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Development, Validation, and Testing of a Novel Ergonomic Backpack

Lyndsey Kate Bouve

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Abstract

Backpacks (BP) are one of the most common means for carrying loads but the loading mechanics that result from carrying heavy loads can have implications across the body. It has been suggested that loads in a BP should not excess 10-15% of the user's body weight (BW) but that is not always feasible. The loads in a BP are transferred to the body via the shoulder strap which induce a shear and compressive force which act externally on the spine and transfer loads through it to the lumbar. Additionally, the weight of the bag induces an external moment that further stresses the spine structures. The ergonomic backpack (EBP) was designed as a possible solution to the problematic loading conditions that are induced by load carriage and therefore improving load carriage efficiency and ergonomic performance. The term ergonomic performance was characterized by an accumulation of variables that could be used to evaluate backpack technology, including decreased shoulder and spine loads, reduction in paraspinal muscle involvement, reduction in oxygen consumption, reduction in lower extremity muscle effort, and improved comfort. The EBP utilizes several design features that alleviates spine and shoulder loading by redirecting and counterbalancing the external load from the backpack.

The objective of study 1 was to validate the design of the EBP. This was done by determining the strap tension-bag load relationship in the EBP compared to a traditional backpack using modified luggage scales which were configured to measure the tension in each strap. Additionally, the shoulder pressure-bag load relationship in the EBP compared to a traditional backpack using pressure sensors. Ten measurements of shoulder load and strap tension were taken in each backpack condition with five weight increments (0 kg to 11 kg). Shoulder loads were significantly reduced with the EBP (50%) at all weight increments (p

The objective of study 2 was to evaluate ergonomic performance while wearing the EBP compared to a traditional backpack during a walking task. The first aim was to measure paraspinal muscle response and the second aim was to measure oxygen consumption and lower limb muscle response. Fifteen healthy participants walked on a split-belt instrumented treadmill at 1.3 m/s in two backpack conditions, the EBP and a traditional backpack, with two loads (7 kg and 11 kg). A 3D motion capture system recorded electromyography and kinematic data, while the force treadmill recorded ground reaction forces. Kinetic and kinematic variable calculations were used to determine trunk angle and muscle powers at each major joint. Electromyography signals were processed and used to determine the muscle activity over the gait cycle. A metabolic cart recorded the volume of oxygen consumed during the walking trial. Results revealed significantly decreased trunk angle (more vertical trunk position), decreased paraspinal muscle activity, and decreased hip muscle power in the EBP compared to the traditional backpack (p

This body of work provides evidence that the EBP could provide the basis for design improvements that should be considered in improving backpacks for safer load carriage.

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Development, Validation, and Testing of a Novel Ergonomic Backpack

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DEDICATION

To my parents, Dave and Lara Bouvé, my sister Abigail Bouvé, and my close friends and family. You all are my village and have supported me more than you may ever realize. Thank you.

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PREFACE

The body of this thesis is organized in a way that first introduces readers to our rationale for choosing to explore load carriage technology, objectives, and hypotheses—as well as to present an overview of the literature. A discussion of the design and validation process is first presented, followed by methods used to functionally test our design which leads to a presentation of the results and final analysis with a discussion of our findings. A concluding chapter relates all research elements back to our final thoughts about the findings, their significance, and considerations for future research.

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ABSTRACT

Backpacks (BP) are one of the most common means for carrying loads but the loading mechanics that result from carrying heavy loads can have implications across the body. It has been suggested that loads in a BP should not excess 10-15% of the user's body weight (BW) but that is not always feasible. The loads in a BP are transferred to the body via the shoulder strap which induce a shear and compressive force which act externally on the spine and transfer loads through it to the lumbar. Additionally, the weight of the bag induces an external moment that further stresses the spine structures. The ergonomic backpack (EBP) was designed as a possible solution to the problematic loading conditions that are induced by load carriage and therefore improving load carriage efficiency and ergonomic performance. The term ergonomic performance was characterized by an accumulation of variables that could be used to evaluate backpack technology, including decreased shoulder and spine loads, reduction in paraspinal muscle involvement, reduction in oxygen consumption, reduction in lower extremity muscle effort, and improved comfort. The EBP utilizes several design features that alleviates spine and shoulder loading by redirecting and counterbalancing the external load from the backpack.

The objective of study 1 was to validate the design of the EBP. This was done by determining the strap tension-bag load relationship in the EBP compared to a traditional backpack using modified luggage scales which were configured to measure the tension in each strap. Additionally, the shoulder pressure-bag load relationship in the EBP compared to a traditional backpack using pressure sensors. Ten measurements of shoulder load and strap tension were taken in each backpack condition with five weight increments (0 kg to 11 kg). Shoulder loads were significantly reduced with the EBP (50%) at all weight increments ($p<0.05$). There was no difference found in the strap tension between the studied backpack systems. Results from this study supported the success of the EBP design as improving the problematic loading at the shoulders due to load carriage.

The objective of study 2 was to evaluate ergonomic performance while wearing the EBP compared to a traditional backpack during a walking task. The first aim was to measure paraspinal muscle response and the second aim was to measure oxygen consumption and lower limb muscle response. Fifteen healthy participants walked on a split-belt instrumented treadmill at 1.3 m/s in two backpack conditions, the EBP and a traditional backpack, with two loads (7 kg and 11 kg). A 3D motion capture system recorded electromyography and kinematic data, while the force treadmill recorded ground reaction forces. Kinetic and kinematic variable calculations were used to determine trunk angle and muscle powers at each major joint. Electromyography signals were processed and used to determine the muscle activity over the gait cycle. A metabolic cart recorded the volume of oxygen consumed during the walking trial. Results revealed significantly decreased trunk angle (more vertical trunk position), decreased paraspinal muscle activity, and decreased hip muscle power in the EBP compared to the

traditional backpack ($p<0.05$). This further supports the success of the EBP design at improving load carriage mechanics.

This body of work provides evidence that the EBP could provide the basis for design improvements that should be considered in improving backpacks for safer load carriage.

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LIST OF ABBREVIATIONS

Ag/AgCl	Silver/Silver Chloride
ANOVA	Analysis of Variance
BP	Backpack
BW	Body Weight
d_B	Bag Weight Distance
DT	Design Task(s)
EBP	Ergonomic Backpack
EMG	Electromyography
F_C	Cord Force
F_{CM}	Net Counterforce
F_{SS}	Shoulder Strap Force
F_{LS}	Reaction Force at Lumbar
GRF	Ground Reaction Force
M_B	External Bag Moment
M_{LS}	Moment at Lumbar Spine
O2	Oxygen
RAH	Rotational Axis of the Hip
sEMG	Surface Electromyography
3D	Three Dimensional

CHAPTER 1. INTRODUCTION

Backpacks (BP) are the most common means for carrying load and are used by a large population around the world, including hikers, climbers, and military personnel. There is particular interest in the excessive usage by students of all ages who carry heavy loads starting in elementary school that continues up through college. However, use of BP has led to a series of health-related problems that not only affects the spine and neck, but has implications down the body in the hips and knees as well. Within the pediatric research community, there is a high incidence of back pain complaints often due to the lack of design for support (1, 2) and excessive weight being carried. The Chiropractic Pediatric Association, American Occupational Therapy Association, Academy of Pediatrics, and Pediatric Orthopedic Surgeons recognize the widespread problems and recommend BP loads should not exceed 10-15% of the user's body weight (BW); unfortunately, this is not always feasible (3, 4). Current BP technology has been studied across children to young adults (2, 4-7), exploring how BP weight affects biomechanics, muscle response, and metabolic response (1, 3-6, 8-11). The effect of load carriage using backpacks has been extensively studied in the literature and it is widely accepted that there are significant effects on a variety of measures from biomechanics, muscle response, and oxygen consumption. Carrying heavy loads also has a significant impact on back and shoulder pain, posture, and gait patterns in the adult population (3, 7, Faiz, 2019 #96, 12-14). Due to their design, the backpack weight acts behind the user which not only compresses but also applies a backward torque to the spine. The straps additionally apply a backward shear force to the spine (9, 15, 16). These increased forces acting on the upper body cause BP users to compensate by forward trunk lean and altered lower extremity movement patterns, which further attributes to overuse injuries (6, 10, 17).

The Ergonomic Backpack (EBP) was designed with the motivation to overcome the health-related problems caused by the load carriage conditions introduced by backpack technology. The goal was to design a backpack that improved ergonomic performance compared to a standard backpack during walking activities. The term ergonomic performance was characterized by an accumulation of variables that could be used to evaluate backpack technology, including decreased shoulder and spine loads, reduction in paraspinal muscle involvement, reduction in oxygen (O2) consumption (metabolic cost), reduction in lower extremity muscle effort, and improved comfort. The EBP utilizes several design features that alleviates spine and shoulder loading by redirecting and counterbalancing the external load from the backpack. The objectives of this thesis were to 1) design and validate the design features of the EBP during a static loading condition, and 2) asses the function of the EBP during a dynamic loading condition (walking task).

The organization of this thesis is as follows: Chapter 2 presents background information and literature review to provide the need and motivation for this work. Chapter 3 details the design goals, design features and validation of the EBP design. Chapter 4 details a functional treadmill walking analysis of muscle response, segment position, and oxygen consumption with healthy individuals comparing the EBP to a traditional school backpack. Chapter 5 provides discussion relating to the significance of the findings and offers future directions of study.

CHAPTER 2. BACKGROUND

Anatomy

To understand the principles of biomechanics and clinical concepts that are described in this thesis, a basic understanding of anatomical terms is important. The human body can be divided into three anatomical planes of movement—the frontal/coronal plane, the midsagittal plane, and the transverse/horizontal plane (**Figure 2-1**). The frontal/coronal plane divides the body front and back, the midsagittal plane divides the left and right, and the transverse/horizontal plane divides the body into top and bottom at the waist. Anatomical relationships are used to describe the relative position in relation to various body parts. Superior refers to toward the head, inferior refers to toward the feet, anterior refers to toward the front of the body, posterior refers to toward the back of the body, medial refers closer to the median of the body, lateral refers to further from the median plane of the body, proximal refers to closer to the trunk, distal refers to farther from the trunk, superficial refers to closer to the surface, and deep refers to farther from the surface. Ligaments (which connect bone to bone) and tendons (which connect muscle to bone) are comprised of connective tissue that helps provide structural stability and allow for muscular contraction for skeletal movement. Skeletal movements occur when muscles contract across the point of interaction between two bones spanning one or more joints. Common skeletal movements include flexion, extension, and rotation. Flexion is defined as a movement that decreases the angle of a joint. Extension is defined as a movement that increases the angle of a joint. Rotation is defined as twisting the body in one direction about an axis (18).

The material presented in this thesis will focus on the vertebral column or the spine which is comprised of 24 individual and moveable vertebrae plus the sacrum and coccyx and serves as the body's axial skeleton. The vertebral column including the sacrum supports and protects the spinal cord and spinal nerves (**Figure 2-2**). The spine is divided into three regions—cervical, thoracic, and lumbar. The seven cervical vertebrae are the smallest since these are in the neck and only have to support the weight of the head. The twelve thoracic vertebrae are larger than the ones above them in the cervical region since there is more weight to carry. Further differentiating them from the other regions is a long and pronounced spinous process on the posterior portion of each segment. The orientation of the processes is important in determining range of motion. There are also additional articulation sites called facets which allow for the ribs to attach directly to the spine. Finally, the five lumbar vertebrae are the largest since they carry the most body weight and transfer the body weight to the pelvis through the articulation of L5 and S1. The spinous processes are also much shorter and rounded than those in the thoracic region (18).

Generally, the vertebrae have the same structural pattern despite some differences depending on where they are found in the spine (**Figure 2-3**). The typical pattern consists of a body, vertebral arch, and seven processes (**Figure 2-4**). The body of each vertebra

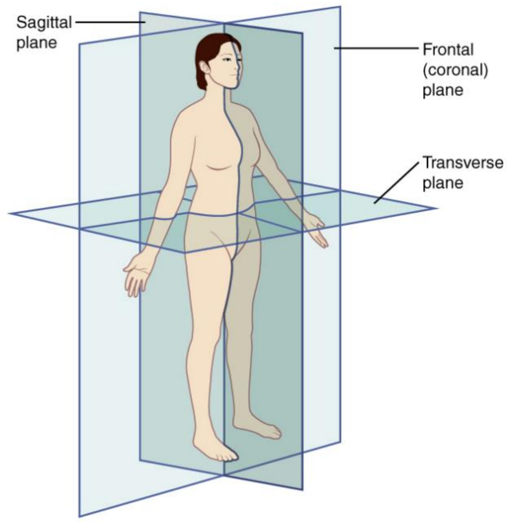

Figure 2-1. Anatomical Planes of the Body.
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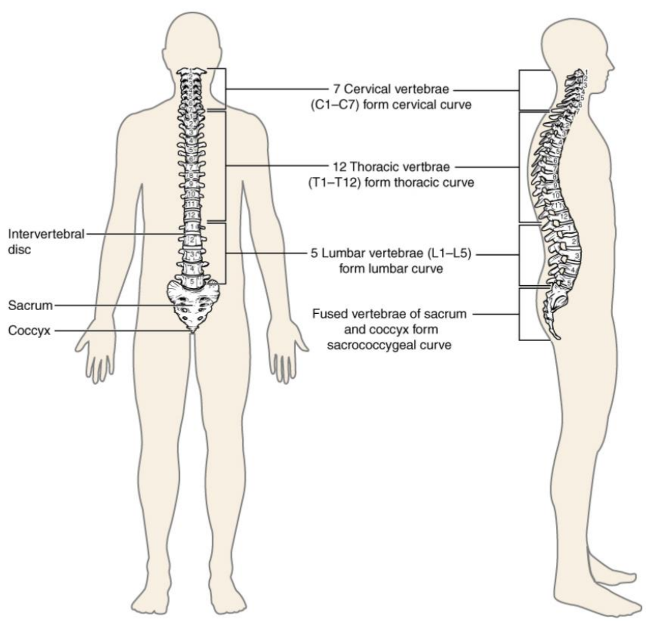

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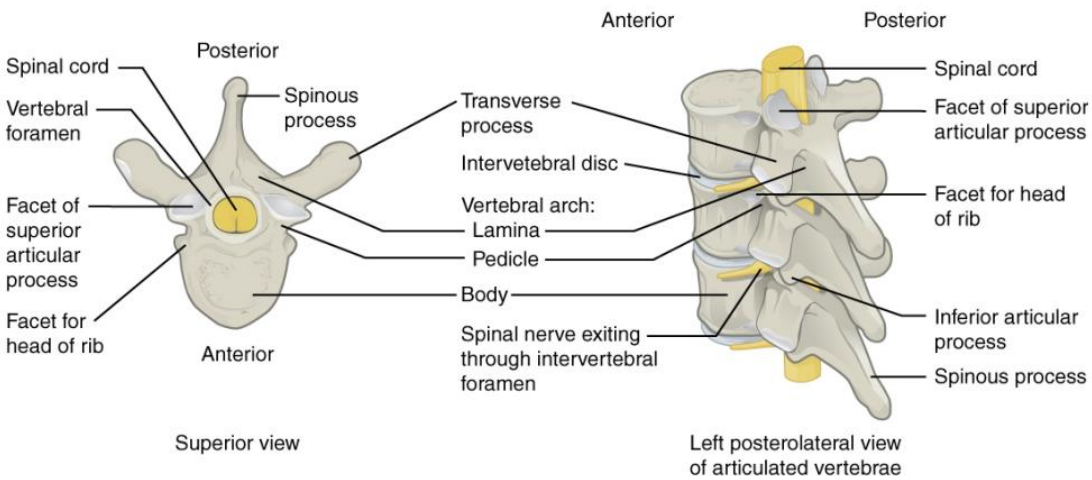

Figure 2-3. General Anatomy of a Vertebrae.
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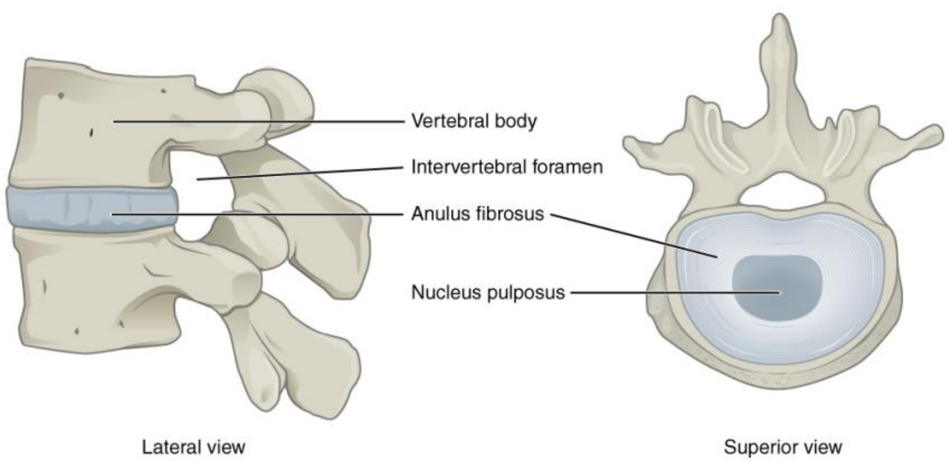

Figure 2-4. Vertebral Body and Intervertebral Disc Anatomy.
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supports the body weight so this anterior portion will increase in size and thickness towards the bottom of the spine since it must support more weight. The vertebral arch is on the posterior portion of each vertebra. From the vertebral arch comes the processes—transverse, spinous, superior articular, and inferior articular. All the processes are paired together, except the spinous process, and these articulations play important roles in motion and serve as muscle attachment sites which provide support and control motion. Between adjacent vertebral bodies, with the exception of C1 and C2 is an intervertebral disc which provides padding and shock absorption and allows for intervertebral movement (18).

