17.5	3.7
				Std. Dev	25.4	30.9
				SE	5.1	6.2
				T-Score	-3.4	0.6
				P-Value	**0.013**	**0.708**

When evaluating the performance of a suspended-load backpack, it is useful to the compare the oscillating force produced by the suspension pack with that of a conventional pack. Hoover and Meguid note that the ideal suspension backpack reduces the oscillating load ratio, B, to zero; when B=1, the packs are performing identically [49].

$$F_{osc} = m_b(a_{b}\_suspended) \quad \text{Equation 14}$$

$$F_{osc\_rigid} = m_b(a_{b}\_rigid) \quad \text{Equation 15}$$

$$B = \frac{|F_{osc}|}{|F_{osc}|_{rigid}} \quad \text{Equation 16}$$

Using Equations 14, 15, and 16, defined above, an oscillating load ratio was calculated for both the valley accelerations and the peak accelerations for each subject. The ratio was calculated for a single time point, the maximum peak or valley acceleration. Table 15 and

Table 16 show the B values for each subject, as well as the mean B value, for the valley and peak accelerations, respectively.

Table 15: Oscillating load ratio for valley accelerations

Subject	Subject Weight (kg)	Backpack Weight (kg)	Avg. Valley Acceleration (m/s^2)		Rigid Force (N)	Oscillating Force (N)	Oscillating Load Ratio, B
			Control	Experimental			
1	71.2	21.4	-3.8	-3.1	-80.2	-66.6	0.8
2	76.2	22.9	-4.7	-4.6	-107	-106	1.0
3	79.8	23.9	-2.4	-1.6	-58.1	-38.8	0.7
4	66.2	19.9	-2.9	-4.1	-57.1	-80.6	1.4
5	90.7	27.2	-4.0	-5.1	-109	-140	1.3
						Mean	**1.0**

Table 16: Oscillating load ratio for peak accelerations

Subject	Subject Weight (kg)	Backpack Weight (kg)	Avg. Peak Acceleration (m/s^2)		Rigid Force (N)	Oscillating Force (N)	Oscillating Load Ratio, B
			Control	Experimental			
1	71.2	21.4	6.0	5.1	127	108	0.9
2	76.2	22.9	4.0	2.3	91.0	53.1	0.6
3	79.8	23.9	2.4	2.5	57.0	59.6	1.0
4	66.2	19.9	3.3	1.8	65.4	35.9	0.5
5	90.7	27.2	4.1	4.5	110	121	1.1
						Mean	**0.8**

Hoover and Meguid developed Equation 17 to calculate the force created by just the oscillating load [49]. This equation was used to compare the measured oscillating force to the theoretical, and relies on the mass of the backpack (m_b), walking frequency (ω), vertical amplitude of the torso (A_t), equivalent pack stiffness (k_b), and the equivalent pack damping coefficient (c_b) to calculate an oscillating force, F_{osc} which serves to predict the performance of the suspended-load system. This equation assumes that the person walks at a constant speed and that this walking induces a periodic vertical movement of the torso. The purpose of using this equation is to check the validity of the model as it was used to design the backpack; thus, the final results should match up with the model. This comparison is presented in Table 17.

$$|F_{osc}| = m_b \omega^2 A_t \sqrt{\frac{\left({k_b}^2 + \omega^2 {c_b}^2\right)}{\left(k_b - m_b \omega^2\right)^2 + \omega^2 {c_b}^2}} \qquad \text{Equation 17}$$

Table 17: Comparison of oscillating load calculated from the model to that of the experimental results

Subject	F_{osc} Model (N)	F_{osc} Measured (N)	Percent Diff (%)
1	56.6	87.5	54.6
2	54.9	79.7	45.1
3	65.0	49.2	-24.4
4	52.6	58.2	10.6
5	70.4	130	85.4
		Mean	34.3
		Std. Dev.	42.3

5.3.4 Fatigue

To evaluate levels of fatigue for each subject during the treadmill sessions in Experiment 2, heart rate data were gathered, once every 2 minutes for 20 minutes, and a qualitative survey was conducted after each backpack condition. The heart rate data were converted to $\%VO_{2max}$ using Equation 9 and the mean difference and standard deviation between each condition of

Experiment 2 for each subject is shown in Table 18 A right tailed paired t-test was performed to determine statistical significance of the %VO_{2max} data with the null hypothesis being that the difference between control and experimental was negative. An alpha value of 0.05 was considered statistically significant.

Table 18: Mean difference and standard deviation of %VO_{2max} data for original testing

	Subject	Mean Diff (%)	Std. Dev
	1	4	2
	2	8	4
	3	11	3
	4	14	3
	5	5	1
Paired T-test Statistics (Null Hyp. = u < 0) (a < .05) (Right Tail)	Mean	8	
	Std. Dev	4	
	SE	2	
	T-Score	4	
	P-Value	**0.006**	

After completing the fatigue testing in the original order, control condition first followed by the experimental condition, the testing was repeated with three of the subjects but in the reverse order. This re-testing was designed to investigate a "warm-up" effect and try to validate the positive impact of the experimental pack as indicated in Table 19. Again, a right tailed paired t-test was performed to determine statistical significance of the heart rate data with the null hypothesis being that the difference between control and experimental was negative. An alpha value of 0.05 was considered statistically significant.

Table 19: Mean difference and standard deviation of %VO2max data for re-testing with reverse order of conditions

	Subject	Mean Diff	Std. Dev
	1	-5	5
	2	-3	2
	5	2	4
Paired T-test Statistics (Null Hyp. = u < 0) (a < .05) (Right Tail)	Mean	-2	
	Std. Dev	4	
	SE	2	
	T-Score	-1	
	P-Value	**0.778**	

In addition, vertical impulse calculations were performed on the force data from Experiment 1 to acquire another indication of energy consumption. The impulse was calculated by numerically integrating the force vs. time curve for a single step, so from the moment the foot makes contact with the force plate to the moment it leaves the force plate. A two-tailed paired t-test was performed on the impulse data with the null hypothesis being that there was no difference in conditions; the alpha value was 0.05.

Table 20: Impulse comparison with T-test evaluation

Subject	Control		Experimental		% Difference	
	Plate 1 Impulse (Ns)	Plate 2 Impulse (Ns)	Plate 1 Impulse (Ns)	Plate 2 Impulse (Ns)	Plate 1 Difference (%)	Plate 2 Difference (%)
1	964	970	950	946	-1	-3
2	1065	1090	1148	1159	8	6
3	1116	1208	1122	1249	1	3
4	801	755	770	774	-4	2
5	922	940	966	968	5	3
			Paired T-test Statistics (Null Hyp. = u = 0) (a < .05) (Two Tail)	Mean	2	3
				Std. Dev	5	3
				SE	1	1
				T-Score	2	4
				P-Value	**0.916**	**0.992**

To get one more quantitative measure of fatigue, the joint moment at the lumbosacral joint was calculated, using Equation 12, for each subject and the percent difference between experimental and control was determined. The joint moment provides an indication of how active the muscles surrounding that joint must be; a smaller moment indicates lower muscle activity, as the muscles surrounding that joint must supply the forces necessary to counter that moment. While it is assumed that lower muscle activity may indicate lower energy, this effect may be highly localized and outweighed by muscle activity elsewhere. A left tailed paired t-test was performed on the percent differences to determine statistical significance. The null hypothesis was that the mean difference would be positive, indicating worse performance by the experimental, and an alpha value of 0.05 was considered significant.

Table 21: Lumbosacral joint moments for all subjects

Subject	Control		Experimental		In Subject Comparison	
	Joint Moment (Nm)		Joint Moment (Nm)		Joint Moment Diff (%)	
	Left	Right	Left	Right	Left	Right
1	6769	8753	1317	3019	-81	-66
2	26597	7378	5952	5461	-78	-26
3	8229	8399	1078	3389	-87	-60
4	7611	6511	4295	7191	-44	10
5	4708	15385	2579	10740	-45	-30
		Paired T-test Statistics (Null Hyp. = u > 0) (a < .05) (Left Tail)		Total Diff Avg.	-67	-34
				Total Diff SD	21	30

	Total Diff SE	9	14
	Total T-Score	-7	-3
	P - Value	**0.001**	**0.033**

A qualitative survey was given to the subjects after each portion of the fatigue testing in Experiment 2. Subjects rated their level of discomfort for each of 14 anatomical regions, selecting that they felt "pain," "discomfort," or "nothing." Table 22 displays a comparison between all the subjects, a dash indicates that there was no difference in pain/discomfort between conditions, more indicates more pain/discomfort with the experimental backpack, and less indicates less pain/discomfort.

Table 22: Qualitative survey results comparison

Anatomical Region	**Pain/Discomfort Comparison**				
	1	**2**	**3**	**4**	**5**
Neck	-	-	-	-	-
Shoulders	-	-	-	More	-
Upper Back	-	-	-	-	-
Lower Back	-	-	-	-	-
Elbow, Right	-	-	-	-	-
Elbow, Left	-	-	-	-	-
Wrist/Hand Right	-	-	-	-	-
Wrist/Hand Left	-	-	-	-	-
Hips/Thighs Right	-	-	Less	-	Less
Hips/Thighs Left	-	-	Less	-	Less
Knee, Right	-	-	-	Less	-
Knee, Left	-	-	-	-	-
Ankle/Foot, Right	-	-	-	Less	-
Ankle/Foot, Left	-	More	-	-	-

Videos were recorded for the first and last 30 seconds of each fatigue test. These videos were used to visually detect and compare fatigue in control and experimental trials. In comparing the beginning and end of each trial in Figure 34, the subject visually exhibits a smaller change in forward lean with the experimental pack. However, the subject in Figure 35 shows negligible gait differences between the beginning and end of both trials. These two image sequences are representative of the other subjects.