Due to the structure of the spine, it is capable of motion in six different degrees of freedom—flexion, extension, lateral (to the side) flexion, and rotation. In the spine, flexion is seen with anterior (forward) bending of the torso, extension involves the same motion but, in the posterior (backward) direction. Rotation in the spine occurs about the vertical spinal axis and is defined as the sum of all the small rotations produced between the vertebrae relative to each other. In terms of mobility, the cervical and lumbar regions of the spine allow for the most range of motion compared to the thoracic region which is more stable due to the rib attachments. Due to its mobility, the lumbar spine lacks in inherent structural stability so further stability is provided by the supporting tissues and musculature. The musculature of the back helps to stabilize the spine and provide movement. Specifically, the erector spinae group provides most of the muscle mass of the back and is primarily responsible for extension. However, it also helps control forward flexion, lateral bending, and axial rotation (18).

Electromyography

Surface electromyography (sEMG) is a common method used to evaluate skeletal muscle responses (electrical activity) from the skins surface (19). Measurement involves cleaning the skin surface and attaching adhesive electrodes over the largest part of the muscle of interest and connection to a transducer for data transmission. The signal from the EMG provides insight into characteristics of the muscle's function (or dysfunction) and provides information about its activities. Analysis of this signal can be combined with kinematic and kinetic parameters to give a more complete understanding of gait and muscle balances and joint performance (20).

Some of the material presented in this thesis pertains to this method of analysis. It was determined to be of particular interest in the paraspinal muscles which offer support and stability across the spinal column, specifically at the lumbar region where much of this research is focused.

Human Locomotion

The act of moving from one location to another, whether by walking, running, or climbing stairs is known as locomotion. Patterns of locomotion, or gait, are defined by repetitive sequences, or cycles, of lower limb progression meant to move the body forward while maintaining stability. The gait cycle (**Figure 2-5**) is divided into two phases—stance phase and swing phase. Stance is considered the period during the gait cycle in which the foot is on the ground and accounts for 60% of the cycle. Swing is the period when the foot is in the air for advancement accounts for 40% of the cycle. The gait cycle is then further divided to define the functional patterns that allow for forward progression. The stance phase is divided into initial contact (heel strike), loading response (shock absorption), midstance, and terminal stance. The transition from stance to swing is defined as pre-swing (final weight transfer to supporting leg). The swing phase is divided into initial swing (toe off), mid-swing (limb advancement) and terminal swing (complete limb advancement to prepare for next stance). The material in this thesis primarily focuses on activity during the stance phase or over the entire gait cycle (21).

Implication of Backpacks

The effect of load carriage using backpacks has been heavily studied in the literature and it is widely accepted that there are significant effects on a variety of measures from biomechanics, muscle response, and oxygen consumption. These effects could increase the risk of injury and other pathologies in those that frequent heavy load carriage.

Biomechanics

Gait biomechanics allows for the study and measurement of the body's function and movement during walking. In evaluating gait patterns, kinematic and kinetic variables are used as standard forms of measurement to better understand biomechanical characteristics. Kinematics help describe spatial movement of the body not considering the forces at play so these measures include joint angles, velocities, and accelerations. Kinetic variables on the other head, consider the forces interacting with and thus affecting the motion of the body, therefore these measures include ground and joint reaction forces, moments, tendon forces, joint contact forces, power, and work (22).

Extensive studies have explored the biomechanics of load carriage looking at joint angles, moments, and muscle powers which help indicate the amount of effort that is required to maintain an activity (i.e. walking) while carrying loads. Studies have shown that joint angles increase with added load (7, 17, 23-26) which is believed to be an attempt at maintaining gait stability after addition of weight. Studies have also shown that joint moments in the lower extremity increased with the addition of loads (6, 17, 25, 27, 28). These results indicate that the mechanical load being applied to the joint and surround tissues is increased with load which could increase the risk for an overuse injury. Consequently, joint muscle powers have also been shown to increase (17, 29, 30) which reveals increases in overall muscle effort. Increases in muscle power are also likely to be explained by the need to support the increased weight above the lower extremity that is experienced in load carriage and to maintain forward motion (propulsion). Another

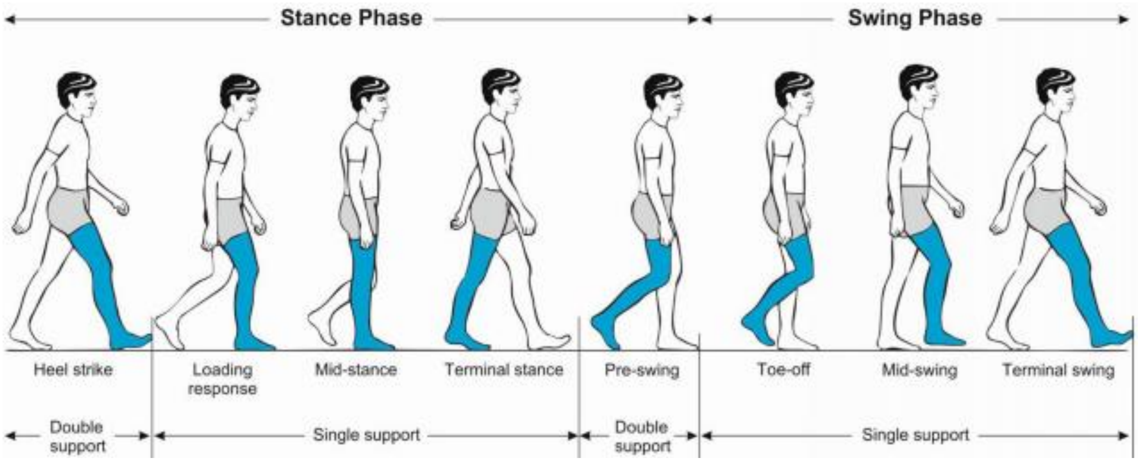

Figure 2-5. The Phases of the Gait Cycle.
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compensation as a result of the posterior center of mass shift with the addition of a loaded backpack is an increase in trunk lean. Results from studies exploring this measure consistently report increased forward trunk lean with added loads (4, 6, 23, 26, 32, 33).

Muscle Response

Muscle response during load carriage has also been explored in various muscle groups from the erector spinae to the lower extremity (quadricep, hamstring, and gastrocnemius) muscle groups. This muscle response is measured using a method called electromyography (EMG) which measures the inherent electrical activity of the muscle from either the skin surface via sticker electrodes or within the muscle itself via needle electrodes. Average and peak amplitudes of EMG have been shown to increase which support greater muscle activity during load carriage, specifically in the erector spinae which could lead to injury from overuse (6, 27, 34-37). EMG responses can also be supported with joint angle and moment results with explanation of more extensor or flexor activity.

Oxygen Consumption

Load carriage has also been shown to have physiological effects on the carrier. Studies have revealed that oxygen consumption increases with incremental load (28, 38, 39). It has been proposed that this response is due to the increased demand for oxygen by the muscles and the increased forward trunk lean that appears with load carriage results in compromised respiratory function, causing the carrier to consume more oxygen. Carriage with more trunk lean also results in an increase metabolic cost (or worse metabolic economy) due to the compromised respiratory function (38, 40).

Backpack Technology

Despite heavy backpacks and the resulting complications being a recognized problem, not much has been done to improve the current design of backpacks (**Figure 2-6**). The current design of school backpacks includes the bag itself (where the weight goes), shoulder straps, a hip strap, and sometimes a chest strap. The additional straps at the hips and chest are meant to hold the bag closer to the body and prevent it from moving too much during walking and running. Another common design is seen in military backpacks where the elements are the same as the school backpack but with the addition of a rigid frame and a thicker hip belt that helps handle the heavier loads that are often carried by military personnel.

Some notable attempts at improvement have appeared in the market through smaller start-up companies. One design from Keep Pursuing, the Zero G Backpack, boasts a reduction in pressure on the shoulders by 9.5% during walking (41). The novel

Figure 2-6. Current Backpack Designs.

feature in this design are the compliant suspension shoulder straps, where the compliance occurs at the top of the straps where they attach to the pack itself. Another design from Lightning Packs LLC, the HoverGlide Pack, boasts an 86% reduction in impact forces during running (42). The novel suspended load technology utilizes a bungee cord to help to keep the loads in the pack at a constant height with respect to the ground. Despite the reduction in inertial loads, there is still minimal reduction of the static loads on the spine during walking. Both designs come at hefty price points ($250 and $500, respectively) and therefore would not be feasible for much of the general population.

Modeling Backpack Mechanics

In this thesis, backpack mechanics are explored initially to understand the forces acting on the body so that design goals for improving a backpack could be defined in an effort to improve carriage mechanics through novel backpack technology. When looking at the mechanics involved in carrying a backpack, the main forces are the vertical weight of the bag, the shoulder strap load, and an inward force on the lower back. The bag weight is transferred to the body via the shoulder strap load which acts downward and backward and the inward force which acts horizontally towards the wearer's lower back. These forces can then be resolved as force triangle to establish a relationship between bag load and position and the resulting shoulder strap load and inward force on the lower back (**Figure 2-7**).

Further exploring the mechanics of backpack wearing and focusing on the mechanics of the straps themselves, the strap force can be split into a backwards shear force and an axial compressive force. These shear and axial forces act externally on the thoracic (upper) and transfer through the lumbar (lower) spine to the pelvis (**Figure 2-8**). Since the additional vertical force from the bag weight is off axis from where the shoulder strap forces are acting (more midline with the body), there is an external moment (torque) that is induced by wearing the bag. Internally, there is a reaction force at the lumbar spine as well as a moment due to the bag weight due to the weight transferred from the straps (**Figure 2-8**). If the loads at the shoulders could be reduced by transferring a portion of the weight to the pelvic region at an external location, then there is a potential to alleviate the common problems associated with backpacks (**Figure 2-9**).

Ergonomic Backpack (EBP)

The ergonomic backpack was designed as a possible solution for the common problems (short and long term) from carry heavy backpacks. Three main design features of the EBP to improve the problematic loading conditions will include: 1) a pivot component located along the sagittal mid-line of the spine, which also vertically aligns with the rotational axis of the hip (RAH) to support the redirected load, 2) a counterbalance system to transfer a percentage of the action of the backward torque from the spine to the pelvic belt, and 3) an adjustable pivot component location on pelvic belt to accommodate different body sizes and optimal moment reduction (**Figure 2-10**). These

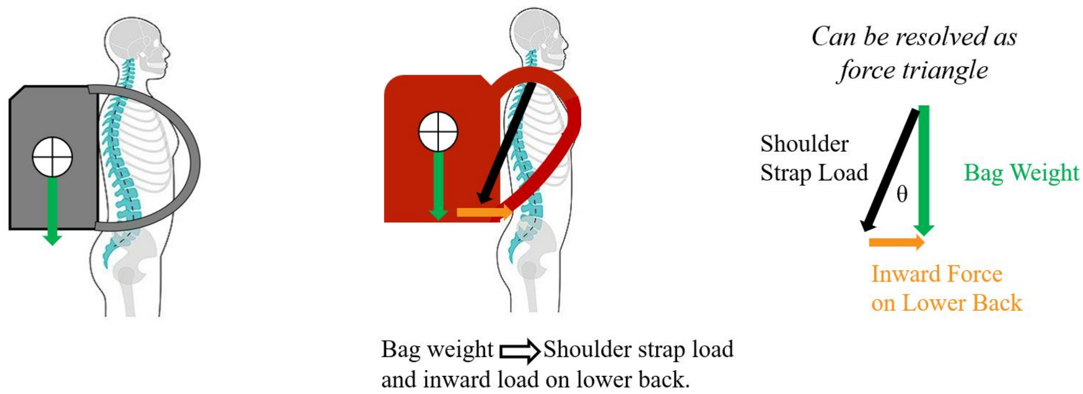

Figure 2-7. Backpack Force Relationship.

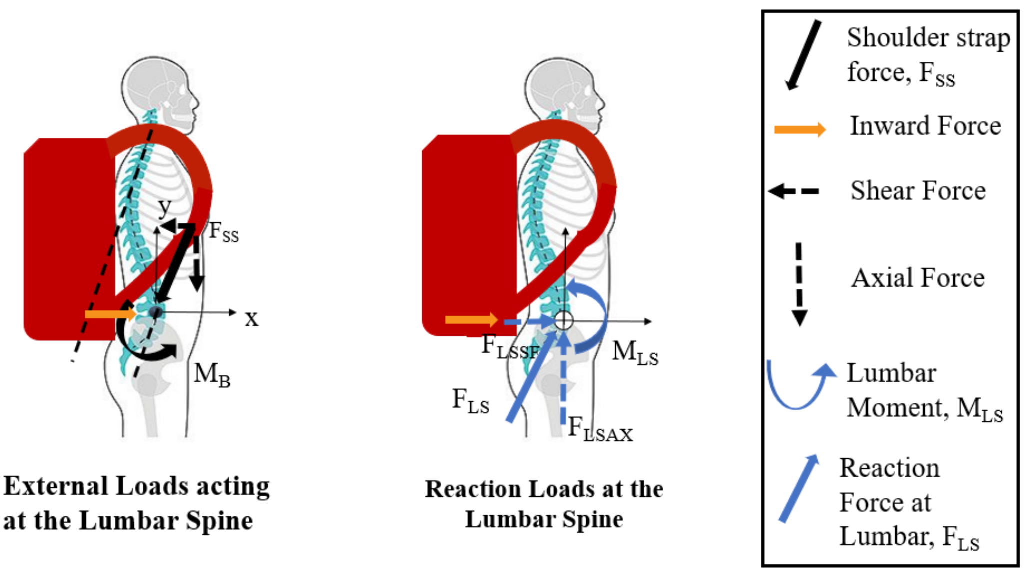

Figure 2-8. External and Internal Forces at Lumbar Spine While Wearing a Backpack.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment, F_{LS}=Reaction Force at Lumbar Spine, M_{LS}=Moment at Lumbar Spine.

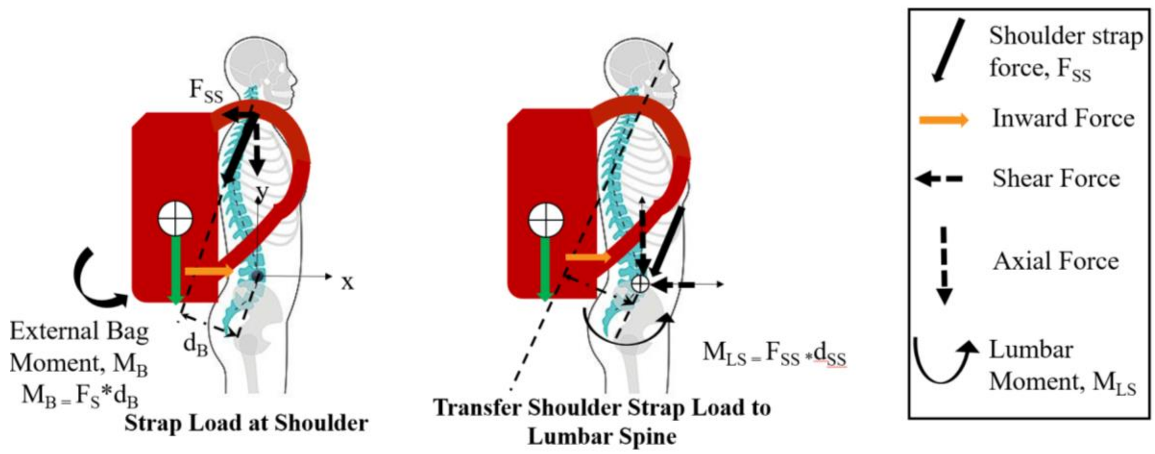

Figure 2-9. Transfer of Shoulder Loads to the Lumbar Spine.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment, d_B=Bag Weight Distance, Spine, M_{LS}=Moment at Lumbar Spine.