Control- Beginning | Control- End | Experimental- Beginning | Experimental- End

Figure 34: Subject 3 Fatigue Testing

Control- Beginning | Control- End | Experimental- Beginning | Experimental- End

Figure 35: Subject 2 Fatigue Testing

5.3.5 Posture

To measure the effect of each backpack on posture, specifically degree of forward lean, the program ImageJ was utilized to pinpoint the 18 markers used for each subject. These locations were input into an Excel macro that calculated forward lean angle; this angle is defined as the angle between the vertical and the line connecting the sternum and pelvic markers. The calculated angles were used to verify that all subjects demonstrated a forward lean within the range of 10-30 degrees; Table 23 shows that all subjects except one were within this range.

Table 23: Degree of Forward Lean

Subject	Control		Experimental	
	Forward Lean		Forward Lean	
	Left Toe-off (Deg)	Right Toe-off (Deg)	Left Toe-off (Deg)	Right Toe-off (Deg)
1	14	15	18	16
2	21	25	16	18
3	7	10	11	13
4	16	21	24	21
5	25	25	24	25

Chapter 6: Final Design and Validation

6.1 Design Process

The first step in the design process was to develop an understanding of customer needs. Utilizing a design matrix and potential user surveys, the most important features were determined. To incorporate these features, the team worked to develop a backpack that met customer expectations as well as project objectives. This pack utilized current industry standards as a guideline for size, features, and function. Once the designing phase was completed, the team purchased an Osprey backpack to deconstruct and use as the base for the experimental pack. This pack was selected because the same model was available for use as a control pack.

After developing a design that met customer needs and was on par with industry standards, the team worked to produce a model in SolidWorks. Each component that was manufactured throughout the build process was first designed in SolidWorks, including the frame, load plate, and pivoting portion of the hip belt. The frame was designed to fit within the size of the purchased pack, be easily manufactured, and be strong enough to withstand loads of 50-70lbs. The load plate was designed based off the size and shape of the actual pack and the size and shape of the frame. The final parts were then assembled within SolidWorks to ensure fit and to check measurements.

After designing the pack and the various components in SolidWorks, the team worked to understand different material properties to select the best material for each piece. Research into current hiking packs showed that aluminum is a common material used for frames due to its high strength to weight ratio. With this information and after investigating various material properties of aluminum, Aluminum 7075 was selected for its high tensile strength. For the load plate, the team selected High Density Polyethylene (HDPE) because of its strength and moldability properties. Finally, Delrin was selected for use in the pivoting hip belt because of its easy accessibility, low friction, and durability.

To determine the correct length of rubber tubing, the team utilized an Instron tensile testing machine to test various lengths of tubing. Once tested, the correct length of rubber and looping configuration was selected to meet the desired elasticity, detailed in Section 4.5.2. Due to the elastic modulus of the elastic cord used, longer segments were needed to achieve the appropriate total linear stiffness. Using this information, the lower elastic attachment rod of the load plate was moved lower to accommodate the increased length of the rubber tubing.

To create the load plate, the design was sketched onto the HDPE and cut with sheet metal shears. The sheet was then heated with a heat gun and bent using a vice. Holes were then drilled to locate the lower elastic attachment rod and linear bearings. Bending the aluminum rod for the frame was more challenging. Ultimately, the rod was bent using a manual pipe bender and a jig to check each angle individually and in relation to all the other angles. The pieces of the pivoting hip belt were made using a manual lathe and tap. The hip belt plate was made using the same method as the load plate. To attach the load plate to the frame, loops were created using grommets and nylon straps. Additional hardware was ordered to assemble the pack.

Once all the pieces were acquired or manufactured, the pack was assembled. Slight modifications were made to the pack throughout the assembly process to ensure correct fit, function, and ease of manufacturability. In terms of ensuring correct fit, the load plate was made narrower to better match the size of the backpack and a small foam pad was added on top of the pivot point of the hip belt. To address proper function aluminum collars were added inside of the fabric bearings to reduce friction on the suspension, two small standoffs were added, one behind the shoulder harness and one behind the hip belt, to prevent the elastic cords from being pinched when the wearer dons the backpack, and a heavy-duty canvas pocket was inserted into the hip belt where the frame inserted to prevent the frame from poking a hole in the hip belt fabric. Finally, to ensure easy manufacturing the angles of the frame changed to prevent stress fractures during bending.

6.2 Experimental Methods

Subject testing was performed to compare the performance of the experimental design to a currently existing backpack. Five subjects were recruited to perform two separate experiments. The data collected were used to compare fatigue, vertical GRF, forward lean, shear and compression at the lumbosacral joint, and the dynamic load of the oscillating pack. All testing was performed per IRB approved protocol that can be found in Section 3.3.2.

6.3 Analysis Methods

Analysis of subject testing data for Experiment 1 was broken up into three trials for each experimental and control test. Each trial captured an instance of the subject's right and left toe-off. For each toe-off instance, a GRF value was visually identified using the graphs output by AMTI-NetForce software, which output force data in the x, y, and z axis and the corresponding moments. This value was chosen under the assumption that the first peak in each gait cycle represented a heel strike, while the second peak represented toe-off. This data was exported to Excel, adjusted to account for the angle of the ramp on which the force plates were located, and analyzed to determine if there was a decrease in GRF from control to experimental. The adjustment was to align the z axis of the force plate with z axis of the laboratory reference frame using trigonometry.

For each toe-off instance, a corresponding series of images were exported from the motion capture footage at a frame rate of 25 frames/s. Three images were chosen to represent the instance before, during, and after the toe-off occurred; these three images were needed to determine the linear and angular acceleration, about the y axis of the laboratory frame, of the torso. So, most of the video footage went unused as for each subject only a total of 18 frames were selected for each test condition. The images for each trial where chosen off visual assumptions based on the location and orientation of the observed foot positioned to apply maximal force on the ramp. Specifically, the during toe-off image was chosen as the image during which the foot undergoing toe-off was not moving in the frame. The three consecutive images were spaced 0.04s apart which corresponds to 25 frames/s; although the camera was capturing at 60 frames/s the video editing software exported screenshots at 25 frames/s. The images were then imported into the image processing software ImageJ to determine the horizontal and vertical position of each motion capture marker. The positions of these points were imported into an Excel document to determine joint angles; the positions and angles were then imported into a second Excel document that calculated the joint forces and moments at the lumbosacral joint.

During each trial, accelerations of the backpack and the person were recorded using two single-axis accelerometers. The raw voltages captured were converted to accelerations based on the sensitivity, in mV/g, of each accelerometer. The accelerations were zeroed by subtracting the initial average acceleration of the subject while they were standing still. Once the accelerations were calibrated with respect to the subject, the acceleration of the subject was subtracted from the acceleration of the pack to determine the independent acceleration of the pack. This data was then passed through a median filter to reduce noise and imported into a custom MATLAB script, where the peaks and valleys were identified and averaged for all trials for each subject. These peak accelerations were used to determine the dynamic force of the oscillating pack.

Heart rate data was continuously recorded throughout the subject's fatigue testing, Experiment 2. Preliminary testing was done on an exercise bike to determine the subject's maximum heart rate. Two rounds of fatigue testing were then performed for the experimental and control pack, with a set amount of recovery time in between test conditions. The subject's heart rate was recorded every two minutes to analyze their change in heart rate throughout the duration of the trial. This heart rate data was then converted to a measure of oxygen consumption using Equation 9.

After fatigue testing was conducted for each pack, subjects recorded their opinion of the pack's performance in a qualitative survey. This provided information on the subject's perceived fatigue to compare to what the calculated data expressed.

6.4 External Impact

6.4.1 Health and Safety Issues

The goal of this project was to reduce injuries in long distance backpackers caused by carrying heavy loads. The purpose of the new backpack design was to optimize load carriage without posing additional health risks. By making use of an oscillating load and better distributing weight to the hips, this pack has the potential to reduce compression and shear in the lumbosacral joint, ideally reducing injuries in wearers of the pack. This potential reduction in injuries would increase the safety of long distance backpacking.

6.4.2 Manufacturability

Manufacturability on a mass scale was a lower priority during the design process of the prototype compared to functionality and ease of prototype creation given available resources and time. If this product were to become commercially available, modifications to the pack would be necessary to make the backpack more robust and easier to manufacture on a mass scale.

Chapter 7: Discussion

7.1 Total Vertical GRF

One of the desired performance specifications for the experimental backpack design was to reduce total vertical GRF by 33%. This specification was based on the results of Rome, Flynn, and Yoo who performed testing on a backpack design with an elastic bungee cord suspension system. Table 11 of Section 5.3.1 shows statistically insignificant results comparing the control and experimental packs in this study. In comparing the experimental to the control, there was an average decrease of 4% ± 5% for right toe-off instances and an average increase of 2% ± 2% for left toe-off instances. An 11% decrease was the greatest reduction calculated when comparing the right toe-off instances in subject 5. All other trials were recorded with less than a 10% change. Right and left toe off GRF are reported separately because, although small, there were differences in the data collected.

Rome, Flynn, and Yoo's suspension system increased the amount of displacement of the load relative to the frame, and therefore reduced the vertical movement of the load relative to the ground frame. This reduction in vertical movement contributed to the reduction in forces exerted during the energetically expensive double support phase of the gait cycle. The minimal and inconsistent change in GRF observed between control and experimental packs shows that the experimental suspension system is not allowing the load to move effectively relative to the frame.

There are various design elements of the pack analyzed by Rome, Flynn, and Yoo that may be allowing the system to function more efficiently as a whole, resulting in a greater reduction of GRF. Their design incorporates a pulley system when routing the elastic bungee cord. This would allow a continuous stretch to be accomplished by the entire length of the cord. The suspension could then be analyzed as a continuous unit, versus separate segments of elastic cord that the design in this study encompasses. In their design, the vertical rod the load plate glides on is isolated from the pack frame. Separating the moving component from the fixed frame allows for the suspension system to perform independently of how the pack is being secured to the subject's body. Their design also incorporates cam cleats which allows for the length of the elastic bungee cord to be altered. This could offer a more customizable approach to the design in its ability to correspond the length and stiffness of the suspension system more specifically to the user. These differences could be contributing to the success in reducing total GRF to the degree the design specifications were based off. However, while their system performs well in regards to the oscillating load, it is bulky and heavy and thus not a suitable solution for the backpackers targeted in this study.

Aspects of the experimental procedure could have introduced variation between the control and experimental GRF data. Variation in walking speeds between subjects introduces inconsistency when comparing trials. While subject speed was not monitored during any trials it was calculated after the fact; the average velocity was about 5.7km/h across all subjects and conditions. The variation in speed differs from the desired speed of 5 km/h. The average velocity during subject testing was both comparable to Rome, Flynn, and Yoo and within the range specified by Hoover and Meguid; therefore, the suspension should still be performing well. The fact that it is not performing well places further emphasis on the factors outlined in Section 7.3 in explaining the poor performance of the suspension. Testing two separate packs for the control and experimental conditions introduced more factors that could be causing variation within the performance analysis. Rome, Flynn, and Yoo used a single backpack during their testing which incorporated a locking mechanism that secured the load during the "control" trials. This allowed the comparison to focus on the effects of the suspension system alone. These two experimental differences in the referenced study allows for a more focused comparison in evaluating the performance of the suspension system directly.

7.2 Compression and shear at the lumbosacral joint

The experimental backpack was designed to reduce compression and shear by 60% based on the results of Goh et al. As seen in Table 13 of Section 5.3.2, the experimental backpack did not meet this requirement for shear or compression during either right or left toe-off instances observed. The mean percent difference for shear of the left foot toe-off was 0% ± 46%, and for shear of the right foot toe-off was –13% ± 42%. The compression mean percent difference was –13% ± 16% for the left foot toe-off and 6% ± 34% for the right foot toe-off. In this case a negative percent difference indicates that the experimental backpack is reducing these forces. Despite not meeting the performance specification for these instances, compression and shear was reduced by a small percentage in some cases. However, these small differences were not statistically significant. Much like the GRF reporting, right and left foot shear and compression are reported separately as there clear percent differences in the right and left foot shear and compression, however there were no consistent trends

One of the interesting results in regards to shear was that the direction of the calculated shear force was not consistent across all trials and subjects. Of the 60-total toe-off events analyzed, 80% resulted in a positive shear force, in agreement with the direction chosen in the model in Section 5.1.3. The observed change in shear direction can only be attributed to specific magnitudes of accelerations. Perhaps there is a more complex relationship underlying this result, but that is beyond the scope of this project.

The two major influences over shear and compression based on the model described in Section 5.1.3 are the vertical and horizontal acceleration of the torso and the forward lean angle of the torso. As seen in Table 27 in Section 5.3.1 there is a small increase, though statistically insignificant, in forward lean angle between the control backpack and experimental backpack across all the subjects. However, the linear acceleration of the torso exhibits much more variance across all subjects. The variance in accelerations result in varying inertial terms used in the equilibrium equations. This variation correspondingly affected the magnitude of the shear and compression forces.

Since these results show that the experimental backpack largely failed to meet the performance specification for compression and shear at the lumbosacral joint, improvements could be made to both the prototype and experimental design to better produce and capture the desired performance. The biggest improvement would be to adjust the suspension of the backpack so that it is effectively moving out of phase with the torso to reduce the total vertical load. Without reducing the vertical load, it is difficult to reduce joint loading. However, the results do show a small difference in shear and compression during some cases. This small reduction can be attributed to the way the experimental backpack more effectively transferred load to the hips. Another improvement to the experimental design would be to use a more accurate method of determining acceleration, as torso acceleration across the x-axis was the most important factor in determining shear and compression. The method used relied on manually locating motion capture markers in still frame, which is both tedious and introduces random errors. If a professional motion capture system, such as an infrared system, was used, the precision of the acceleration values would be increased and the source of error would be systematic as opposed to random.

Although the backpack did not meet the desired specification it is useful to compare the results to other literature on spinal loading. According to a 2005 CDC report, the maximum recommended compression at any vertebral disc is 3.4kN for any activity [70]. At compression levels above this threshold, back pain and spinal damage are extremely likely. For all control and experimental trials, both shear and compression are far below this threshold. As per this metric, neither backpack was inducing severe back pain and putting the subjects at risk.

7.3: Oscillating Load

The most important component of the suspended-load system evaluated in this study was the oscillating load itself. This component was analyzed using single-axis accelerometers with results presented in Section 5.3.3. The desired performance of this feature was to reduce the oscillating load by 80%, as this reduction was shown by Hoover and Meguid in a similar suspended-load backpack system. Hoover and Meguid predicted that with a spring constant of 1,000 N/m and a damping coefficient of 100 Ns/m, this 80% reduction would be possible under typical hiking scenarios. The results of the oscillating load analysis seen in Table 14 of Section 5.3.3 show that the experimental suspension system reduced peak accelerations by an average of 17.5% ± 25.4%, and increased valley accelerations by an average of 3.7% ± 30.9%, as compared to the control backpack. In the context of this study, peak accelerations are those which occur while the backpack is in the upward motion and reach a maximum, while valley accelerations occur when the backpack is moving downward and reach a maximum. The movement of the pack in the downward direction would contribute more to the total vertical loading. For this reason, the analysis results of the valley accelerations were more important than that of the peak accelerations. While the decrease in peak acceleration proved to be statistically significant, it did not reach the desired reduction of 80%; and the valley accelerations had the opposite desired outcome.

The peak and valley accelerations were used to calculate the overall performance of the experimental backpack via an oscillating load ratio. This ratio, taken from the suspended-load analysis performed by Hoover and Meguid, should be less than 1; indicating the oscillating forces were lower than the rigid forces. Results, shown in Table 15 and

Table 16 of Section 5.3.3, demonstrate that the oscillating load produced slightly larger forces on average in valley accelerations, with an oscillating load ratio of 1, while it generated lower forces for the peak accelerations with a ratio of 0.8. The average of these two ratios is 0.9, indicating that the experimental backpack performed slightly better than the control.

The model developed by Hoover and Meguid to calculate the theoretical oscillating force was used to compare the measured oscillating forces collected in this study to the theoretical. These results, seen in Section 5.3.3 in Table 17, show that the actual oscillating load was on average 34% higher than predicted by the model. Interestingly, this is not correlated with the 12-13% difference in stiffness between the ideal performance stiffness and the actual backpack. A 12-13% difference in stiffness should result in a 23% increase in oscillating load according to Equation 17, and thus there is an 11% increase in oscillating load that is not accounted for.

The inability of the oscillating load to perform as expected can be attributed to several shortcomings of both the design and the experimental set-up. The most influential design restriction found was that the attachment points of the shoulder harness on the frame acted as a mechanical stop for the fabric loops on the load plate. This restricted the vertical movement of the plate on the frame, reducing the distance the load plate could oscillate, and thus reducing the peak and valley accelerations of the pack. Due to this restriction, the oscillations of the backpack were not fully 90° out of phase with the movement of the person, as can be seen in the peak and valley graphs output by MATLAB and shown in Figure 33. One of the reasons for this was that the accelerometers were not perfectly vertical on the body or the pack, which could have resulted in inaccurate data collection. In addition, the testing situation in Experiment 1 for which acceleration data was collected was pseudo-static in comparison to fairly dynamic normal hiking conditions. Also, there was no quantitative speed control across trials for each a subject, as well as across subjects in Experiment 1. The suspended-load model was shown by Hoover and Meguid to be most accurate at walking speeds in the range of 3 to 6 km/h, with the best accuracy at 5 km/h. The inability to maintain consistent trial speeds likely played a role in not achieving consistent acceleration and in turn resulted in inconsistent data for the oscillating load.

7.4 Fatigue

The fatigue performance specification for the experimental design was to decrease with respect to the control backpack. Section 5.3.3 shows a statistical comparison of the results of both mental and physical fatigue between packs. The physical assessment of fatigue estimated oxygen consumption and muscle activity using data collected in subject testing. The mental assessment of fatigue is based upon subject questionnaires given post-testing of each backpack condition.

Evaluating heart rate involved taking heart rate measurements every 2 minutes for each 20-minute session in Experiment 2; analysis of this data was conducted by converting the heart rates to $\%VO_{2max}$ and taking the mean percent difference between the two conditions at each time point. This data, found in Table 18, indicates a statistically significant decrease in fatigue for the experimental condition. While this trend was in favor of the experimental design, results of the subject questionnaire challenged this. One of the subjects commented, “I felt noticeably less tired using the new backpack but I am unsure if this was because of the pack or already being warmed up.” This led to the re-testing for fatigue in the reverse order, walking first with experimental pack and then with the control pack, to investigate this "warm-up effect" theory. Three subjects were available to re-test, and results showed an increase in oxygen consumption for the experimental pack that was not statistically significant, see Table 19. From this testing, it was concluded that the warm-up effect was sufficient to influence results. With this knowledge, a longer testing time should be considered.

In testing the control pack first there was an 8% ± 4% VO_{2max} mean decrease between the control pack and the experimental pack; while there was a 2% ± 4 % VO_{2max} mean increase when the experimental pack was tested first. The results of the first-round testing were statistically significant, while the results of the second round of testing were not. This suggests that the experimental pack did in fact reduce fatigue, but by only about 6%. Due to the lack of statistical significance, more subjects would be needed to confirm this effect. While use of the VO_{2max} model, detailed in Section 5.1.2, provided a quantitative way to compare fatigue between subjects, equipment capable of directly measuring oxygen consumption would provide a more reliable estimate for this comparison.

Impulse calculations based on force plate data were also performed as a tertiary measure of energy consumption. However, given the insignificance of GRF data, this comparison, shown in Table 20, also proved to be insignificant between control and experimental packs. The difference in moments at the lumbosacral joint was then calculated as another estimation of fatigue, as large joint moments indicate more muscle activity surrounding the joint. For both left toe-off and right toe-off instances, there was a percent decrease, 67% ± 21% and 34% ± 30% respectively, in moment comparing control to experimental pack. The analysis performed in Table 21 also shows both comparisons to be statistically significant. This result indicates that there is reduced muscle activity at the lumbosacral joint, but since the overall difference in oxygen consumption was much smaller, other factors played a larger role.