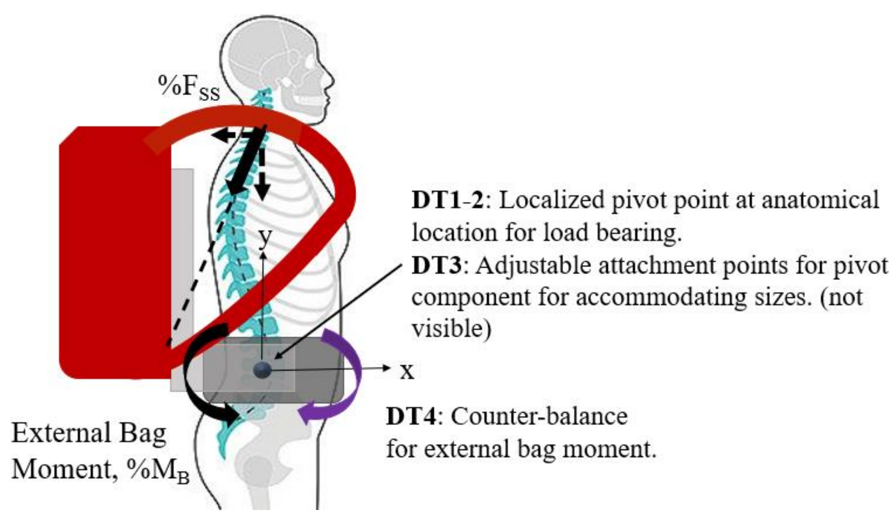

Figure 2-10. Ergonomic Backpack Design Tasks.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment.

design features aim to offload the shoulder and spine by redirecting a portion of the loads experienced there to the pelvis. **Figure 2-11** shows a model of the assembled EBP being comprised of a frame, pelvic belt, pivot component, and counterbalance mechanism. More details on the design, validation, and assessment of the EBP are provided in Chapters 3 and 4.

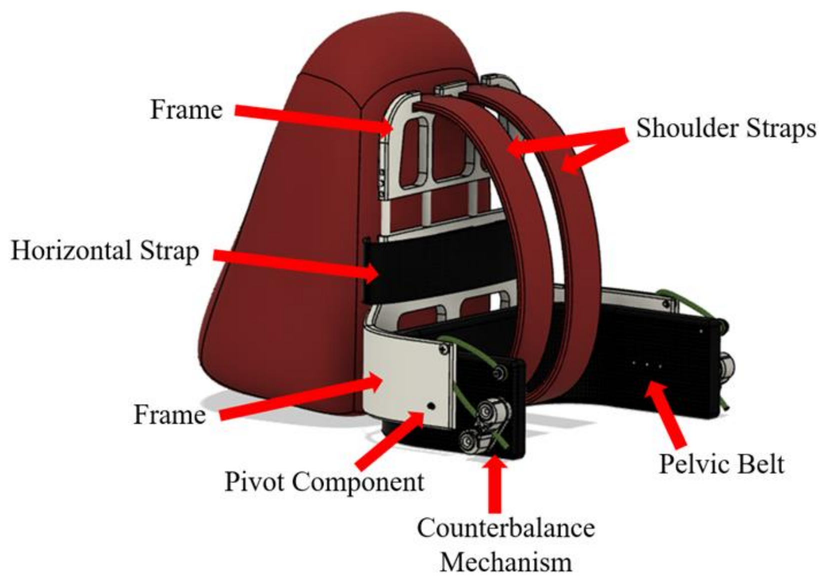

Figure 2-11. Assembled Ergonomic Backpack Concept.

CHAPTER 3. STUDY 1: DESIGN AND VALIDATION OF A NOVEL ERGONOMIC BACKPACK

Introduction

Backpacks (BP) are the most common means for carrying load but heavy loads that are often seen can lead to a variety of health-related problems that can affect the major joints and structures of the body. It has been previously suggested that BP loads should not exceed 10-15% of the user's body weight (BW); unfortunately, this is not always feasible (3, 4). Current BP technology has been studied across ages (2, 4-7), exploring how BP weight affects biomechanics, muscle response, and metabolic response (1, 3-6, 8-11). It is widely accepted that using backpacks has a significant impact on back and shoulder pain, posture, and gait patterns in the adult population (3, 7, Faiz, 2019 #96, 12-14). Due to their design, the backpack weight acts behind the user which not only compresses but also applies a backward torque to the spine, additionally the straps further apply a backward shear force to the spine (9, 15, 16). These increased forces acting on the upper body can increase the risk of musculoskeletal injuries to the spine but also cause BP users to compensate by forward trunk lean and altered lower extremity movement patterns, which further attributes to overuse injuries (6, 10, 17).

The objective of this study was to validate the design tasks that were defined for the EBP. It was determined that the measures that would validate the EBP design were 1) the strap tension-bag load relationship in the EBP compared to a traditional backpack, and 2) the shoulder load-bag load relationship in the EBP compared to a traditional backpack. It was hypothesized that the measurements of strap tension and shoulder load taken in the EBP would be lower compared to the measurements taken in the traditional backpack.

Ergonomic Backpack

An Ergonomic Backpack (EBP) was designed as a potential solution to reduce the problematic loading conditions that arises with heavy backpack carriage. **Figure 3-1** shows how the load from backpack shoulder straps is transferred to and results in reaction loads at the lumbar spine. With the motivation to combat the loading mechanics from the straps, the novel backpack design is meant to reduce a portion of the load at the shoulders and thus transferred to the spine. Therefore, the goal of this study was to design and validate an ergonomic backpack. Four design tasks (DT) for developing of the EBP were established in order to obtain the goal of offloading the shoulders and spine: 1) redirect the load from the spine and shoulders to the midline of (or posterior to) the pelvic region, 2) use a pivot component to support the redirected loads at a specific anatomic location to minimize the off-axis moments that are induced from the load carriage, 3) establish a means of accommodating different body size with adjustable pivot component attachment locations, and 4) design a counter-moment or counter-balance mechanism for the external bag moment (**Figure 3-2**). Mathematically, this counterbalance mechanism would be

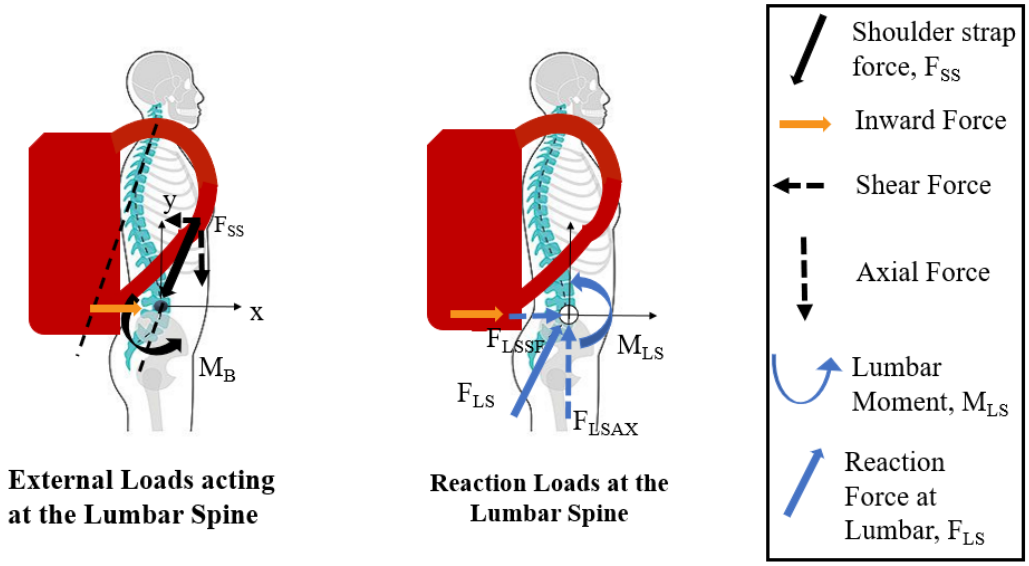

Figure 3-1. External and Internal Spine Loads with a Backpack.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment, M_{LS}=Moment at Lumbar Spine, F_{LS}=Force at Lumbar Spine.

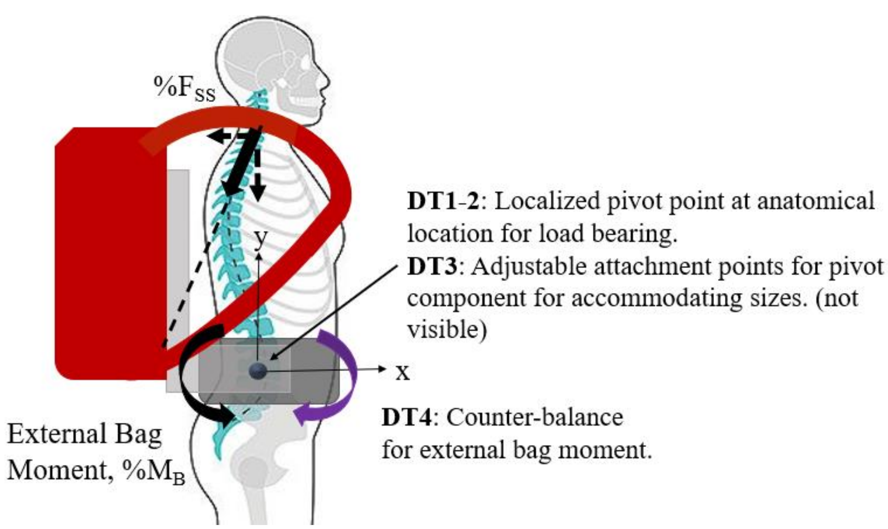

Figure 3-2. Ergonomic Backpack Design Tasks.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment.

capable of balancing either all or some percentage of the known external bag weight (that produces the external moment) for effective offloading (**Figure 3-3**). **Figure 3-4** provides a visual for the derived equation (**Equation 3-1**) that establishes a relationship of the counterbalance mechanism relative to the external bag moment.

$$M_B = 2F_C * h = F_{CM} * h \qquad \textbf{(Eq. 3-1)}$$

A step in the fabrication process involved setting the amount of rotation of the frame about the pivot component so that the frame and attached backpack would remain as vertical as possible thus improving the loading mechanics of the straps. By knowing the moment arm and the weight of the bag, it was determined how much force would need to be produced by the counterbalance mechanism to balance the bag weight and control the backward rotation of the frame. For this study, a 9.525 mm (3/8-inch) diameter bungee cord with an estimated stiffness of 2863.16 N/m (2.86 N/mm) was found to be effective as it could hold the frame and bag system up in all tested loads, allowing for approximately five to ten degrees of rotational compliancy. This known relationship could be used in design modifications to optimize the net counterforce of the counterbalance mechanism to balance the external bag moment more effectively by controlling the amount of movement or displacement of the bag. Doing so would further improve the loading mechanics from the straps and create opportunity for additional embodiments of the counterbalance mechanism to be explored.

EBP Features

The EBP design consists of a backpack, a frame, a pelvic belt, pivot component, and a counterbalance mechanism. The backpack itself (**Figure 3-5**) is comprised of the pack portion which contains separate compartments for loads, an adjustable chest strap, and two adjustable shoulder straps. An additional horizontal strap has been attached which helps to hold the back portion of the frame to the bag. The frame used for the EBP is comprised of a heat molded material and was cut to have a section that goes up the back and arm portions that wrap around the hips. The arms of the frame each have a hole for the pivot attachment directly to the pelvic belt and a pin for the counterbalance mechanism to act on the frame (**Figure 3-6**). When the counterbalance mechanism is activated, the frame supports the backpack and its loads which then offers offloading to the shoulders and spine. The pelvic belt that is used for the ergonomic backpack has a configuration that is utilized to engage around the wearer's hips and contour the wearer's natural anatomical profile in the pelvic region (at the level of the iliac crest). In the EBP assembly, there are several tapped t-bushings which are secured to a plastic plate within a pocket on each side of the pelvic belt. The holes are arranged horizontally to accommodate different body sizes and varying ideal locations of the pivot component that would result from wearers of different sizes adjusting the belt to be worn as it is intended (**Figure 3-6**).

The counterbalance mechanism used for the ergonomic backpack is presently a bungee cord which is attached directly to the belt, interacts with the frame, and is then

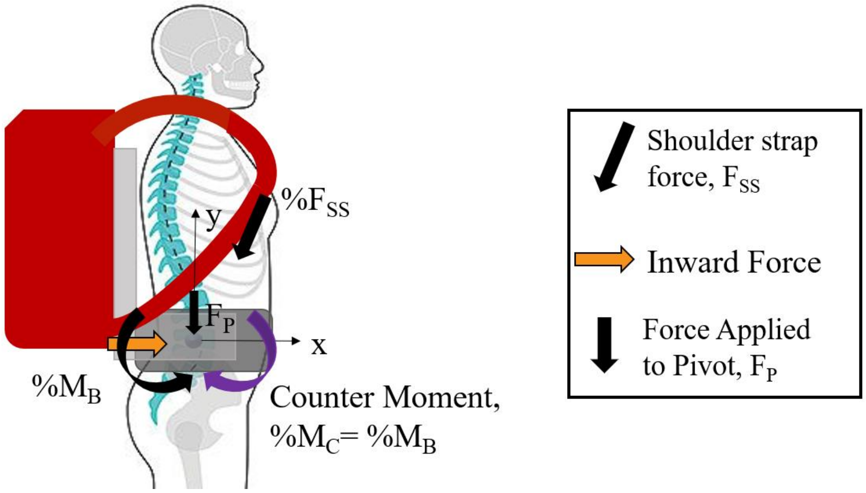

Figure 3-3. Counter Moment as a Percentage of External Bag Moment.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment, M_C=Counter-moment Mechanism, F_P=Force Applied at Pivot.

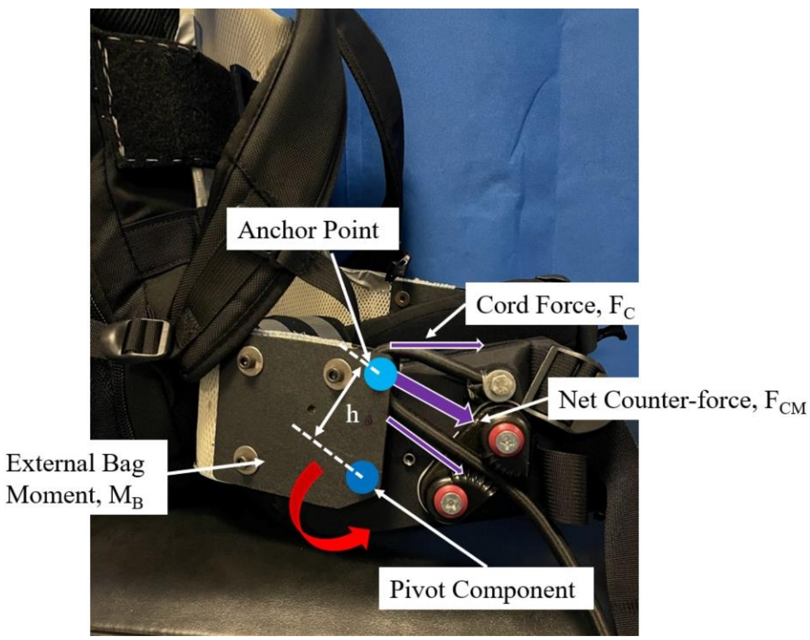

Figure 3-4. Counterbalance and Bag Moment Relationship.
M_B=External Bag Moment, F_C=Cord Force, F_{CM}=Net Counter-Force.

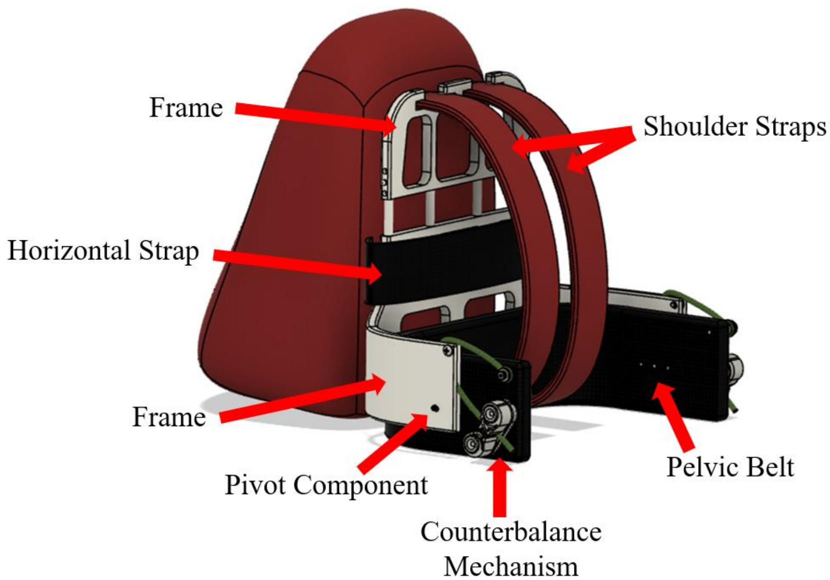

Figure 3-5. Ergonomic Backpack Components.