Based on the results of the qualitative survey, subjects reported a higher pain average rating for upper back and shoulders. Based on comments made by subjects in the survey, this rating could be explained by less padding within the user interface of the experimental pack as compared to the control pack. Subjects on average reported a lower rating for both hips/thighs when using the experimental pack. This could indicate better load transference to the hips, another indication of why fatigue would be reduced. However, this rating could also have been influenced by the "warm-up effect" previously discussed.

Combining the results of oxygen consumption, qualitative surveys, impulse calculations, and joint moment calculations indicates that, as a whole, the experimental backpack did create a small reduction in fatigue. However, due to the small magnitude of this effect, further subject testing would be needed to fully confirm it.

7.5 Posture

A performance specification of the experimental pack design was to allow for the user to maintain a forward lean at or above 10-12 degrees while not exceeding 30 degrees. Forward lean greater than 30 degrees can reduce the effectiveness of the hip belt. All but one of the subjects tested were above the 10-12-degree threshold in both the experimental and the control pack. Also in all instances but one, forward lean was marginally increased. Forward lean angles observed for all subjects were below the upper threshold of 30 degrees. Weight and size of the pack are two contributing factors that affect forward lean. While the loading compartments on both packs were the same, the experimental pack had a custom load plate, frame, and hip belt which all worked to better distribute the overall load to the hips. As was discussed in Section 2.6.2, distributing loads lower on the back and to the hips works to increase forward lean.

7.6 Other interesting results

7.6.1 Horizontal GRF

Although this project was not targeted to affect horizontal ground reaction force, horizontal GRF is an important factor related to energy expenditure and blister formation. Horizontal GRF is the force that propels the body forward and slows the body when decelerating. An increase in horizontal GRF can indicate an increase in energy expenditure. Based on the results in Table 10 and Table 11 in Section 5.3.4, the horizontal GRF was higher for the control pack: 2.546% for the left foot and 4.913% for the right foot. Of these differences, only the difference for the right foot was statistically significant. This difference indicates that the subjects had to exert slightly more effort when walking with the control pack, indicating that fatigue was lower for the experimental pack. A reduction in horizontal GRF can also indicate a reduction in blister formation as a lower horizontal GRF requires a lower deceleration force.

7.6.2 Gait Compensation

Cadence, stride length, step length, and velocity are parameters often used to determine the effect of loading on a person's gait, as the body has to adjust to counterbalance the load. While a habituation session was used to position the force plates before motion capture was performed, these parameters could still have been influenced in response to aiming for the plates. In a visual comparison performed between control and experimental instances, seen in Figure 36, minimal changes in gait from experimental to control were noticed. The horizontal velocities calculated for each subject, see Section 7.1, also showed statistical insignificance between experimental and control conditions. The lack of a significant difference in gait parameters between the two conditions is actually a positive result. This means that the positive results in fatigue and shear and compression are primarily a result of the backpack design itself and not a result of gait compensation. However, due to the inconsistency in measuring gait parameters with this setup, better motion capture allowing for more natural walking and at controlled speeds would be needed to confirm the lack of gait compensation.

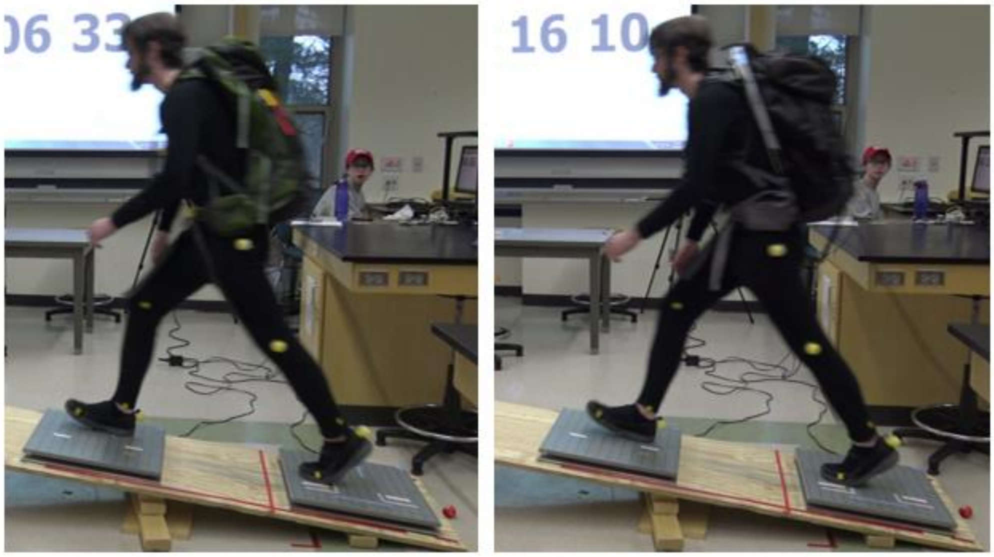

Figure 36: Visual Comparison of Subject during MoCap

7.7 Experimental Design

The goal of the experimental design was to compare performance of the control and experimental packs. Subject testing was structured to measure the design performance specifications. Experiment 1 measured posture, compression and shear at the lumbosacral joint, oscillating load, and total vertical GRF while Experiment 2 measured fatigue. Throughout subject testing, various improvements were made to increase efficiency of testing and data analysis.

During Experiment 1, colored tape was used for feet markers instead of ping-pong balls to reduce the number of re-trials from markers falling off. Visual cues were also added at the beginning of each trial to make trial identification easier. The original goal of placing 18 markers on subjects during Experiment 1 was to create a full model that would identify differences in positioning of major body segments throughout the gait cycle. Originally, this full model was to be used to calculate the true position of the center of mass of the backpack. Locating the center of mass of the backpack is critical to determining the joint loading at the lumbosacral joint. However, this model proved to be inadequate at predicting the location of the COM due to the more dynamic nature of the testing and the fact that the model relied largely on estimations of segment COMs from an anthropometric table. After the analysis of the first subject, this model was discarded; to save time in analysis only the sternum and pelvic markers were used. After data analysis was performed to investigate the major performance specifications, ImageJ was then used to further analyze gait compensations between packs during Experiment 1 trials. This process also did not use any of the marker positions. A future recommendation for this experimental design would be to only mark subject sternum and pelvic position to cut down on time and materials needed. In regards to the sternum and pelvic positions, markers that protruded out further from the subject would assist in identifying the positions through the laterally positioned cameras. Spacing the cameras farther from the subject would also offer a solution to increase visibility. While two cameras were set up on opposing sides of the subject to see all 18-marker positions, only one camera would then be needed to capture the sternum and pelvic markers.

During Experiment 2, inconsistency with the FitBit monitor during subject testing led to the use of heart rate monitors that were built into the treadmill and stationary bike. As the accuracy of these monitors was not known, more reliable heart rate equipment would offer a better indication of the subject's heart rate. Additionally, as mentioned earlier, the ability to directly measure oxygen consumption using a metabolic cart would eliminate much of the estimation error in the current results.

In the previous discussion of performance specifications, experimental recommendations were also made to measure design features more effectively. The use of a professional motion capture system is recommended for more precise acceleration values of body segments to determine shear and compressive forces of the lumbosacral joint. Fixture attachments on the subject and pack would also be beneficial in ensuring vertical position of accelerometers to better analyze the performance of the suspension system. While subject velocity was determined from the positions of the torso, physically monitoring their velocity would allow for speed control between trials and between subjects. It was also discussed that the fatigue test should be redesigned to incorporate the "warm up effect." Testing for a longer period or testing the two packs on different days could potentially overcome this effect. Due to the given time constraints and subject availability, structuring fatigue testing in this manner was not feasible.

7.8 Limitations of Data

7.8.1 Small Sample Size

Given the time constraints of this study, it was not possible to collect and analyze data from a large number of subjects. Therefore, a sample size of 5 was chosen, as explained in Section 3.3.2.1. This sample size was satisfactory for the analysis of posture, compression and shear at the lumbosacral joint, oscillating load, and total vertical GRF. However, a 5-subject sample size proved to be limiting in the analysis of heart rate and therefore oxygen consumption. The results of the heart rate data, discussed in Section 7.5, demonstrate that there may have been a slight "warm-up" effect to the testing, given that the experimental backpack performed better than the control at first in a statistically significant manner, but upon re-testing performed marginally worse than the control. Therefore, the overall effect of the backpack on fatigue was small. A larger sample size could have proved whether a trend in oxygen consumption with the experimental or control pack was in fact present.

7.8.2 Sensitivity Analysis

Due to the small sample size and the relative simplicity of the model used to analyze this pseudo-static data, a sensitivity analysis was conducted to assess the validity of the model. As discussed in Section 7.2, the primary factors affecting the compression and shear were the forward lean angle, horizontal acceleration, and vertical acceleration of the torso. To assess the sensitivity of the model, the forward lean angle, horizontal acceleration, and vertical acceleration were changed by 10% and the effect on compression and shear noted, see Table 24. The changes as a result of forward lean were not significant and the forward lean angle is known with better precision than 10% so the model was insensitive to relatively small changes in forward lean. The horizontal acceleration has more influence than vertical acceleration over shear and compression, but even a 10% increase or decrease only results in a small effect. Since the goal of the project was to reduce shear and compression by 60%, this model is accurate enough to detect that change.

Table 24: Results of Sensitivity Analysis

Variable	Change (%)	Compression Effect (%)	Shear Effect (%)
Forward Lean	+ 10	+ 0.04	+ 9.4
	-10	+ 0.62	+ 4.3
Horizontal (x) Acceleration	+ 10	+ 0.33	+ 6.9
	- 10	- 0.33	- 6.9
Vertical (z) Acceleration	+ 10	+ 0.22	+ 1.4
	-10	- 0.22	+ 1.4

The next step in this analysis was to evaluate the maximum precision to which the acceleration could be known. The precision of this was limited by the resolution of the manual marker capture method in ImageJ. In this software, the smallest increment of motion is 1.91mm and thus the location of the torso marker can only be known to ± 1.91mm. As the acceleration is calculated using three consecutive points (before, during, and after toe-off), simply adding 1.91mm to a single value is not possible. Instead, four different configurations were tested, see Table 25.

Table 25: Configurations for evaluating acceleration

Before Point	During Point	After Point
+1.91	-1.91	+1.91
-1.91	+1.91	-1.91
+1.91	+1.91	-1.91
-1.91	-1.91	+1.91

These small differences actually had a very significant effect on the acceleration values: the smallest difference was 47% and the largest difference was 762%. These large differences indicate that the method used to determine the accelerations of the torso is not good enough to provide accurate and precise results. This could be addressed, as suggested earlier, by using a professional infrared motion capture system.

7.8.3 Static Motion Capture

One shortcoming of the testing set-up in this study was the inability to accurately replicate natural hiking conditions and analyze dynamic data. All GRF and motion capture data were collected and analyzed in pseudo-static cases, generally in the 150% BW range for GRF, of toe-off for each subject. Natural hiking is more dynamic than what is represented for each trial, and thus the data in this study does not necessarily reflect the performance of the suspended-load pack in real conditions. Dynamic data collection could have been achieved with the use of instrumental insoles with force sensitive resistors. With the use of such insoles, testing would not have been limited to within a laboratory setting and could have involved physically hiking in a natural setting instead of walking up a ramp. However, the disadvantage of using insoles is that professional systems are prohibitively expensive and do-it-yourself systems are far less accurate and precise than force plates.

7.8.4 Oxygen Consumption Modeling

There are several limitations that come with estimating oxygen uptake using Bot and Hollander's approximation method. This method is intended to approximate oxygen consumption during steady state exercise, such as walking or running at a consistent speed, similar to this experiment. However, Bot and Hollander recognize that outside events such as emotional factors may affect heart rate and are not accounted for in this equation. Fear, concern or excitement, all examples of emotional factors, may have played a role in the minds of participants. Another limitation in this data is the method of data collection. Heart rate was observed using the heart rate monitors on the treadmill, collected by gripping the monitor with one's hands. Oxygen consumption could have been observed using a metabolic cart; however, this method is very expensive.

Chapter 8: Conclusion and Recommendations

In this project, a novel load carriage system for recreational backpackers was investigated, designed, manufactured, and tested compared to a commercially available backpack. With the main objectives to reduce injury and fatigue among long-distance backpackers, this new design incorporated a suspension system and pivoting hip belt in efforts to meet the desired performance specifications. Motion capture and fatigue analysis were completed through a series of subject testing to quantitatively compare the two packs. Ultimately, the produced backpack slightly reduced user fatigue as observed in a quantitative test and through a 8% ± 4% decrease in VO2 consumption when compared to the commercial pack. Additionally the pack induced the desired amount of forward lean, between 10 and 30 degrees. Despite small decreases in shear force at some instances, these small differences were not statistically significant. Compared to the control pack, the experimental pack did not significantly influence compression and shear forces at the lumbosacral joint, oscillating load, or total vertical ground reaction force.

Several recommendations are offered for the pack's design to enhance its performance. These changes may be incorporated into the manufacturing process to better allow for oscillation. The first is to create a wider load plate that will accommodate the frame and the required hardware to attach the frame to the load plate. This would reduce obstructions that are present in the current prototype between the side of the load plate and the frame. An additional plate should also be incorporated between the back of the user and the load plate to stop any pinching of the elastic cord. Another modification that will allow for free movement of the load plate is a new method of fixing the shoulder harness to the frame, with a secondary rail for example. Finally, the last modification is an alternative method of fixing the hip belt to the frame. This modification is important so the load may be transferred to the hips.

While numerous improvements have been recommended for the experimental procedure as previously discussed, further testing with a larger sample size and in a more natural backpacking environment would offer the best analysis. Collecting data with a larger sample size would help strengthen the analysis statistically. Testing the experimental design during backpacking expeditions on various trails would offer the best representation of how well the pack performs.

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Appendix A: Full breakdown of performance specifications

Table 26: Performance Specification Breakdown

Priority	Parameter	How will it be affected?	Why is it important?	How much will it be affected by?	How will this be measured?
1	Posture	Increase	Increases metabolic efficiency, can reduce shear loads in the spine	10-12 degrees	Motion capture
1	Compression and Shear at the lumbosacral joint	Decrease	Decreases back pain	<60% increase under load	OpenSim analytical model based on GRF with full motion capture
1	Oscillating Load	Decrease	Reduces total GRF, reduces injuries and fatigue	80%	Accelerometers on the load itself
1	Total Vertical GRF	Decrease	Reduces injuries and fatigue	33%	Force Plates and force sensors embedded in insoles
1	Fatigue	Decrease	Reduces injuries and increases enjoyment	Comparison between conditions	Qualitative questionnaire and predictive equations
2	Spinal Curvature	Induce neutral spinal curvature	Non-neutral curvature increases back pain.	Unclear	Spring displacement rods attached to backpack frame
2	Heat Dissipation	Increase/Leave Unchanged	Decreased heat dissipation increases fatigue	Comparison between conditions	Qualitative questionnaire and thermal imaging
3	Horizontal Braking Force	Decrease	Causes blisters	10%	Force Plates
3	Required Propulsive Force	Decrease	Reductions improve metabolic efficiency	Unclear	Force Plates
3	Lower limb EMG	Decrease	Increased activity leads to faster fatigue. Over-exertion can cause strains or sprains	Comparison between conditions	EMG surface electrodes or OpenSim modeling
3	Thrust force at toe-off	Decrease	High thrust forces may influence lower limb injuries	Unclear	Force Plates
3	Intraabdominal Pressure	Increase	Supports spine and reduces spinal loading	Unclear	Radio-transmitting pill
3	Oxygen Consumption	Decrease	Indicates metabolic efficiency	5%	VO_{2max} testing backpack

3	Air flow between pack and body	Increase/Leave Unchanged	Decreased air flow increases fatigue	Comparison between conditions	Qualitative questionnaire

Each parameter was given a priority rating, with a 1 indicating that measuring this parameter is necessary to meet the project goal, a 2 indicating that measuring this parameter would be useful but would not prevent the project goal from being accomplished, and a 3 representing something that is unfeasible to measure or does not help achieve the goal of the project.

The following parameters were eliminated due to the unfeasibility of measurement: oxygen consumption, air flow, intraabdominal pressure, and spinal curvature. While air flow and oxygen consumption will not be explicitly measured, their influence will be partially accounted for in the questionnaire and via equations used to determine fatigue. Thrust force at toe-off, braking force, and required propulsive force were eliminated primarily because the connection of these parameters to reducing fatigue and back pain is less clear and they can only be measured easily and conclusively via force plates in a lab setting. Such a setting, however, presents an unrealistic test condition and thus is far less useful in evaluating the actual field performance of the backpack. Lower limb EMG was eliminated because it is primarily associated with a reduction in lower limb injuries, which are not conclusively linked to load carriage. Heat dissipation was eliminated because its effects would be accounted for in the fatigue questionnaire.

Appendix B: Gait parameters measured to serve as a control

Table 27: Control Performance Specifications

Priority	Parameter	How will it be affected?	Why is it important?	How much will it be affected by?	How will this be measured?
1	Stride length	Decrease	Decreased stride length decreases total GRF	Comparison between conditions	Force plates and motion capture
1	Cadence	Increase	Increased cadence decreases total GRF	Comparison between conditions	Force plates and motion capture
1	Support time	Increase	Increased support time decreases total GRF	Comparison between conditions	Force plates and motion capture
1	Knee Flexion	Increase	Increased knee flexion reduces total GRF	Comparison between conditions	Motion capture
3	Pelvic Rotation	Increase/Leave Unchanged	Increases allow better stability	Unclear	Motion capture

Appendix C: Subject Anthropometric Data

Table 28: Subject Anthropometric Data

Test Information	
Date	
Time	
General Characteristics	
Subject #	
Height	
Weight	
Segment Lengths	
Thorax and Abdomen	
Head and Neck	
Foot	
Shank	
Thigh	
Forearm and hand	
Upper arm	
Segment Widths	
Knee	
Ankle	

Appendix D: Marker locations for motion capture

Table 29: Motion Capture Markers

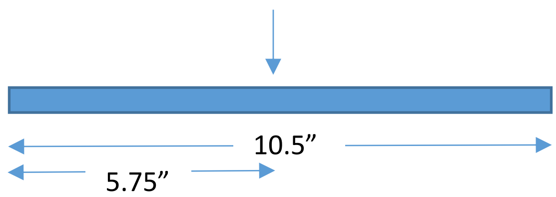
Marker	Anatomical Location
R.Knee.Lat	Right lateral femoral condyle (approximating joint center)
R.Knee.Med	Right medial femoral condyle (approximating joint center)
L.Knee.Lat	Left lateral femoral condyle (approximating joint center)
L.Knee.Med	Left medial femoral condyle (approximating joint center)
R.Ankle.Lat	Right lateral malleolus
R.Ankle.Med	Right medial malleolus
L.Ankle.Lat	Left lateral malleolus
L.Ankle.Med	Left medial malleolus
Sternum	Distal end of the sternum
R.Heel	Calcaneus at the same height above the plantar surface as the MTP markers
L.Heel	Calcaneus at the same height above the plantar surface as the MTP markers
R.MTP1	Big toe joint
R.MTP5	Little toe joint
L.MTP1	Big toe joint
L.MTP5	Little toe joint
Pelvis.Center	Center between the hips just below the naval
L.Hip	Left hip joint center
R.Hip	Right hip joint center

Appendix E: Frame stress calculations

Top bar deflection

Find: Deflection, y_{max}, at center of 10.5” rod

Assume: Isolated rod, d = 0.25”, Force applied in one location



$$deflection = y = \frac{Wx}{48EI}(3l^2 - 4x^2)$$

$$I = \frac{\pi d^4}{64}$$

$$W = 50\ lbf$$

$$l = 10.5"$$

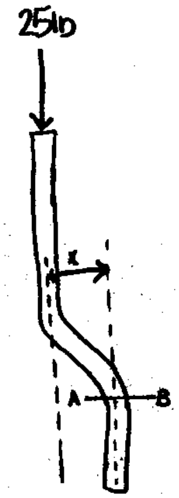
$$x = 5.75"$$

$$E_{7075-T6} = 11{,}603\ KSI$$

$$y = \frac{50 * 5.75}{48 * 11603 * 10^3 * 1.9175 * 10^{-4}}(3 * 10.5^2 - 4 * 5.75^2)$$

$$\boldsymbol{y_{max} = 0.534"}$$

Side Bar X distance



7075 Aluminum Yield Strength: 62,000psi

Our desired maximum bending stress we would want the side frame to experience is 31,000psi. This is calculated by taking the yield strength and dividing by 2 to account for a safety factor.