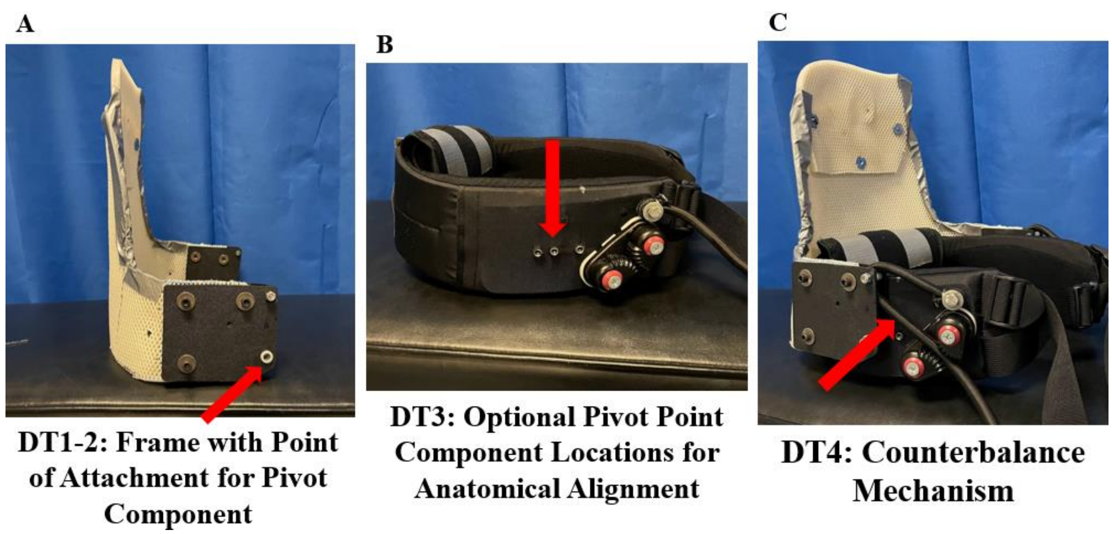

Figure 3-6. Ergonomic Backpack Features Based on Design Tasks.
DT: Design Task. A) Depicts the molded frame with the pivot component highlighted as DT 1-1, B) Depicts the pelvic belt with adjustable locations for the pivot component as DT 3, and C) Depicts the counterbalance mechanism and how the frame interacts directly with the pelvic belt via the pivot component.

secured using a clamping cleat (**Figure 3-6**). Using a bungee cord offers a counterbalance to the external moment that is induced by the backpack and could reduce the forces experienced by the spine by holding the frame and thus the bag in place. In the assembled ergonomic backpack, the frame attaches via the hole created in each arm and attaches to the outside of the pelvic belt and is held in place by a shoulder screw to allow for free rotation of the frame with respect to the pelvic belt. The back portion of the frame is also held in place against the back portion of the backpack with the added strap. The counterbalance mechanism is attached to the pelvic belt towards the front of the belt, where it then wraps around a pin on the frame to allow it to pull/act on the frame and thus holding it in place. Once around the pin, the bungee cord is then secured into a cleat which is a spring-loaded clamp that allows for easy securing and release of the counterbalance mechanism.

Methods

Experimental Protocol

Strap Tension Measurement

To quantify the strap tension-bag load relationship and thus validate the offloading effects of the EBP design, the following set up and procedures were used for measurements in both the traditional backpack and EBP. For strap tension measurement, standard portable luggage scales (Esky® – Sky of Electronics) were modified and attached directly to the backpack shoulder straps (**Figure 3-7** and **Table A-1**). Seatbelt clips were attached to the back of the luggage scale via a nut and screw before being fixed to the top portion of the backpack strap. Snap buckles with strap adjusters were used to attach the bottom strap to the luggage scale. Further details on the assembly of the scale system can be found in **Figure B-1**. With this configuration, the tension in each strap was measured directly by the luggage scale since the shoulder straps were not connected to the bag.

Once each backpack was fitted on a participant, weight was added to the bag in five-weight increments (0 kg to 11 kg). The luggage scales were zeroed at each increment by lifting them up to release any excess weight they may be measuring and pressing the zero button before dropping the scale for recording. The readings on each scale were recorded and summed for analysis of the total strap tension. Once the weight in the backpack reached the highest weight (11 kg), the same process was performed in reverse with weight being removed from the bag and the scales being zeroed once again prior to recording the reading. This process of adding/removing weight and zeroing the scales was performed three times in both the traditional backpack and ergonomic backpack.

Figure 3-7. Strap Tension Measurement Set Up.
BP: Backpack.

Shoulder Load Measurement

To quantify the shoulder load-bag weight relationship and thus further validate the offloading effects of the EBP design, pressure sensors (100 Hz, loadsol, Novel, St. Paul, MN) were used underneath the shoulder straps which provided an estimate of the total force being applied to them (**Figure 3-8, Table A-1** and **Figure B-2**). To optimize contact with the shoulder, foam padding was placed below the pressure sensor against the sensor could estimate the loads between the strap and foam padding on each shoulder.

Prior to testing, the pressure sensors were calibrated and zeroed using the loadsol application on a smart phone. During testing, net contact loads from the sensors were continuously recorded using the loadsol application while weight was added to the bag in five-pound increments (0 kg to 11 kg). Once the weight in the backpack reached the highest weight, the same process was performed in reverse order with weight being removed from the bag in the same recording session. It was ensured that the force values stabilized (about ten seconds) in the recording prior to adding more weight, thereby providing an accurate and stable reading of the shoulder pressure at each incremental weight. The recorded data were then exported from the loadsol application for analysis. This process was repeated three times in a randomized order of the traditional backpack and ergonomic backpack (EBP).

Data and Statistical Analysis

Recorded strap tension data from the luggage scales and exported shoulder pressure data were processed and analyzed using Microsoft Excel (Microsoft Corporation, Redmond, WA). The recorded strap tension measurements from each strap at each weight increment were summed so that a total strap tension value could be obtained. The shoulder pressure values were interpreted directly from the exported data at each ten-second increment of weight recording. The average of all trials from each measurement were used for statistical analysis.

A one-way repeated measures analysis of variance (ANOVA) with post hoc Tukey tests for multiple comparisons (α=0.05) were used to determine the effect of the backpack design on the measurements at each weight increment that passed the normality test. Cohen's d effect size was determined to assess the effect size for differences between the backpack conditions (i.e., small: $d < 0.2$, medium: $0.2 \leq d < 0.8$, large: $d \geq 0.8$).

Results

The EBP showed somewhat of a reduction effect on the strap tension in the in the higher backpack loads, however they were not significant despite the large effect size (**Figure 3-9**). However, the EBP did reveal a significant reduction effect of approximately 50 % in the shoulder load in all the backpack loads (**Figure 3-10**).

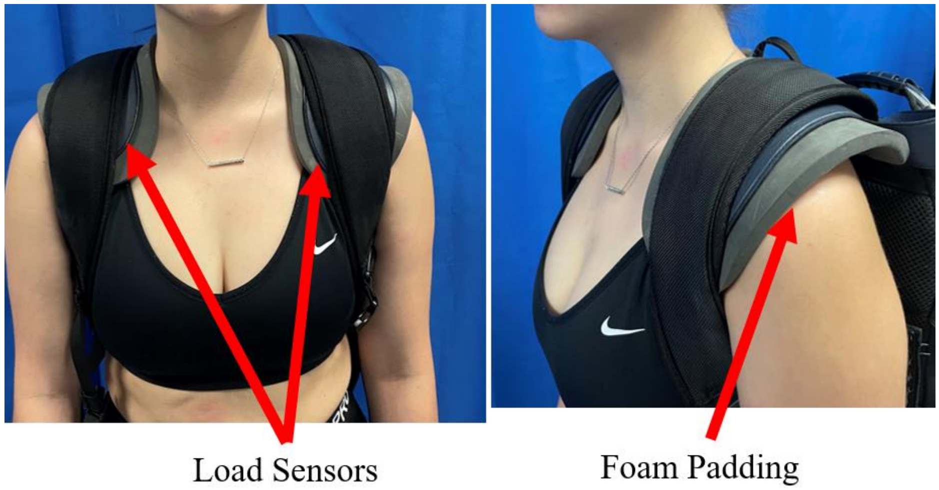

Figure 3-8. Shoulder Load Test Set Up.

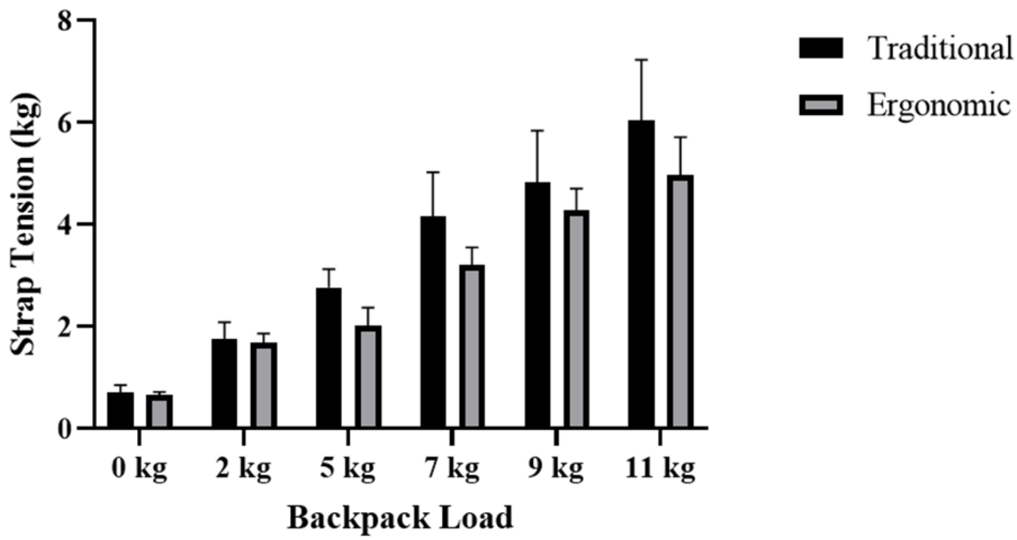

Figure 3-9. Strap Tension Measurements in Each Backpack Condition.

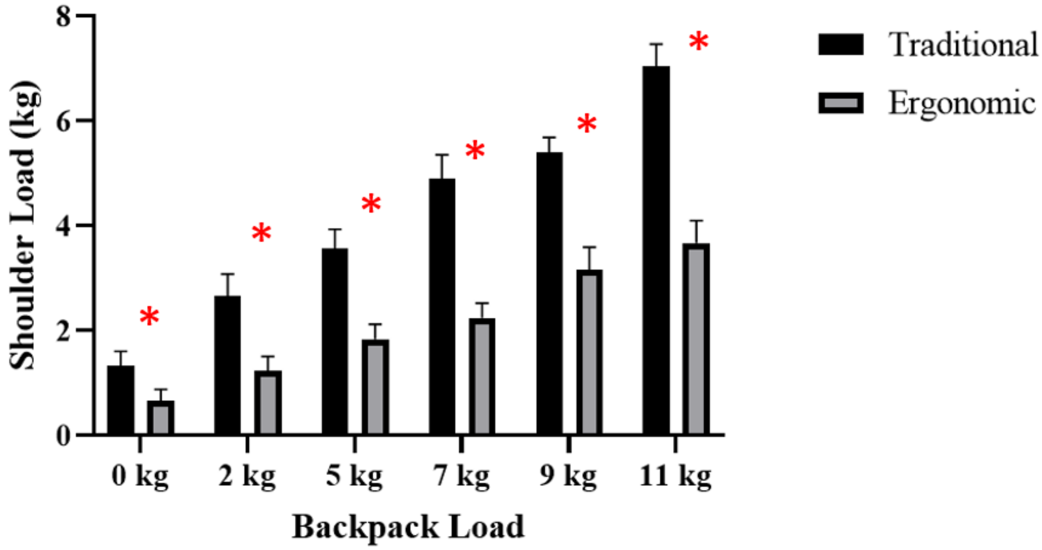

Figure 3-10. Shoulder Load Measurements in Each Backpack Condition.
* Denotes significant difference from traditional backpack.

Table 3-1 summarizes the measured strap tension and shoulder loads in each backpack at the five weight increments.

Discussion

The purpose of this phase of the project was to validate that the design tasks (DT) of a reduction in shoulder loads (specifically DT 1-2) had been satisfied. It was hypothesized that the measurements of strap tension and shoulder pressure taken in the EBP would be lower compared to the measurements taken in the traditional backpack.

The hypothesis was supported by the results of the measurements in both strap tension and shoulder load. The results revealed that the EBP has the capability to demonstrate shoulder offloading. This indicates that the design tasks affiliated with offloading the shoulders (DT 1-2) were achieved. This accomplishment of the design tasks validates part of our design goals to offload the shoulders (and therefore the spine though a reduction in the transmitted loads) while wearing the EBP. Data from other novel backpack designs report decreases of 9.5% and 86% reduction in shoulder loads and inertial loads, respectively (41, 42). The results from the validation study revealed a much larger reduction in the shoulder loads with the EBP compared to the backpack with novel compliant straps. (41) Despite the significant reduction in inertial loads from the backpack with suspended load technology, there was no shoulder offloading as demonstrated by the EBP (42). Without the shoulder offloading element that the EBP provides, there is minimal reduction of the loads on the spine during walking despite reduction in inertial loads.

The results of this study are limited to static load carriage and backpack wear since measurements were taken while standing and weight was added, not while walking. To better understand the dynamic effects of the EBP compared to a traditional backpack, a gait study where participants wear each backpack system while walking with the same weights being added would need to be conducted since current findings would not be generalizable to walking.

Conclusion

Benchtop and static validation of the EBP provided evidence of the efficacy of the EBP to provide significant offloading to the user’s shoulders. The next phase of the EBP design evaluation is to assess the functionality of the EBP in a healthy population to determine its capability to improve ergonomic performance during a dynamic walking task compared to a traditional backpack.

Table 3-1. Strap Tension (kg) and Shoulder Load (kg) Measurements in Each Backpack Condition.

Bag Load (kg)	Strap Tension					Shoulder Load				
	Traditional	Ergonomic	Percent Change	P-Value	Effect Size	Traditional	Ergonomic	Percent Change	P-Value	Effect Size
0	0.7±0.1	0.6±0.1	-6%	0.6611	-0.36	1.3±0.7	0.6±0.2*	-51%	0.0100	-2.66
2	1.7±0.3	1.6±0.2	-4%	0.7397	-0.27	2.7±0.4	1.2±0.2*	-54%	0.0017	-3.95
5	2.8±0.4	2.0±0.4	-27%	0.0637	-2.11	3.5±0.3	1.8±0.2*	-49%	0.0002	-5.37
7	4.2±0.9	3.2±0.3	-23%	0.1068	-1.44	4.8±0.4	2.2±0.2*	-54%	0.0002	-7.01
9	4.8±1.1	4.2±0.4	-11%	0.3660	-0.71	5.4±0.3	3.2±0.4*	-42%	0.0001	-6.22
11	6.1±1.2	4.9±0.7	-18%	0.0801	-1.07	7.1±0.4	3.6±0.4*	-48%	0.0002	-7.88

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

CHAPTER 4. STUDY 2: FUNCTIONAL ANALYSIS OF A NOVEL ERGONOMIC BACKPACK COMPARED TO A TRADITIONAL BACKPACK

Introduction

Backpack (BP) use is a common form of load carriage across the world. However, the current design of backpacks that are commonly used create problematic loading conditions that increase the risk of injury due to the lack of support to compensate for the excessive load being carried. This problematic loading is of particular concern in the lower back as there are a variety of structures that can be affected from the musculature to the intervertebral discs and the nerve roots (43, 44). Besides affecting the spine through direct increase in loads, the posterior addition of weight to the wearer's back can further alter walking mechanics which could increase the risk for injury and speed up fatigue.

Most studies have focused on the effect of traditional load carriage on various performance or biomechanical measures, but others have looked at comparing different methods of load carriage compared to the traditional load carriage method. Current backpack designs result is all weight being carried in the shoulders on the posterior side of the body and have shown that it increases muscle activity (6, 25, 27, 35-37, 45, 46), joint muscle power (17, 30), trunk lean (4, 6, 26, 32), and oxygen consumption (28, 33), especially at high loads. Different methods of load carriage could include an anterior-posterior loading system, a military system, a suspended system, or simply where the load is placed in the backpack. The results of these studies revealed that improving load carriage parameters is possible and the biomechanical changes seen could potentially prevent injury and slow fatigue (23, 29, 38, 47).

An Ergonomic Backpack (EBP) could offer a potential solution to the health concerns and the problematic loading conditions that arises with heavy backpack carriage. To combat the loading mechanics from the straps, the novel design is meant to reduce a portion of the load at the shoulders and thus transferred to the spine resulting in reaction forces at the lumbar (**Figure 4-1**). Four design tasks (DT) for developing of the EBP were established in order to obtain the goal of offloading the shoulders and spine: 1) redirect the load from the spine and shoulders to the midline of (or posterior to) the pelvic region, 2) use a pivot component to support the redirected loads at a specific anatomic location to minimize the off-axis moments that are induced from the load carriage, 3) establish a means of accommodating different body size with adjustable pivot component attachment locations, and 4) design a counter-moment or counter-balance mechanism for the external bag moment (**Figure 4-2**).

The purpose of this study was to evaluate ergonomic performance while wearing the EBP compared to the traditional backpack. The first aim was to measure paraspinal muscle response (through EMG). It was hypothesized that paraspinal muscle activity

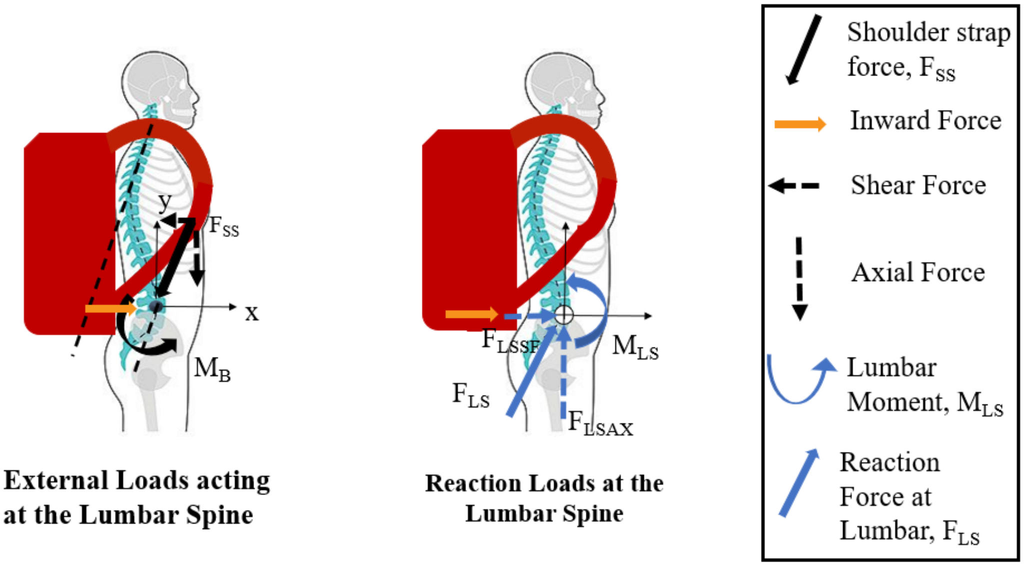

Figure 4-1. External and Internal Spine Loads with a Backpack.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment, M_{LS}=Moment at Lumbar Spine, F_{LS}=Force at Lumbar Spine.

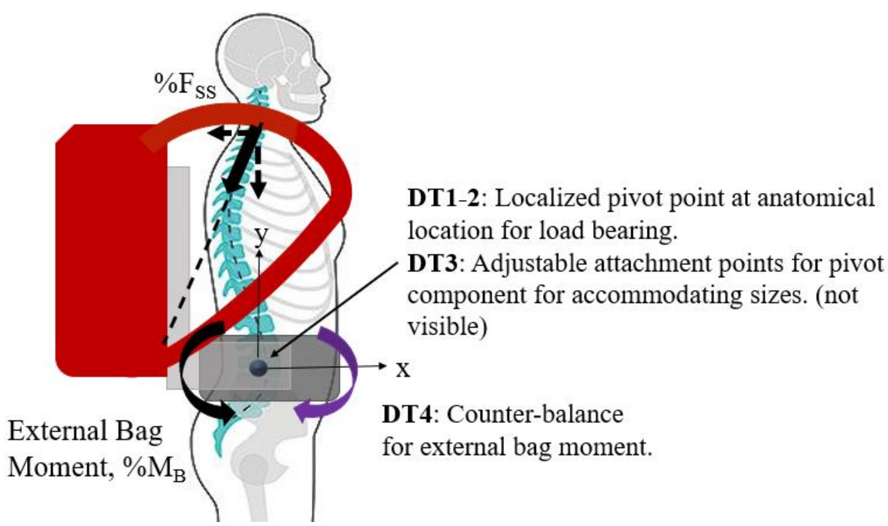

Figure 4-2. Ergonomic Backpack Design Tasks.
F_{SS}=Shoulder Strap Force, M_B=External Bag Moment.

would be reduced with the ergonomic backpack due to the counterbalance mechanism acting against the external bag load. The second aim of this study was to measure oxygen (O_2) consumption and lower limb muscle response (through EMG and kinetics/kinematics). It was hypothesized that O_2 consumption and lower extremity muscle activity will be reduced with the ergonomic bag due to less effort being needed to execute the task. It was hypothesized that the overall ergonomic performance would improve during load carriage with the EBP. These means of measurement were chosen since they would be useful in determining overall ergonomic performance outcomes.

Methods

Participants

An a priori power analysis (G*Power 3.1.9.7, Heinrich Heine University Dusseldorf, Germany) using an average effect size of 2.2 (from paraspinal EMG measures between the traditional and ergonomic backpacks in preliminary analyses which were determined to be the most important measure), alpha set to 0.05, and a power of 0.8 for a repeated measures ANOVA suggested that a minimum of 4 participants was necessary to obtain the statistical effect size and power to test our hypotheses. Fifteen participants were recruited (8 women, 7 men; 24±2.72 years old, 1.69±0.067 m, 75.7±12.19 kg) for this study. Inclusion criteria required participants to be between the ages of 18 and 40 years old with the ability to carry the chosen loads for the study. Participants were excluded if they had any current or recent (last 6 months) musculoskeletal injury or surgery that could be aggravated by the load carriage or aerobic exercise. They were also excluded if they presented with any underlying health conditions that might make physical activity dangerous based on their answers from the Physical Activity Readiness Questionnaire (PAR-Q). Pregnant women would also be excluded. Prior to data collection, participants were informed of all procedures and possible risks and signed a written consent form approved by the Institutional Review Board (IRB Number: 22-08924-FB UM). Further equipment specifications for this study are detailed in **Table A-1**.

Backpack Conditions

Two backpack conditions were tested in this study: a traditional school backpack and the ergonomic backpack (EBP) design (**Figure 4-3**). The traditional school backpack included the pack itself, two shoulder straps, and a chest strap. The ergonomic backpack (EBP) design included a modified pelvic belt and supportive frame which integrated into the traditional backpack via horizontal straps (**Figure 4-4**). In this study, both backpack conditions would contain two load conditions of 7 and 11 kg in which all participants carried the same weights regardless of body mass. The chosen loads for the low and high loads were determined to be 10% and 15% of the average participant's body weight,

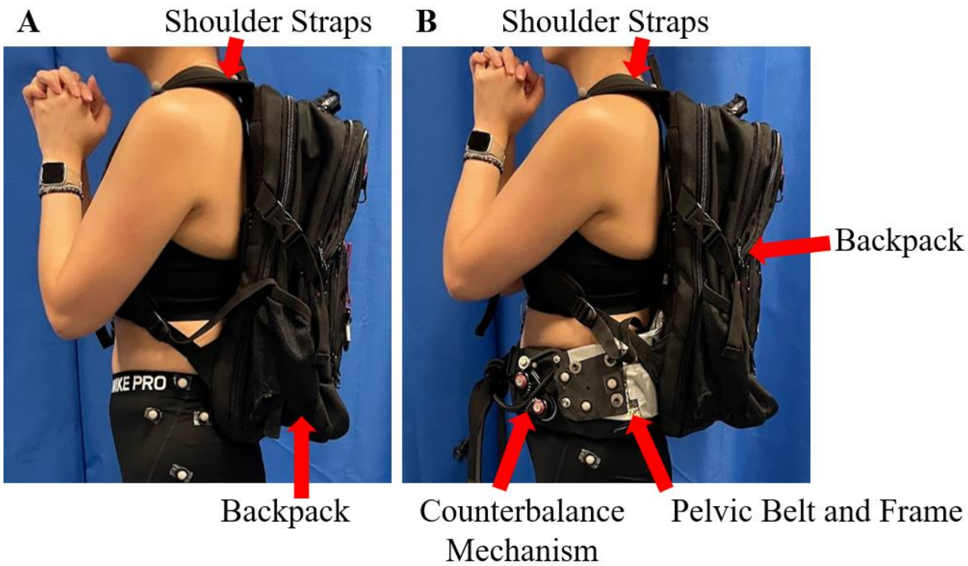

Figure 4-3. Backpack Conditions.
A) Traditional Backpack and B) Ergonomic Backpack.

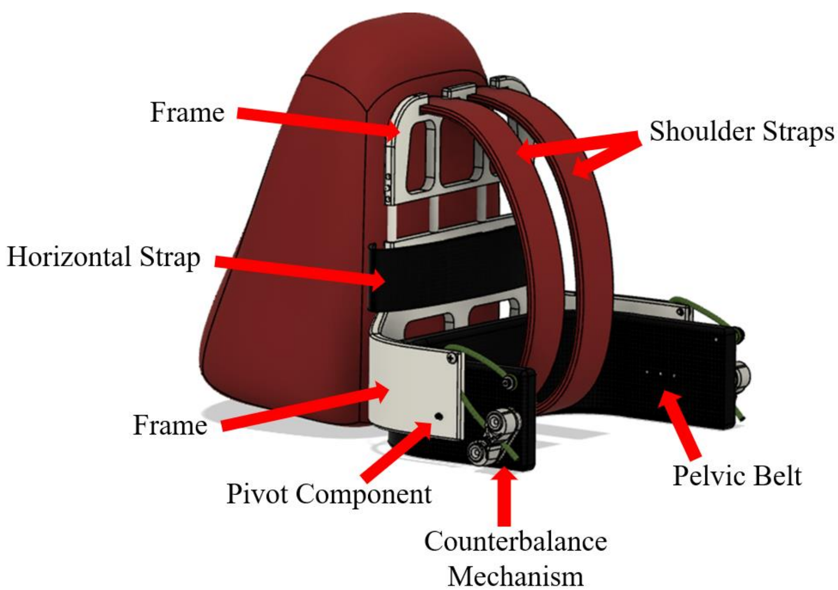

Figure 4-4. Ergonomic Backpack Components.

respectively, which has been cited to be the recommended bag weight for backpacks (3, 12, 13).

Experimental Protocol

The two backpack conditions were randomized for each participant, and within each backpack condition, the order in which the loads (low—7 kg, high—11 kg) were carried was also randomized. For the ergonomic backpack (EBP) condition, participants were instructed and assisted in proper placement and fit of the pelvic belt to ensure optimal wear. The system was fit such that the pivot component was attached at the tapped hole in the belt that would allow for alignment at the midline (or posterior to) the midline of the spine. The belt was fit so that it sat at the level of the iliac crest on the pelvis. Each backpack was worn for 5 minutes prior to data collection to provide a period a system familiarization.

Surface electromyography (sEMG) sensors (3000 Hz, Noraxon USA, Inc, Scottsdale, AZ) were placed on seven target muscles (iliocostalis, longissimus, multifidus, biceps femoris, vastus lateralis, rectus abdominus, and upper trapezius) on the right side of each participant according to previously established guidelines (48) (**Figure 4-5** and **Table B-1**). Since the recruited subject population was considered healthy, muscle symmetry was assumed so the sensors were not placed bilaterally. Placement of each sEMG sensor involved cleaning the area using alcohol wipes to ensure optimal skin contact and palpation of body landmarks with instructions to contract and relax the target muscles for electrode (Ag/AgCl hex dual electrodes with 2 cm distance) placement on the belly of each muscle. Each sEMG sensor was connected to its respective electrode via a split cable with alligator clips.

Additionally, individual retro-reflective markers were positioned to define segment dimensions, joint coordinate systems, and to establish a relationship between joint centers and anatomical tracking markers (**Figure 4-6**). The markers were placed bilaterally on the first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, femoral trochanters, iliac crests, and acromion. Additional markers were placed on the superior sternum and the C7 vertebrae. Clusters of tracking markers were placed on the heel, shank, and thigh to track each segment. For the traditional backpack, the pelvic markers were placed directly on each participant.

However, for the ergonomic backpack, the pelvic markers were placed on the pelvic belt over the respective anatomical landmarks. For additional pelvis tracking, two markers were placed on each side of the pelvis below the iliac crest markers forming a triangle shape. An 8-camera three-dimensional (3D) motion capture software with Qualisys Track Manager software (200 Hz, Qualisys AB, Gothenburg, Sweden) captured 3D kinematic data while a force instrumented split-belt treadmill (2000 Hz, Bertec, Inc, USA) collected 3D ground reaction force (GRF) data (**Figure B-3**). A 5-second standing calibration trial was obtained for each backpack condition, and prior to the walking trials in each backpack condition, anatomical markers were removed.

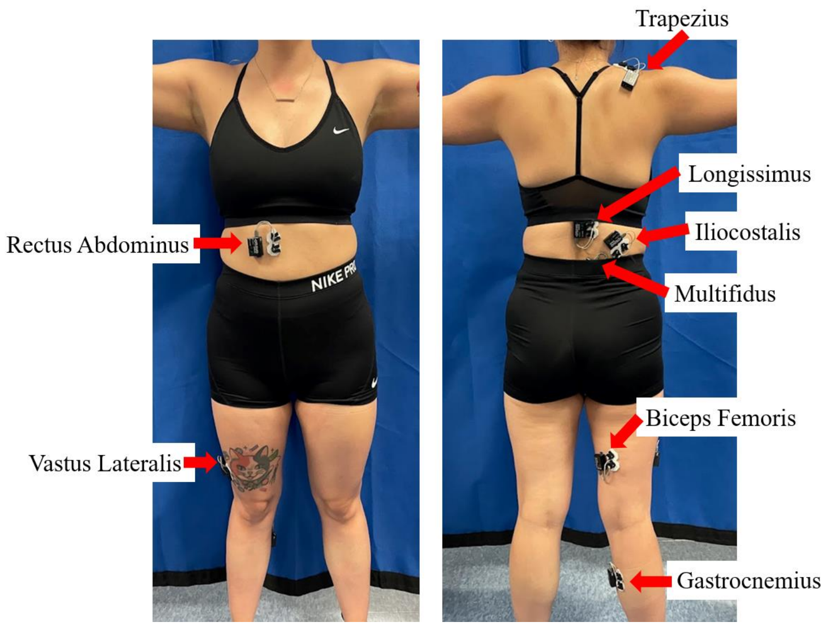

Figure 4-5. Surface EMG Sensor Placement.

Figure 4-6. Retroreflective Marker Placement.

A metabolic cart (ParvoMedics, Inc, Salt Lake City, UT) was used to measure oxygen consumption. The metabolic cart was calibrated using the procedure provided by the manufacturer which involved a gas and flow calibration before the beginning of each data collection. Participants were connected to the metabolic cart via a tube connected to a face mask which sealed over their nose and mouth and held in place by Velcro straps. The mask contained an attachment with two one-way valves which allowed the participant to inhale and exhale normally, the volume of carbon dioxide and oxygen moving through the tube and metabolic system was recorded for the entire ten minutes of each walking trial (**Figure B-4**).

Participants walked on the 3D force treadmill with one foot on each belt at 1.3 m/s for ten minutes while connected to the metabolic cart (**Figure 4-7**). The first two minutes were allotted for acclimation to the treadmill and for the oxygen consumption to achieve a steady state after the walking task began. Once the acclimation period was complete, 3D kinematic, GRF and sEMG data were captured for fifteen seconds, every four minutes (data were recorded at minute two, minute six, and minute ten). After each ten-minute walking task, participants were disconnected from the metabolic cart and allowed to rest for five minutes. From the fifteen seconds worth of data captured, five sequential steps were used from each backpack and load condition for data analysis. Following each walking task participants rated their comfort level in each backpack and load condition using a custom visual analog scale. Comfort was rated with 0: “extremely uncomfortable,” 2: “uncomfortable,” 4: “moderately uncomfortable,” 6: “moderately comfortable,” 8: “comfortable,” 10: “extremely comfortable” (**Figure B-5**).