Method used from Mechanics of Materials, pg. 323

$$Drod \ = \ 1/4\ "$$

$$Cross\ Sectional\ Area\ of\ rod\ = \frac{\pi}{64} in^2$$

$$Radius\ of\ curvature\ (rbar) = \ 2.5"$$

$$Location\ of\ Neutral\ Axis\ R = \frac{A}{\int \frac{dA}{r}}$$

$$\int \frac{dA}{r} = 2\pi\left(rbar - \sqrt{rbar^2 - c^2}\right) = 2\pi\ (2.5 - \sqrt{2.5^2 - \left(\frac{1}{8}\right)^2} = 0.02"$$

$$R = 2.45\ in$$

$$Moment\ about\ the\ cut\ section:\ M - 25(x) = 0$$

$$r_A = 2.38$$

$$\sigma_A = \frac{M(R - r_A)}{A * r_A(rbar - R)}$$

$$31{,}000psi = \frac{M(2.5 - 2.38)}{\frac{\pi}{64} * 2.38(2.5 - 2.45)}$$

$$M = 60.36\ lb * in$$

So,

$$60.36 - 25(x) = 0$$

$$\boldsymbol{x = 2.4}"$$

Appendix F: Calculating linear and angular acceleration

The following is the procedure used to calculate the linear and angular accelerations of the torso:

1. The positions of the pelvic and sternum markers were determined using ImageJ and their coordinates in the lab frame were recorded in an Excel sheet.
2. The angle of the torso was determined by using the dot product of the vertical unit vector and the vector between the pelvic and sternum markers.
3. The following equations were used to calculate the linear acceleration of the torso. The X and Z coordinates were the coordinates of the sternum marker. The Δt term was 0.04s as determined by the frame rate of the video editing software used.

$$a_x = \frac{x_{after} - 2 * x_{during} + x_{before}}{\Delta t^2}$$

$$a_z = \frac{z_{after} - 2 * z_{during} + z_{before}}{\Delta t^2}$$

4. The following equation was used to determine the angular acceleration of the torso as it rotated about the lumbosacral joint.

$$\propto = \frac{\propto_{after} - 2 * \propto_{during} + \propto_{before}}{\Delta t^2}$$

An example result of this analysis is included in Table 28.

Table 30: Linear and angular acceleration of the torso

Toe-off Foot	x Before (m)	x During (m)	x After (m)	z Before (m)	z During (m)	z After (m)	Alpha Before (rad)	Alpha During (rad)	Alpha After (rad)	HAT a_x (m/s^2)	HAT a_z (m/s^2)	HAT Angular Acc. (rad/s^2)
Left 1	0.88	0.946	1.01	1.35	1.34	1.34	0.222	0.251	0.241	-1.88	2.5	-140
Left 2	0.937	1.00	1.06	1.26	1.26	1.26	0.283	0.282	0.228	-0.625	2.5	-33.1
Left 3	0.917	0.983	1.06	1.36	1.37	1.38	0.249	0.213	0.237	5	-5	216
Right 1	1.90	1.95	2.02	1.71	1.72	1.72	0.281	0.256	0.266	8.75	-0.625	126
Right 2	1.84	1.90	1.95	1.44	1.43	1.43	0.283	0.264	0.319	-4.38	4.37	266
Right 3	1.82	1.88	1.94	1.42	1.42	1.43	0.216	0.234	0.221	-3.75	3.12	-112

Appendix G: Processing accelerometer data

The following is the procedure used to capture and analyze the accelerometer data:

1. Data captured at 60Hz using a portable DAQ and the following LabView VI

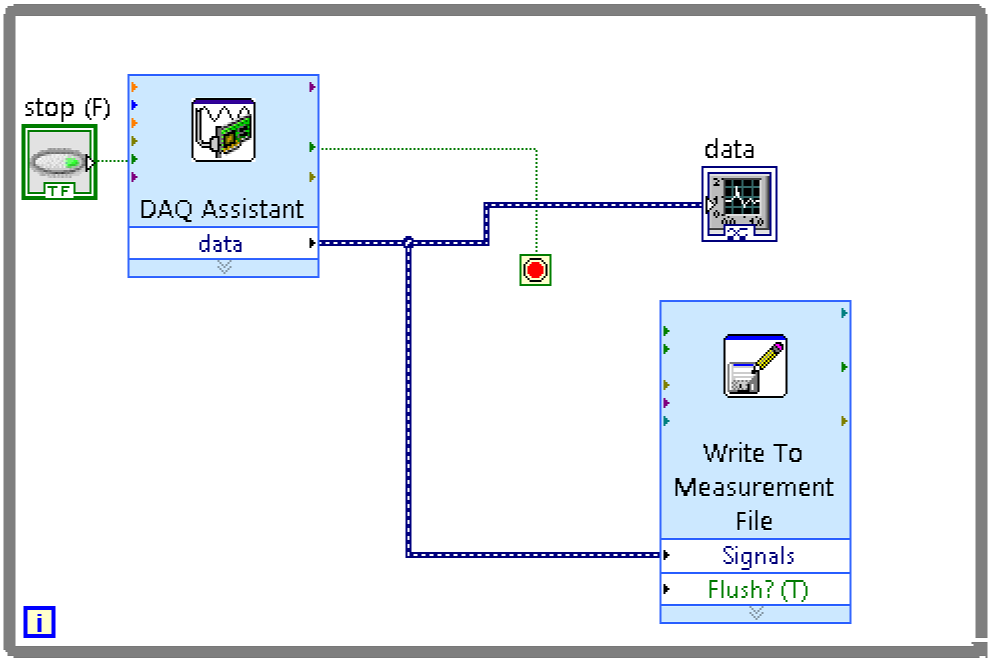


Figure 37: Accelerometer VI

2. Raw data imported into Excel and plotted

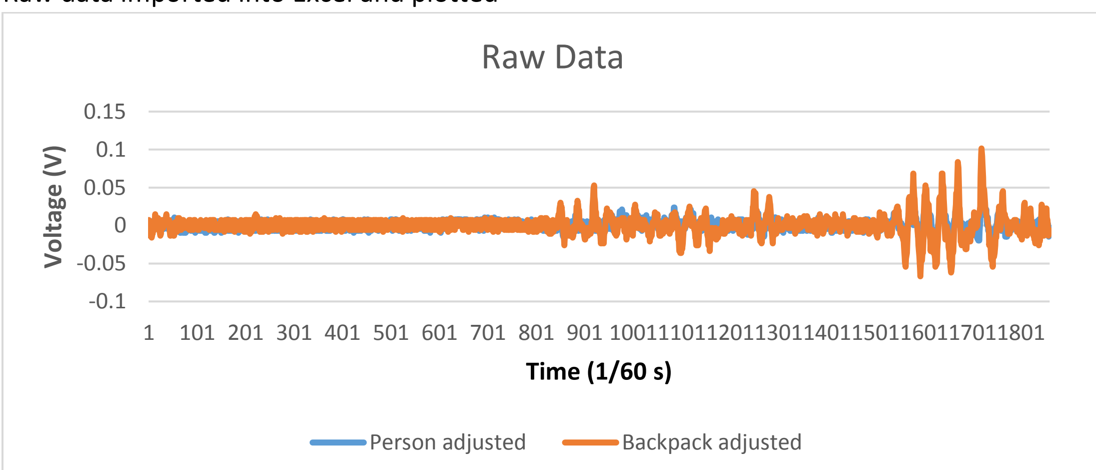


Figure 38: Raw accelerometer data

3. Raw voltages converted to m/s^2 and replotted

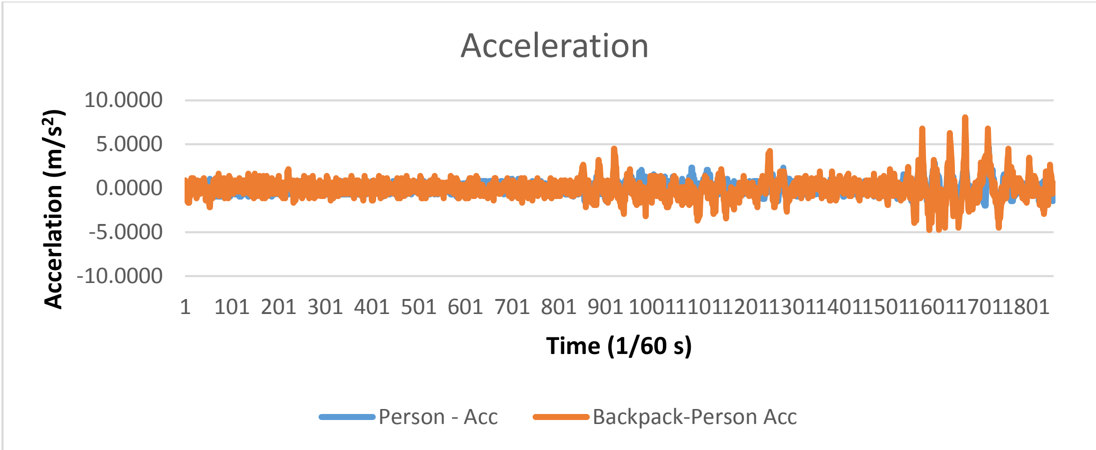


Figure 39: Accelerometer data converted to m/s²

4. Data truncated to only include section were subject was walking and the relative acceleration of the backpack calculated by subtracting the person's acceleration from the backpack acceleration and the data is replotted.