Data and Statistical Analysis

3D kinematic, GRF, and sEMG data were processed for five sequential steps using Visual 3D software (C-Motion, Germantown, MD). A skeletal model was generated based on the location of the retroreflective markers for kinetic and kinematic calculations in the Visual 3D software (**Figure B-6**). The raw kinematic and GRF data were interpolated to fill data gaps no greater than 10 frames and filtered using a Butterworth low-pass filter with cut off frequencies of 12 Hz and 40 Hz respectively. sEMG data were filtered using a bandpass filter with cut off frequencies of 350 Hz and 50 Hz, and rectified by taking the root mean square of the signal with a window of 10 frames.

Right-hand rule with Cardan rotational sequence (x-y-z) was used for 3D angular kinematic computations, where x represents rotations about the mediolateral axis, y represents the rotation about the anteroposterior axis, and z represents the rotation about the vertical axis of the distal segment. Sagittal plane trunk angles were resolved in the lab coordinate system and analyzed over the gait cycle (right heel strike to right heel strike). Sagittal plane joint powers for the ankle, knee, hip, and L4/L5-S1 joints were resolved to the proximal segment and analyzed over the stance phase of the gait cycle (right heel strike to right toe off). Additionally, muscle power was further analyzed in its positive

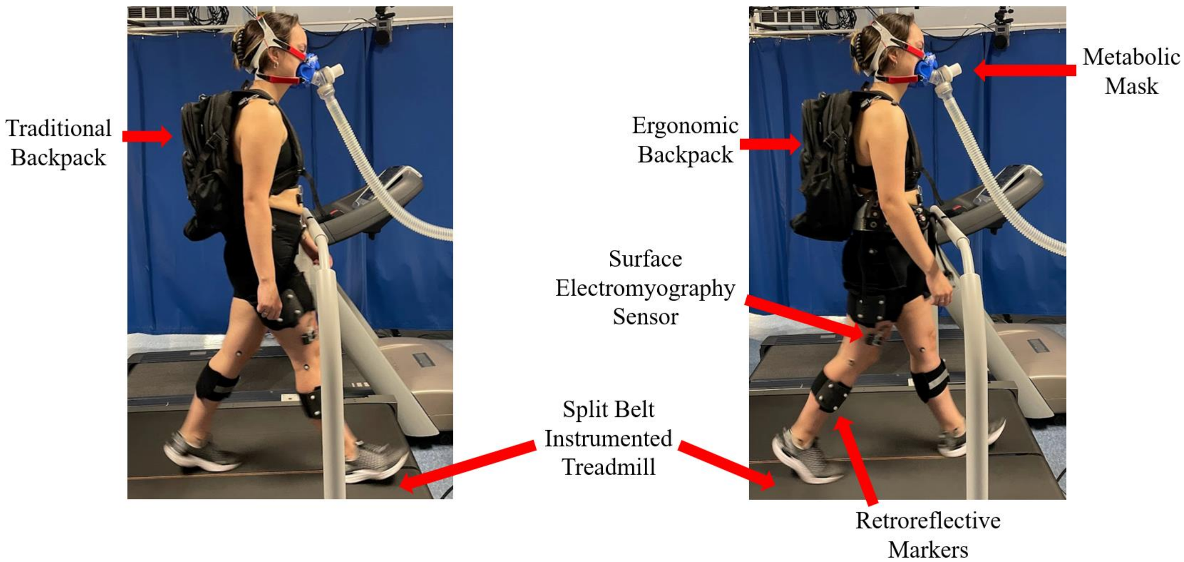

Figure 4-7. Functional Gait Study Test Set Up.

(concentric activity) and negative (eccentric activity) components, also over the stance phase of the gait cycle. The difference in the trunk center of gravity (COG) and hip joint positions in the anteroposterior axis were evaluated by subtracting the trunk COG position from the hip joint position at each time point. A vertical force threshold of 45 N was used to define heel contact and toe-off, a vertical force threshold of 400 N was used to define load response, and a medio-lateral force threshold of 0 N was used to define midstance for the GRF data. The sEMG and GRF data were correlated with the time point of specific gait events to determine the activity of the muscle over the gait cycle (right heel strike to right heel strike).

A one-way repeated measures analysis of variance (ANOVA) with post hoc Tukey tests for multiple comparisons (α=0.05) were used to determine the effect of the backpack design on the dependent variables that passed the normality test. Cohen's d effect size was determined to assess the effect size of any differences found between the dependent variables. A small effect size was defined as $d<0.2$, a medium effect size was defined as $d\leq0.2<0.8$, and a large effect size was defined as $d\geq0.8$. Overall comfort scores based on the comfort survey results were analyzed with a Mann-Whitney U Test (α=0.05) for ordinal data.

Results

The effects of the EBP compared to the traditional backpack on muscle response during the gait cycle are provided in **Table 4-1**. Mean paraspinal muscle response was significantly lower in the EBP compared to the traditional BP during the walking tasks in both low and high loads (**Figure 4-8**). **Table 4-2** shows the effect of the backpacks on forward trunk lean (**Table 4-2**). While significant difference was not found, the forward trunk lean in the EBP compared to the traditional BP during the heavy load walking task was trending toward significance (**Figure 4-9**). This decreased trunk lean is further supported through a smaller difference in the trunk center of gravity (COG) location relative to the hip joint position, indicating a more upright walking position. **Table 4-3** shows how this calculated difference was found to be significantly lower in the EBP for the heavy load condition (**Figure 4-10**). **Table 4-4** shows the negligible effects of the EBP compared to the traditional BP on O2 consumption (metabolic cost) in both load conditions (**Table 4-4**). **Table 4-5** shows the calculated muscle power at each joint (**Table 4-5**). A significant reduction in the hip muscle power was found in only the high load condition with the EBP compared to the traditional backpack (**Figure 4-11**). Focusing further on the hip joint, **Table 4-6** shows the significant differences with large effect size found in the concentric hip muscle activity (**Table 4-6** and **Figure 4-12**). Improved comfort scores (**Table 4-7** and **Figure 4-13**) were also significantly improved in the EBP walking tasks.

Table 4-1. Muscle Response (μV) Over Gait Cycle in Each Backpack and Load Condition.
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Muscle	7 kg				11 kg			
	Traditional	Ergonomic	P-Value	Effect Size	Traditional	Ergonomic	P-Value	Effect Size
Paraspinal	1.95±0.09	1.76±0.06*	0.045	2.50	1.95±0.21	1.61±0.13*	0.042	1.91
Bicep Femoris	0.77±0.17	0.74±0.05	0.705	0.252	0.83±0.29	0.85±0.14	0.963	-0.092
Vastus Lateralis	10.55±0.53	10.84±0.94	0.893	-0.374	10.98±0.95	9.97±0.66	0.961	1.243
Gastrocnemius	4.31±1.76	3.99±2.72	0.985	0.141	4.53±1.51	4.39±3.18	0.998	0.0534
Trapezius	4.80±0.81	6.85±0.97	0.443	-2.278	4.65±0.86	5.67±1.12	0.783	-1.056
Abdominal	0.84±0.05	0.90±0.06	0.998	-1.028	1.02±0.14	0.87±0.08	0.515	1.296

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

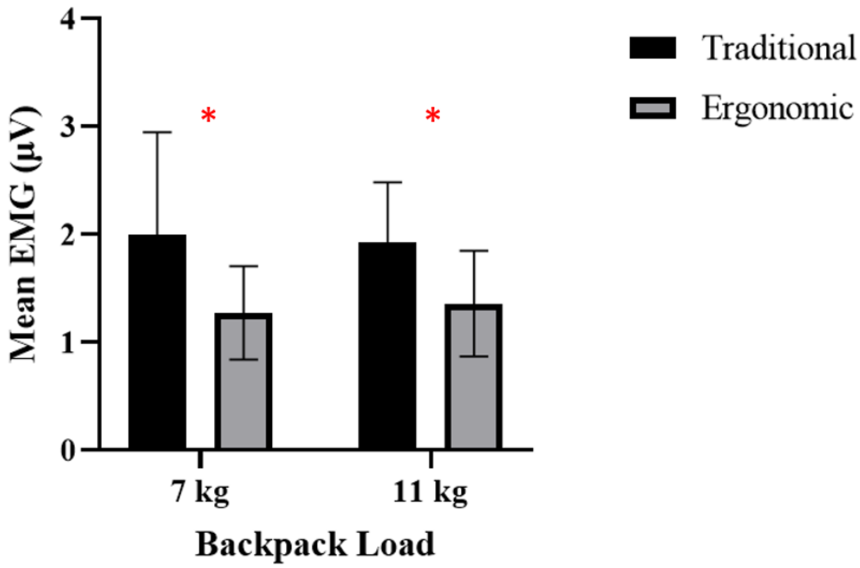

Figure 4-8. Mean Paraspinal EMG Over Gait Cycle in Each Backpack and Load Condition.
* Denotes significant difference from traditional backpack.

Table 4-2. Forward Trunk Lean Over Gait Cycle in Each Backpack and Load Condition.

Weight	Traditional	Ergonomic	P-Value	Effect Size
7 kg	8.03±0.58	7.55±0.16	0.391	1.124
11 kg	11.13±0.16	9.92±0.41*	0.016	3.867

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

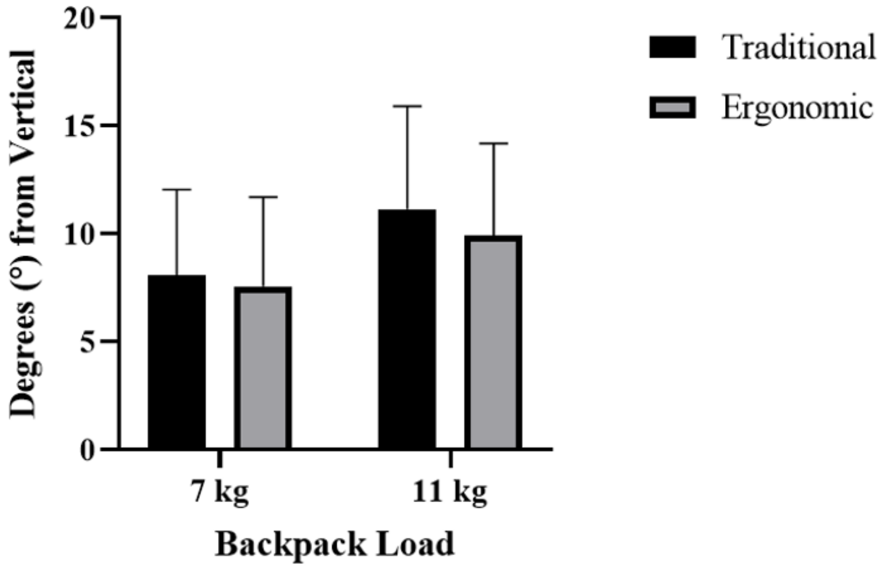

Figure 4-9. Mean Trunk Lean Over Gait Cycle in Each Backpack and Load Condition.

Table 4-3. Trunk COG Position Relative to the Hip Joint Position Over Stance Phase in Each Backpack and Load Condition.

Weight	Traditional	Ergonomic	P-Value	Effect Size
7 kg	0.061±0.031	0.048±0.028	0.357	0.449
11 kg	0.072±0.023	0.066±0.029*	0.048	0.218

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

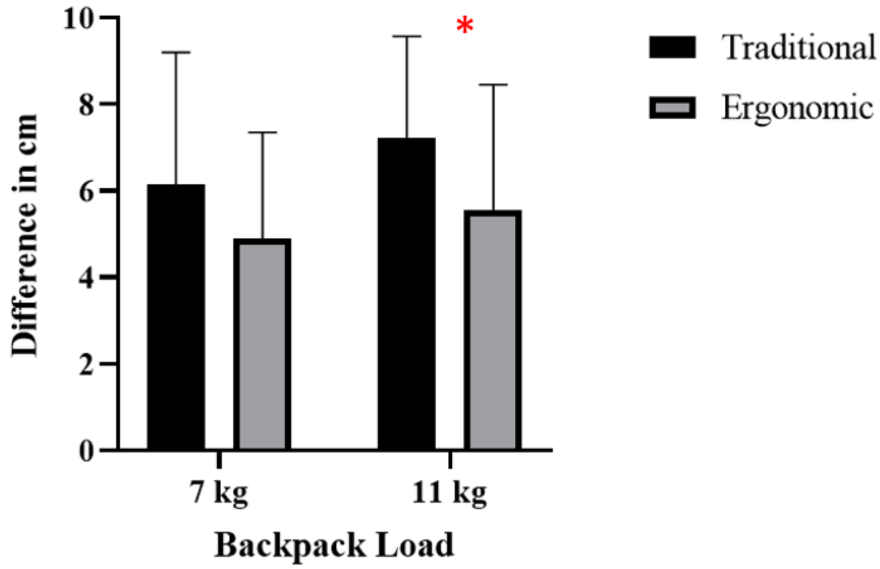

Figure 4-10. Trunk COG Position Relative to Hip Joint Position in Each Backpack and Load Condition.
* Denotes significant difference from traditional backpack.

Table 4-4. Oxygen Consumption in Each Backpack and Load Condition.

Weight	Traditional	Ergonomic	P-Value	Effect Size
7 kg	11.09±1.25	11.08±1.46	0.999	0.069
11 kg	11.30±1.75	11.48±1.67	0.728	-0.102

Mean ± Standard Deviation. Effect size: small effect = *d* < 0.2, medium effect = 0.2 ≤ *d* < 0.8, large effect = *d* ≥ 0.8.

Table 4-5. Muscle Power (W/kg) Over Stance Phase in Each Backpack and Load Condition.

Joint	7 kg				11 kg			
	Traditional	Ergonomic	P-Value	Effect Size	Traditional	Ergonomic	P-Value	Effect Size
Ankle	-0.044±0.126	-0.082±0.165	0.475	0.253	-0.056±0.133	-0.104±0.242	0.787	0.249
Knee	-0.151±0.097	-0.114±0.108	0.646	-0.357	-0.113±0.101	-0.137±0.101	0.873	0.209
Hip	0.181±0.172	0.040±0.127*	0.022	0.933	0.229±0.337	0.016±0.143*	0.012	0.825
L4/L5-S1	-0.372±1.227	-0.549±0.532	0.939	0.187	-0.250±0.891	-0.328±0.596	0.951	0.103

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

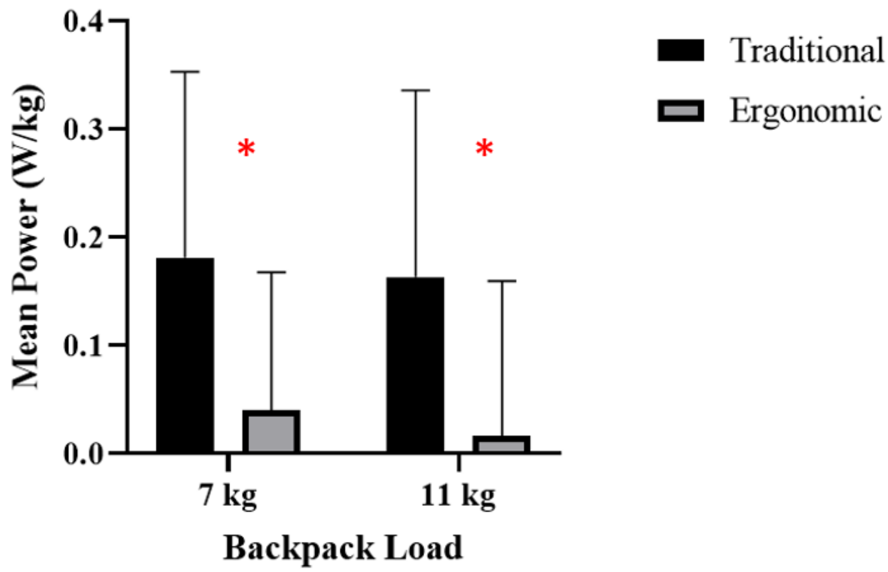

Figure 4-11. Mean Hip Muscle Power Over Stance Phase in Each Backpack and Load Condition.
* Denotes significant difference from traditional backpack.

Table 4-6. Positive and Negative Hip Muscle Power (W/kg) Over Stance Phase in Each Backpack and Load Condition.

	7 kg				11 kg			
Power	**Traditional**	**Ergonomic**	**P-Value**	**Effect Size**	**Traditional**	**Ergonomic**	**P-Value**	**Effect Size**
Positive	0.372±0.112	0.264±0.113*	0.049	0.951	0.417±0.139	0.341±0.182*	0.023	2.64
Negative	-0.279±0.123	-0.311±0.114	0.908	0.269	-0.452±0.217	-0.336±0.182	0.439	-2.61

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

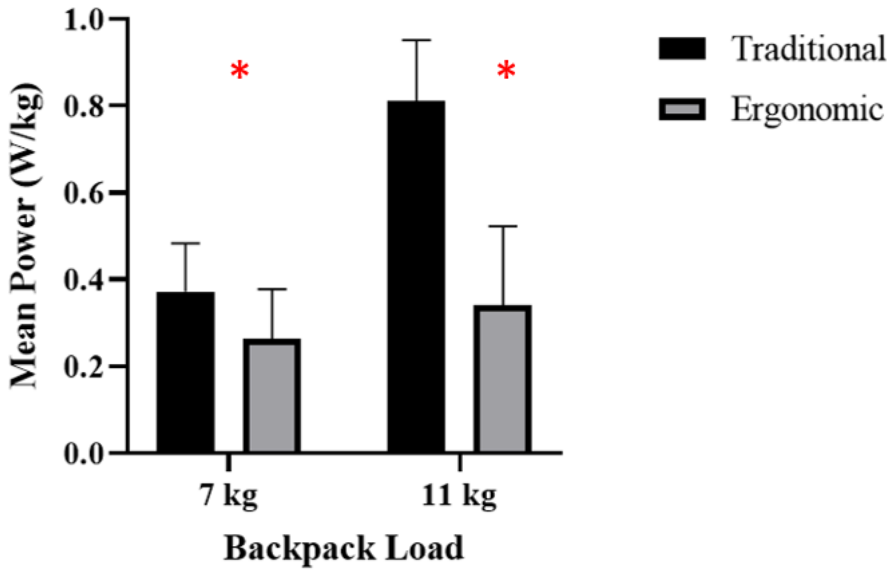

Figure 4-12. Mean Positive Muscle Power Over Stance Phase in Each Backpack and Load Condition.
* Denotes significant difference from traditional backpack.

Table 4-7. Reported Comfort Scores in Each Backpack and Load Condition.

Weight	Traditional	Ergonomic	P-Value	Effect Size
7 kg	4.5±1.5	6.3±1.7*	0.005	-0.331
11 kg	3.3±2.0	6.1±2.1*	0.002	-0.583

Mean ± Standard Deviation. * Denotes significant difference from traditional backpack. Effect size: small effect = $d < 0.2$, medium effect = $0.2 \leq d < 0.8$, large effect = $d \geq 0.8$.

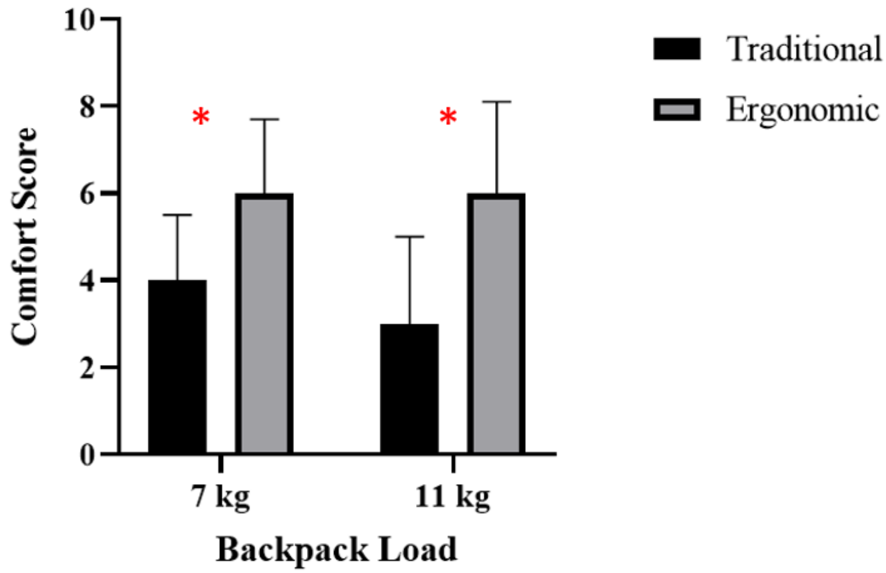

Figure 4-13. Average Reported Comfort Scores in Each Backpack and Load Condition.
* Denotes significant difference from traditional backpack.

Discussion

The overall purpose of this study was to evaluate ergonomic performance in a healthy population while wearing the EBP compared to the traditional backpack while carrying two different loads (7 kg and 11 kg). Since ergonomic performance was defined as an accumulation of variables, several measurements and calculations were made during the study, including muscle response, oxygen consumption, kinetics, and kinematics. Over the gait cycle, there was a significant decrease in the paraspinal muscle activity in the EBP in both backpack loads. This supported our first hypothesis. This indicates that there was less muscle effort and potential stress on this the muscle group and surrounding tissue as a result of wearing the EBP.

Other studies have reported increases in paraspinal muscle activity with increasing loads in traditional and military style backpacks, specifically at the higher loads. Harman et al. explored military load carriage using 6, 20, 33, and 47 kg bag loads and found that paraspinal muscle responses significantly increased significantly between the 20 kg and 47 kg tasks (6). Li et al. reported paraspinal muscle increase at heavy loads as well (15-20% body weight) (36). It has also been revealed in studies that at lower loads, such as 10% body weight, there is a decrease in the paraspinal muscle response (6, 35, 37, 45). These previous results are notable to mention in conjunction with our findings in that we were able to elicit a decreased paraspinal muscle response with the use of the EBP, meaning the load experienced by the muscle group when wearing the EBP may be around or below 10% of our user's body weights. Therefore, our reduced muscle activity additionally provides evidence for the success of our offloading BP design. Of the other muscles that were measured in this study, none of them exhibited any differences between the backpacks in either load condition

Over the gait cycle, there was also a decrease in trunk lean in the EBP (approaching significance) indicating a more vertical walking position. The increased trunk lean is commonly claimed to be a compensatory response to the posterior center of gravity shift that occurs when the backpack load is added to the user. To maintain stability and forward progression during walking, it is common to see an increase in trunk lean. **Figure 4-14** shows trunk lean results from previous studies exploring the effect of load carriage on trunk lean. Significant trunk lean increase has been reported also at the heavier weight conditions used in previous studies. Harman et al reported significant increases in trunk (2-11 degrees) lean starting at 20 kg bag load that was used in the study (6). Others have reported significant increase in trunk lean (2-10 degrees) in bag loads at 15% body weight and beyond (26, 32). Li et al. studied similar loads and found significant increases in trunk lean (5 degrees) at 20% body weight bag loads. This aligns with the results of this study considering our chosen bag loads were 10% and 15% of the average of the participant's body weights. The evidence of a more vertical walking pattern in the EBP was further confirmed by comparing the position of the trunk's COG relative to the hip joint center of gravity. This difference was significantly lower in the EBP for the high load condition indicating that the trunk COG and hip joint positions were more closely in line than they were in the traditional backpack. This closer

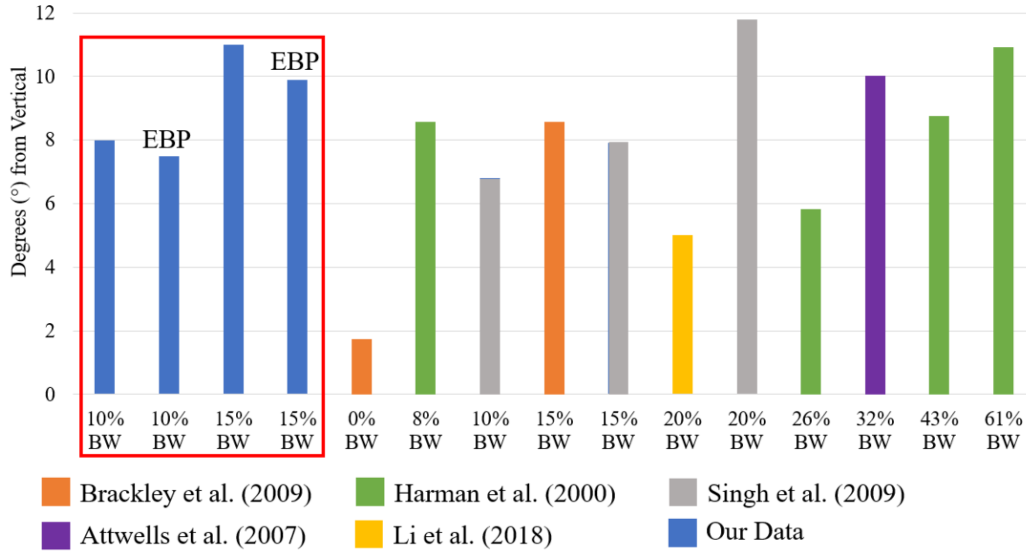

Figure 4-14. Forward Trunk Lean from Presented Study Compared to Previous Literature.
BW: Body Weight. Our data is presented as measures in the Traditional backpack followed by the EBP at each load.

alignment further confirms that there was decrease trunk lean and a more upright walking position in the EBP. External bag loads from backpacks induce an overturning moment on the spine which forward lean helps to compensate for, the accomplishment of DT 3-4 is evident through these results due to the counter-moment mechanism helping compensate the external bag moment.

Despite there being evidence of increased trunk lean in the traditional backpack which has been noted to potentially affect the cardiorespiratory response during load carriage (38, 47), there was no difference found in the oxygen consumption between the backpacks in either load condition. This does not support a portion of our second hypothesis. As shown in **Figure 4-15**, previous load carriage studies have reported oxygen consumption values of 9-20 ml/kg/min depending on the load carriage method which falls within the range of this study. (28, 47) It should be noted that suspending the added load might offer added benefit to improving metabolic cost. Huang et al. measured metabolic cost in suspended load and not suspended load carriage conditions and found improvement in the metabolic cost. (40) Further design improvements for the EBP have been proposed which include further suspending the weight transferred to the pivot component via a spring damper or similar mechanism. This iteration may be able to reveal an improved oxygen consumption measure.

The other portion of our second hypothesis was also partially supported with the significant decrease in the hip muscle effort in the EBP at the heavy load condition over the stance phase of gait. As shown in **Figure 4-16**, previous studies exploring muscle power at each joint have reported increases with increasing load. (17, 29, 30) Muscle power can be further broken down for analysis into their positive and negative components with positive muscle power corresponding to concentric muscle activity and generation of energy while negative muscle power corresponds to eccentric muscle activity to absorb energy. Previous studies using 0,15, and 30 kg of load reported increases in positive hip power with increasing load from 0.51 W/kg to 0.81 W/kg. (29) The calculated positive hip muscle power from this study falls within and below this range, specifically in the EBP backpack. We believe that the significant differences found solely at the hip overall and in the positive hip muscle power component are due to the fact it was the closest joint to the intervention. Additionally, the mechanism of the EBP system might be allowing for the hip belt to help and the counter-moment mechanism might also be aiding in the reduction of muscle effort based on the anatomical location of the load suspension (in line with or posterior to midline of spine via hip joint). This optimal positioning of a counter-moment that is unique to the EBP might be helping to eliminate torque on the hip joint and minimizing the muscle effort needed to balance the load. This provides further evidence of the accomplishment of DT 3-4. There were no differences found in the muscle power at the other joints of interest.

Finally, the overall comfort while wearing the EBP in each load condition did improve compared to the traditional backpack. The most common comment left on the survey provided after each traditional backpack walking task was that the participant’s shoulders hurt or were very uncomfortable. This improvement in comfort scores provides a qualitative data to support that our design does improve load carriage experience. Based

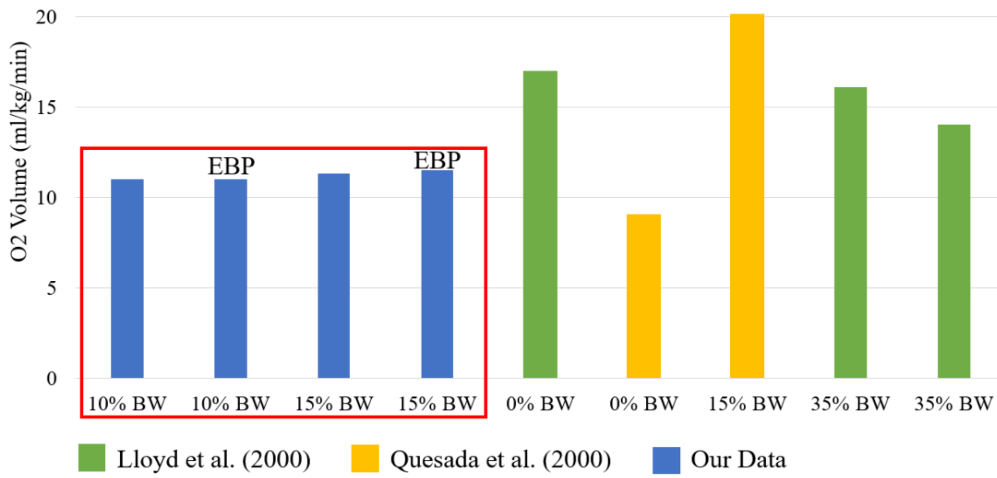

Figure 4-15. Oxygen Consumption from Presented Study Compared to Previous Literature.
BW: Body Weight, O2: Oxygen. Our data is presented as measures in the Traditional backpack followed by the EBP at each load.

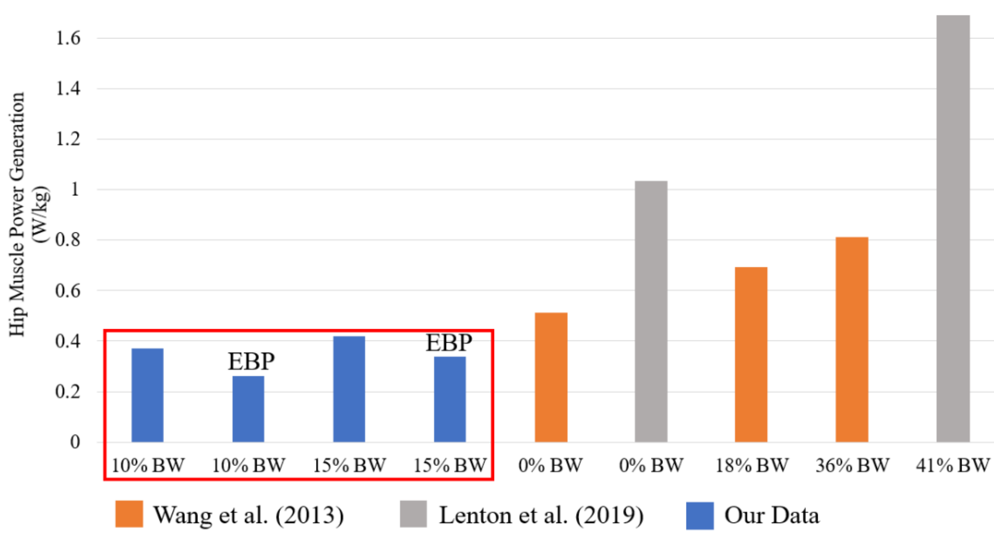

Figure 4-16. Hip Muscle Power Generation from Presented Study Compared to Previous Literature.
BW: Body Weight. Our data is presented as measures in the Traditional backpack followed by the EBP at each load.

on the previous definition of ergonomic performance, the results support the claim that the EBP has the potential to improve ergonomic performance through offloading the shoulders and spine and lower extremity reduced muscle effort.

The results of this study are limited to acute load carriage and backpack wear since participants were only allowed 5 minutes to become acclimated to the backpack systems and an additional 20 minutes of walking total in each backpack system. To better understand the long-term effects of the EBP compared to a traditional backpack, a study where a more focused population, such as the military or student, wear either backpack system over multiple weeks would need to be conducted. For the EBP, hip belt sizes were limited to two options. Any belt adjustments were limited to what was feasible between within the laboratory setting rather than creating wearer specific customized belts. The chosen loads for the load carriage tasks were also lower than what has previously been used in the literature due to the study population being more general and not specialized like military or advanced hiking groups who are more suitable to carrying heavier loads. Lastly, in this study, treadmill walking was chosen to control participant walking speed during testing so, current findings may not be generalizable to overground conditions.

Conclusion

This study demonstrates the capacity of the EBP to provide a relevant level of improved ergonomic performance during loaded walking tasks compared to a traditional BP. The present study also quantified the shortcomings of the EBP design and current traditional BP technology. The findings and feedback received during this study will be used to improve EBP design for further offloading and optimal load positioning for comfort and effort. Future work will assess the efficacy of the EBP in relevant populations such as students and military personnel who are at risk for pain and injury due to heavy backpack loads. The findings of this future work will provide insight into the marketability of the novel backpack design for improving the problematic loading conditions that come with backpack carrying.