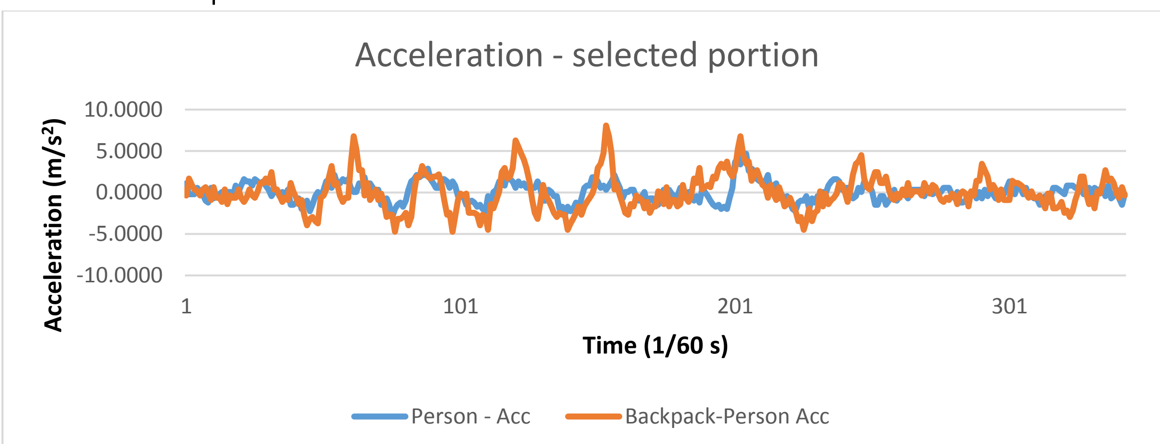


Figure 40: Accelerometer data truncated and relative backpack acceleration determined

5. Median filter applied to smooth data.

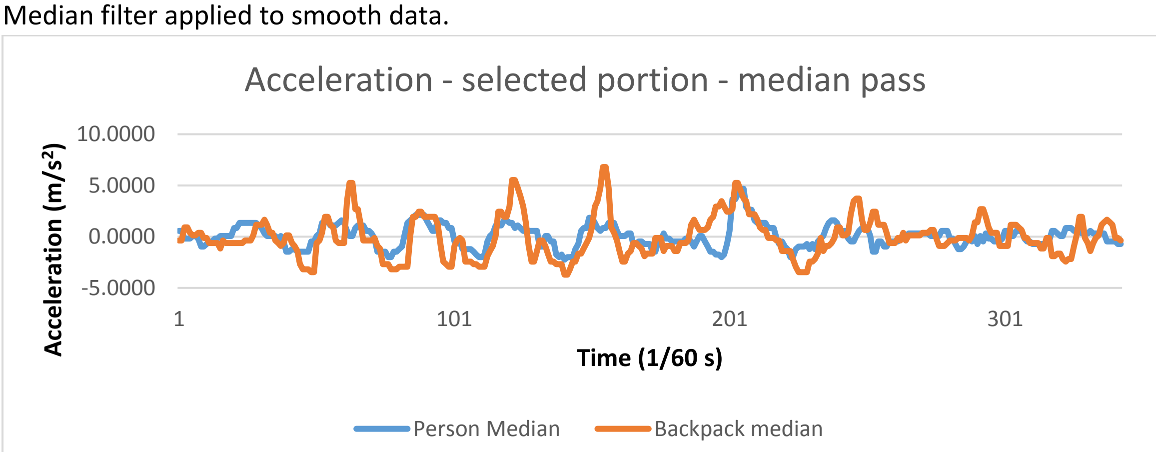


Figure 41: Smoothed accelerometer data

6. Truncated and smoothed relative backpack acceleration and person acceleration imported into MATLAB and plotted.

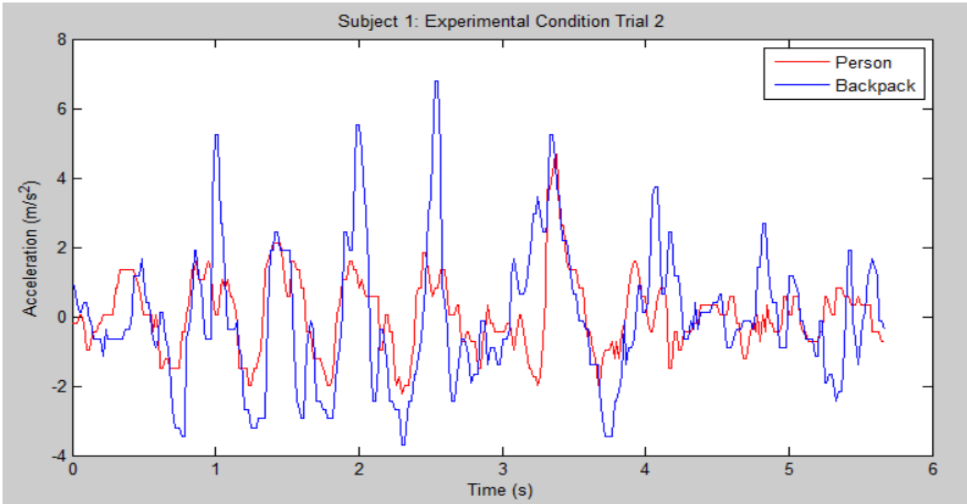


Figure 42: Smoothed accelerometer data plotted in MATLAB

7. Peaks and valleys identified, average peak and valley acceleration determined, and percent difference between control and experimental calculated using the following script.

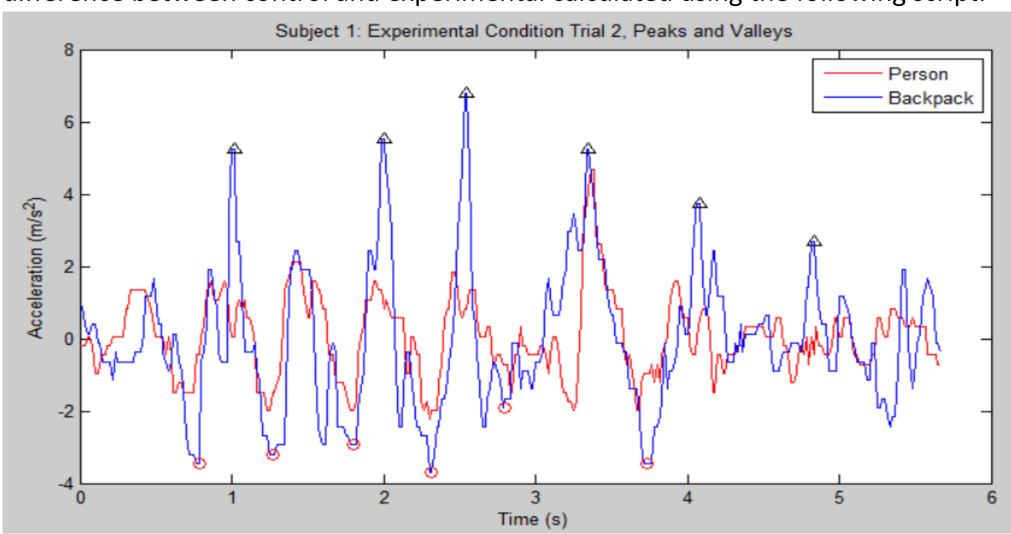


Figure 43: Peaks and valleys in the relative backpack acceleration

```
close all
%% Accelerometer Peak Processing
%% Loading Data
data =
xlsread('Subject1_Part1_AccData.xlsx');
c1_p = data(2:end,1); %trial 1 control,
person
c1_b = data(2:end,2); %trial 1 control,
backpack
c2_p = data(2:end,3); %trial 2 control,
person
c2_b = data(2:end,4); %trial 2 control,
backpack
c3_p = data(2:end,5); %trial 3 control,
person
c3_b = data(2:end,6); %trial 3 control,
backpack
e1_p = data(2:end,7); %trial 1
experimental, person
e1_b = data(2:end,8); %trial 1
experimental, backpack
```

```
e2_p = data(2:end,9); %trial 2
experimental, person
e2_b = data(2:end,10); %trial 2
experimental, backpackA
e3_p = data(2:end,11); %trial 3
experimental, person
e3_b = data(2:end,12); %trial 3
experimental, backpack
%% Clipping and plotting data
% Recording the start and end time for
the trials for each subject
Con1_startTime = 1959; %start point of
control trial 1, determined by looking
at excel sheet
Con1_endTime = 2226;
Con2_startTime = 1261;
Con2_endTime = 1500;
Con3_startTime = 900;
Con3_endTime = 1441;
Exp1_startTime = 1700;
Exp1_endTime = 2281;
Exp2_startTime = 1519;
Exp2_endTime = 1861;
Exp3_startTime = 1657;
Exp3_endTime = 1861;

%Clip data to only have the data
relevant for the actual walking part of
%the trial
c1_p =
c1_p(Con1_startTime:Con1_endTime);
c1_b =
c1_b(Con1_startTime:Con1_endTime);
c2_p =
c2_p(Con2_startTime:Con2_endTime);
c2_b =
c2_b(Con2_startTime:Con2_endTime);
c3_p =
c3_p(Con3_startTime:Con3_endTime);
c3_b =
c3_b(Con3_startTime:Con3_endTime);
e1_p =
e1_p(Exp1_startTime:Exp1_endTime);
e1_b =
e1_b(Exp1_startTime:Exp1_endTime);
e2_p =
e2_p(Exp2_startTime:Exp2_endTime);
e2_b =
e2_b(Exp2_startTime:Exp2_endTime);
e3_p =
e3_p(Exp3_startTime:Exp3_endTime);
e3_b =
e3_b(Exp3_startTime:Exp3_endTime);

%Plot all the clipped data to verify
correct clipping
figure
plot(c1_p, 'r');
hold on
plot(c1_b);
hold off

figure
plot(c2_p, 'r');
hold on
plot(c2_b);
hold off

figure
plot(c3_p, 'r');
hold on
plot(c3_b);
hold off

figure
plot(e1_p, 'r');
hold on
plot(e1_b);
hold off

figure
plot(e2_p, 'r');
hold on
plot(e2_b);
hold off

figure
plot(e3_p, 'r');
hold on
plot(e3_b);
hold off

%% Calculating min peak height values
and max number of peaks

%Min peak height is defined as 25% of
the global max
Con1_Height = .25 * max(c1_b);
Con2_Height = .25 * max(c2_b);
Con3_Height = .25 * max(c3_b);
Exp1_Height = .25 * max(e1_b);
Exp2_Height = .25 * max(e2_b);
Exp3_Height = .30 * max(e3_b);

%Max number of peaks is set by the
number of clearly visible peaks on the
%plot of the person's accelerometer
data.
Con1_NumPks = 6; %fig 1, 7
Con2_NumPks = 5; %fig 2, 8
Con3_NumPks = 5; %fig 3, 9
Exp1_NumPks = 6; %fig 4, 10
Exp2_NumPks = 6; %fig 5, 11
Exp3_NumPks = 5; %fig 6, 12

%% Finding peaks and valleys
%Control 1 peaks and valleys
[c1_pks, c1_locs] =
findpeaks(c1_b,'MinPeakHeight',
Con1_Height, 'NPeaks', Con1_NumPks,
'MinPeakDistance',25);
[c1_vals, c1_locsV] = findpeaks(-
c1_b,'MinPeakHeight', Con1_Height,
'NPeaks', Con1_NumPks,
'MinPeakDistance',25);
figure
```

```
plot(c1_p, 'r');
hold on
plot(c1_b);
plot(c1_locs, c1_pks,'k^');
plot(c1_locsV,-c1_vals,'ro');
hold off

%Control 2 peaks and valleys
[c2_pks, c2_locs] =
findpeaks(c2_b,'MinPeakHeight',
Con2_Height, 'NPeaks', Con2_NumPks,
'MinPeakDistance',25);
[c2_vals, c2_locsV] = findpeaks(-
c2_b,'MinPeakHeight', Con2_Height,
'NPeaks', Con2_NumPks,
'MinPeakDistance',25);
figure
plot(c2_p, 'r');
hold on
plot(c2_b);
plot(c2_locs, c2_pks,'k^');
plot(c2_locsV,-c2_vals,'ro');
hold off

%Control 3 peaks and valleys
[c3_pks, c3_locs] =
findpeaks(c3_b,'MinPeakHeight',
Con3_Height, 'NPeaks', Con3_NumPks,
'MinPeakDistance',25);
[c3_vals, c3_locsV] = findpeaks(-
c3_b,'MinPeakHeight', Con3_Height,
'NPeaks', Con3_NumPks,
'MinPeakDistance',25);
figure
plot(c3_p, 'r');
hold on
plot(c3_b);
plot(c3_locs, c3_pks,'k^');
plot(c3_locsV,-c3_vals,'ro');
hold off

%Exp 1 peaks and valleys
[e1_pks, e1_locs] =
findpeaks(e1_b,'MinPeakHeight',
Exp1_Height, 'NPeaks', Exp1_NumPks,
'MinPeakDistance',25);
[e1_vals, e1_locsV] = findpeaks(-
e1_b,'MinPeakHeight', Exp1_Height,
'NPeaks', Exp1_NumPks,
'MinPeakDistance',25);
figure
plot(e1_p, 'r');
hold on
plot(e1_b);
plot(e1_locs, e1_pks,'k^');
plot(e1_locsV,-e1_vals,'ro');
hold off

%Exp 2 peaks and valleys
[e2_pks, e2_locs] =
findpeaks(e2_b,'MinPeakHeight',
Exp2_Height, 'NPeaks', Exp2_NumPks,
'MinPeakDistance',30);
[e2_vals, e2_locsV] = findpeaks(-
e2_b,'MinPeakHeight', Exp2_Height,
'NPeaks', Exp2_NumPks,
'MinPeakDistance',25);

figure
t = 0:1:length(e2_p)-1;
t = t.*(1/60);
plot(t,e2_p, 'r');
hold on
plot(t,e2_b);
plot(e2_locs.*(1/60), e2_pks,'k^');
plot(e2_locsV.*(1/60),-e2_vals,'ro');
hold off
title('Subject 1: Experimental
Condition, Peaks and Valleys')
xlabel('Time (s)')
ylabel('Acceleration (m/s^2)')
legend('Person','Backpack')

%Exp 3 peaks and valleys
[e3_pks, e3_locs] =
findpeaks(e3_b,'MinPeakHeight',
Exp3_Height, 'NPeaks', Exp3_NumPks,
'MinPeakDistance',25);
[e3_vals, e3_locsV] = findpeaks(-
e3_b,'MinPeakHeight', Exp3_Height,
'NPeaks', Exp3_NumPks,
'MinPeakDistance',25);
figure
plot(e3_p, 'r');
hold on
plot(e3_b);
plot(e3_locs, e3_pks,'k^');
plot(e3_locsV,-e3_vals,'ro');
hold off

%% Combining peak vectors, finding
outliers
%vector containing all of the control
peaks (trials 1-3) for subject
c_pks = [c1_pks; c2_pks];

% iqr_c is the difference between the
75th and the 25th percentiles of the
% sample data contained in c_pks
iqr_c_pks = iqr(c_pks);

%the average of all of the peaks in the
experimental trials for subject
avg_c_pks = mean(c_pks);

% finds a cutoff value to determine if
an outlier is present
cutoff_c_pks = 1.5*iqr_c_pks;

%returns the difference between each
peak in vector c_pks and the average
%of all peaks. If this value is greater
than cutoff_c, the peak is an
%outlier
c_outlier_pks = c_pks - avg_c_pks;
```

```
%finds the locations where the elements
in c_outlier meet the condition
%that they are less than the cutoff
value; a 1 is placed in the indeces
%that satisfy this condition, and a 0
is placed where the condition is not
%met
loc_out_c_pks = abs(c_outlier_pks) <
cutoff_c_pks;

%using loc_out_c to index into the
original matrix c_pks and re-writing
the
%matrix so that the outliers are no
longer present
c_pks = c_pks(loc_out_c_pks);


%vector containing all of the
experimental peaks (trials 1-3) for
subject
e_pks = [e2_pks; e3_pks];

% iqr_e is the difference between the
75th and the 25th percentiles of the
% sample data contained in e_pks
iqr_e_pks = iqr(e_pks);

%the average of all of the peaks in the
experimental trials for subject
avg_e_pks = mean(e_pks);

% finds a cutoff value to determine if
an outlier is present
cutoff_e_pks = 1.5*iqr_e_pks;

%returns the difference between each
peak in vector e_pks and the average
%of all peaks. If this value is greater
than cutoff_e, the peak is an
%outlier
e_outlier_pks = e_pks - avg_e_pks;

%finds the locations where the elements
in e_outlier meet the condition
%that they are less than the cutoff
value; a 1 is placed in the indeces
%that satisfy this condition, and a 0
is placed where the condition is not
%met
loc_out_e_pks = abs(e_outlier_pks) <
cutoff_e_pks;

%using loc_out_e to index into the
original matrix e_pks and re-writing
the
%matrix so that the outliers are no
longer present
e_pks = e_pks(loc_out_e_pks)

%% Combining valley vectors, finding
outliers

%vector containing all of the control
valleys (trials 1-3) for subject
c_vals = [c1_vals; c2_vals];

% iqr_c is the difference between the
75th and the 25th percentiles of the
% sample data contained in c_vals
iqr_c_vals = iqr(c_vals);

%the average of all of the valleys in
the experimental trials for subject
avg_c_vals = mean(c_vals);

% finds a cutoff value to determine if
an outlier is present
cutoff_c_vals = 1.5*iqr_c_vals;

%returns the difference between each
valley in vector c_vals and the average
%of all valleys. If this value is
greater than cutoff_c, the valley is an
%outlier
c_outlier_vals = c_vals - avg_c_vals;

%finds the locations where the elements
in c_outlier meet the condition
%that they are less than the cutoff
value; a 1 is placed in the indeces
%that satisfy this condition, and a 0
is placed where the condition is not
%met
loc_out_c_vals = abs(c_outlier_vals) <
cutoff_c_vals;

%using loc_out_c to index into the
original matrix c_vals and re-writing
the
%matrix so that the outliers are no
longer present
c_vals = c_vals(loc_out_c_vals);


%vector containing all of the
experimental peaks (trials 1-3) for
subject
e_vals = [e2_vals; e3_vals];

% iqr_e is the difference between the
75th and the 25th percentiles of the
% sample data contained in e_vals
iqr_e_vals = iqr(e_vals);

%the average of all of the valleys in
the experimental trials for subject
avg_e_vals = mean(e_vals);

% finds a cutoff value to determine if
an outlier is present
cutoff_e_vals = 1.5*iqr_e_vals;

%returns the difference between each
peak in vector e_vals and the average
%of all peaks
```

```
e_outlier_vals = e_vals - avg_e_vals;

%finds the locations where the elements
in e_outlier meet the condition
%that they are less than the cutoff
value; a 1 is placed in the indeces
%that satisfy this condition, and a 0
is placed where the condition is not
%met
loc_out_e_vals = abs(e_outlier_vals) <
cutoff_e_vals;

%using loc_out_e to index into the
original matrix e_vals and re-writing
the
%matrix so that the outliers are no
longer present
e_vals = e_vals(loc_out_e_vals);

%% Averaging peaks and valleys
%calculates the average peak/valley
acceleration in the control
conAvgPk = mean(c_pks);
conAvgVal = mean(-c_vals);
%calculates the average peak/valley
acceleration in the experimental
expAvgPk = mean(e_pks)
expAvgVal = mean(-e_vals);

%Percent difference between control and
experimental
PkDiff = ((expAvgPk-
conAvgPk)/conAvgPk)*100;
ValDiff = ((abs(expAvgVal)-
abs(conAvgVal))/abs(conAvgVal))*100;

%Outputs matrix with R1 as the control
pks and vals, R2 as the exp pks and
%vals and R3 as the percent diff
OutputMat = [conAvgPk,conAvgVal;
expAvgPk,expAvgVal;PkDiff,ValDiff]
```