CHAPTER 5. DISCUSSION: RELATING STUDY 1 AND STUDY 2 OUTCOMES

The purpose of this research was to evaluate the novel EBP design in terms of the accomplishment of the design tasks and how the EBP improved ergonomic performance compared to a traditional backpack system. The design tasks (DT) that were evaluated were as follows: 1) redirect the load from the spine and shoulders to the midline of (or posterior to) the pelvic region, 2) use a pivot component to support the redirected loads at a specific anatomic location to minimize the off-axis moments that are induced from the load carriage, 3) establish a means of accommodating different body size with adjustable pivot component attachment locations, and 4) design a counter-moment or counter-balance mechanism for the external bag moment. In order to effectively evaluate the accomplishment of the design tasks, two studies were performed: 1) a validation study to determine the shoulder offloading capability of the EBP and 2) a function study in a gait laboratory with healthy individuals to evaluate ergonomic performance in the EBP compared to a traditional backpack.

For study 1, the reduced shoulder loads seen in the EBP system compared to the traditional backpack system confirm the accomplishment of design task 1 and design task 2, congruently. Since configuration of the frame allows for interaction with the pelvic belt via the pivot component attachment and with the backpack itself via the horizontal straps, it can be concluded that any loading that is not lost at the shoulder or back due to friction, is being transferred to the pelvis since the load where backpack straps are present decrease with the use of the backpack system. This feature of redirecting and suspending a portion of the backpack load off of the shoulders additionally indirectly offloads the spine since the mechanics of the strap loading results in a direct transfer of the weight felt in the shoulders through the spinal column to the lumbar. This loading that is transferred contains an axial and shear component which could increase the risk of pain and potential injury when carrying heavy loads for extended time.

The EBP demonstrated its ability to improve ergonomic performance which has been previously defined as an accumulation of measures that includes decreased shoulder and spine loads, reduction in paraspinal muscle involvement (reduced loads), reduction in oxygen ($O2$) consumption (metabolic cost), reduction in lower extremity muscle effort, improved comfort. The results from study 2 reveal reduced paraspinal muscle involvement, reduced lower extremity muscle effort and improved comfort. Despite the lack of difference in oxygen consumption between the two backpack conditions with either load, it could be concluded based on the other defined measures, including those measured in study 1 (shoulder loads) that the EBP did in fact improve ergonomic performance. The features of the adjustable pelvic belt and counter-moment mechanism reflect these results in that the placement of the redirected load (in line with or posterior to the lumbar spine) and counter-moment mechanism allow for minimizing the overturning backward moment that is applied to the spine when a backpack is added. The position of the belt and action of the counter-moment also seem to aid in minimizing the concentric hip muscle power, thus reducing lower extremity effort.

CHAPTER 6. FUTURE WORK

Considerations for Future Research

Since the effects of load carriage are well established, future research should focus on improving the loading mechanics experienced through modifications to design features. **Table 6-1** compares different backpack designs along with design features that are commonly seen or mentioned in this body of work. In order to improve the problematic loading and the resulting effects due to load carriage, the effectiveness of these backpack features need to be better understood in order to develop an effective design. The unique features of the EBP compared to other designs already existing on the market appear to be the anatomically located pivot component for the redirected load and a counter-moment mechanism that aids in reducing the shoulder loads (and consequently the load on the spine), not just the inertial loads as other designs do.

The combination of features in the EBP, have provided evidence that it in fact improves not only load carriage experience through subjective scores but also biomechanically. The next phase of research would be to evaluate the effectiveness of the EBP in a specific setting where load carriage is common such as schools, military training, or advance hiking. Additionally, a plan for patenting and marketability could be considered once the EBP is proven to be effective in the target populations of those who engage in heavy load carriage often.

Conclusions

This body of work provides validation of set design goals in addition to evidence of the effectiveness of a novel ergonomic backpack design. The EBP provided significant reduction in shoulder loads, paraspinal muscle response, forward trunk lean, and hip muscle effort. The EBP also provided significant improvement in the overall load carriage experience. Aspects of this work provide further evidence that the EBP design improves the problematic loading conditions that appear in load carriage from loading at the shoulders that is transferred through to the spine. This could improve the load carriage experience and potentially prevent injuries that might be caused by altered biomechanical activity as a result of load carriage.

Table 6-1. Comparison of Backpacks and Their Features.

	Backpack Design				
Backpack Design Feature	**Ergonomic**	**Traditional**	**Military**	**HoverGlide**	**Zero G**
Pack with straps	●	●	●	●	●
Hip Strap		●			
Chest Strap	●	●	●	●	●
Pelvic Belt	●		●	●	
Supportive/Rigid Frame	●		●	●	
Anatomically Location Point for Load Redirection	●				
Counterbalance/Relief Mechanism for External Bag Weight (*Static* Load)	●				
Counterbalance/Relief Mechanism for External Bag Weight (*Dynamic* Load)	●			●	●
Different Sizes/Accommodations for Body Size	●	●	●	●	●

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APPENDIX A. SPECIFICATIONS

This appendix provides specifications of the equipment (**Table A-1**) used throughout this body of work.

Table A-1. Equipment Specifications.

System Information	Specifications
Qualysis cameras Oqus 3	Sampling frequency: 200 Hz Full resolution of 1280x1024 Normal mode (full FOV): 1.3 MP, 500 fps High-speed mode (full FOV): 0.3 MP, 1750 fps Max capture distance: 22 mm
Electromyography Sensors Noraxon DTS	Sampling frequency: 3000Hz Resolution: 16 bit
Hex Dual Electrodes Noraxon	Material: Ag/AgCl Distance: 2 cm
Metabolic Cart ParvoMedics	**Oxygen Analyzer** Paramagnetic Range: 0-100% or 0-25% Accuracy: 0.1% Response time: 200 ms at 21%-16% **Flow Measurement** Rudolph heated pneumotach Range: 0-800 L/min Accuracy: +/- 0.5% with Precision "Yeh" Algorithm **Mixing Chamber** 4-Liter high-efficiency mixing chamber **Calibration** 3-Liter syringe 16% O2/4% CO2 E-cylinder cal gas 2-stage regulator **Environmental and Electrical** Temperature: 14 to 30 degrees C Humidity: 20 to 80% Warm-up time: 30 minutes Power requirements: 100-240V/50-60 Hz
Portable Luggage Scale Esky® – Sky of Electronics	Weight range: 110lb/50kg Weight unit: kg, lb, oz Blue LCD backlight

Table A-1. Continued.

Source data:

Qualisys AB. (2011) Qualisys Track Manager User Manual. Retrieved from https://www.qualisys.com/hardware/5-6-7/ (49).

Noraxon (2015) DTS Lossless EMG Sensor User Manual. Retrieved from https://tienda.fisaude.com/files/Sensores-EMG-Manual-de-Usuario.pdf (50).

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APPENDIX B. EXTENDED METHODOLOGY OF STUDY 1 AND STUDY 2

This appendix provides additional information regarding the methodology used during the validation study described in Chapter 3 and the functional gait study described in Chapter 4. **Figure B-1** shows the modified luggage scale that was used for the strap tension measurements taken during the validation study. **Figure B-2** shows the load insoles used for the shoulder load measurement taken during the validation study.

Table B-1 shows the sEMG sensor placements that were used according to previously established guidelines for the functional study of the EBP. These guidelines allowed for consistent placement across participants despite potential size differences in participant anatomy. **Figure B-3** shows sample motion capture data of a participant walking on the treadmill. **Figure B-4** shows an up close of the metabolic mask that was worn to collect oxygen consumption data which provided a seal around the nose and mouth for volumes of expired air to travel into the connected tube. **Figure B-5** is the backpack comfort survey that each participant filled out to quantify the comfort level of each backpack and load condition. **Figure B-6** shows a sample skeletal model made for data analysis in Visual 3D.

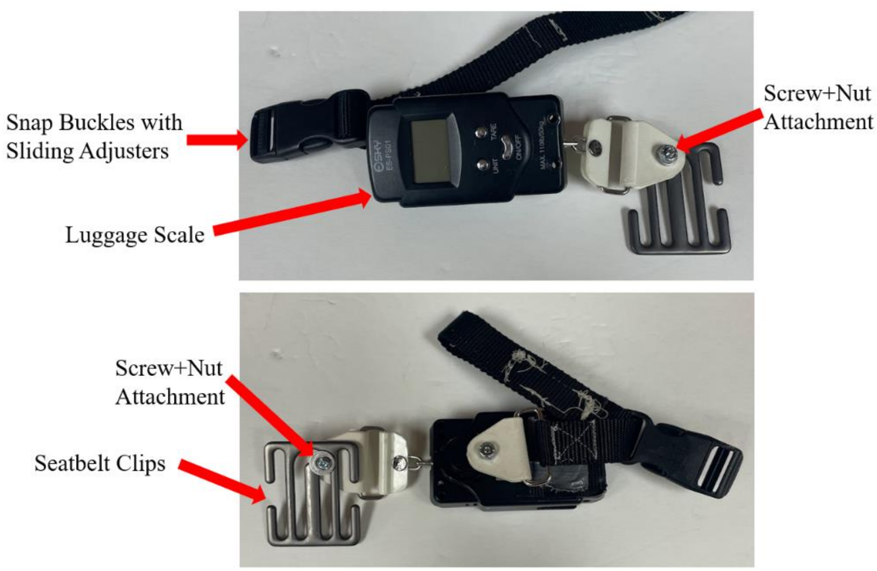


Figure B-1. Modified Luggage Scales.

Figure B-2. Loadsol Load Sensors.

Table B-1. EMG Sensor Placement Guidelines.

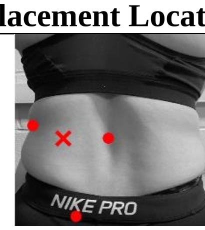
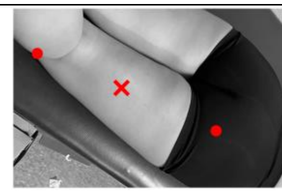
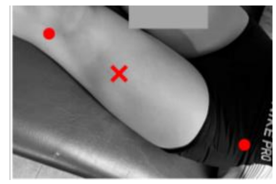
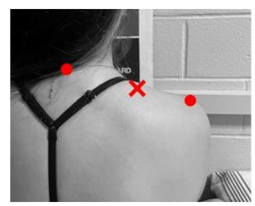
Muscle	Sensor Location	Orientation	Placement Location
Iliocostalis	1 finger width medial from line between lowest point of ribs and PSIS, level of L2	In line with lowest point of the ribs and PSIS	
Longissimus	2 finger width away from spine at level of L1	Vertical	
Multifidus	2-3 cm from midline between L1/L2 interspace at the level of L5	Direction of the line between PSIS and L1/L2	

Table B-1. Continued.

Muscle	Sensor Location	Orientation	Placement Location
Biceps Femoris	50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia	Direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia	
Vastus Lateralis	2/3 on the line between the ASIS and lateral side of the patella	Direction of the line between ASIS and lateral patella	
Abdominal	2-3 cm from midline of the stomach (50% from xyphoid process and umbilicus)	Vertical	
Trapezius	50% on the line from the acromion to the spine on vertebra C7	Direction of the line between the acromion and the spine on vertebra C7	
Gastrocnemius (medial)	Largest bulge of the muscle	In line with the direction of the leg	

Source Data:

SENIAM (2000) EMG Sensor Placement Guidelines. Retrieved from http://www.seniam.org/ (48).

Silva GB, Morgan MM, Gomes de Carvalho WR, Silva E, de Freitas WZ, da Silva FF, et al. (2015) Electromyographic Activity of Rectus Abdominis Muscles During Dynamic Pilates Abdominal Exercises. J Bodyw Mov Ther. Retrieved from http://dx.doi.org/10.1016/j.jbmt.2014.11.010 (54).

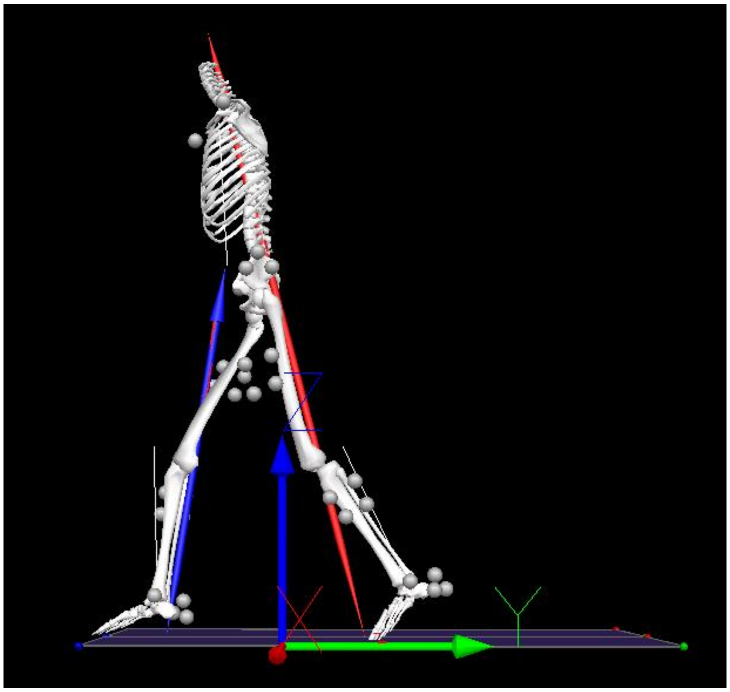


Figure B-3. Example Motion Capture Data.

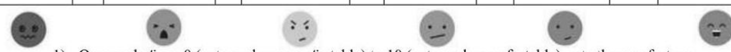
Figure B-4. Metabolic Mask.

Subject Number: ________

Backpack Comfort Survey

Please complete this survey to the best of your ability and as honest as possible immediately after each walking trial. We plan to use these responses for future design improvements to the offloading backpack.

0	1	2	3	4	5	6	7	8	9	10
Extremely uncomfortable		Uncomfortable		Moderately uncomfortable		Moderately comfortable		Comfortable		Extremely Comfortable



1) On a scale from 0 (extremely uncomfortable) to 10 (extremely comfortable), rate the comfort you experienced while wearing the **traditional school** backpack.

Low Weight:

0	1	2	3	4	5	6	7	8	9	10

High Weight:

0	1	2	3	4	5	6	7	8	9	10

Comments:

____

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2) On a scale from 0 (extremely uncomfortable) to 10 (extremely comfortable), rate the comfortability of the **offloading backpack (OBP)** for each weight you carried.

Low Weight:

0	1	2	3	4	5	6	7	8	9	10

High Weight:

0	1	2	3	4	5	6	7	8	9	10

Comments:

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____

Figure B-5. Example Backpack Comfort Survey.

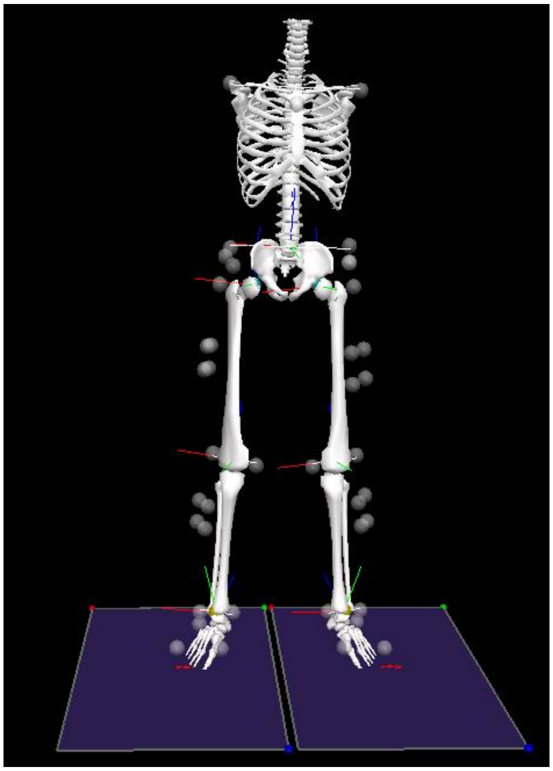

Figure B-6. Example Skeletal Model Generated in Visual 3D.

VITA

Lyndsey was born in Norfolk, VA in 1998. She moved with her family across the country and world growing up as her father was in the US Navy but they ultimately stationed in Memphis, TN where she graduated from Arlington High School in 2017. She attended the University of Arkansas and graduated with a Bachelor of Science degree in Biomedical Engineering. She then attended graduate school at the University of Tennessee Health Science Center.

Lyndsey performed graduate research under her advisor, Dr. Denis DiAngelo in the Orthopedic BioRobotics and Rehabilitation Laboratory, a well-established lab with a history of advanced biomechanical evaluation of surgical implants. Lyndsey's research extended beyond surgical implants to include the design, fabrication, and functional testing of a novel ergonomic backpack design. During her graduate work, Lyndsey collaborated with fellow scientists to evaluate this new technology for potential uses in student and military populations. She also was granted the opportunity to attend the Orthopedic Research Society Conference and the MidSouth Biomechanics Conference where she was awarded a Student Presentation Award, two years in a row. Following the approval of this thesis, Lyndsey expects to graduate and receive her Master of Science in Biomedical Engineering in October 2023 and pursue a professional career in the medical device industry.