

Optimizing the MOLLE for the Female Soldier

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Authorship

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

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Abstract

As female Soldiers become more prevalent in the U.S. military, it is becoming increasingly important to address the physical differences that may limit their performance in the field. The purpose of this project was to design a female specific hip belt for the MOLLE system that complies with the United States Army standards to effectively distribute the load on the body while allowing the Soldier to complete all necessary tasks that occur in the field. The team developed a new hip belt with winged padding attached to an outer shell. Various modifications were made to increase the comfort and ease of adjustability of the belt. To validate the design, the team performed various tests including an obstacle course, which included survey questions, and pressure film testing. The results of the team's tests showed that their modified hip belt was an improvement from the current model in that it distributed the weight more evenly across the user's hips and provided more comfort for the user.

Chapter 1: Introduction

A Soldier's individual combat equipment, the gear he or she is required to have on person for mission success, has always been an essential part of the of the foot Soldier's burden. Over time, load-bearing equipment has evolved and the Army has adopted new models to address the needs and demands of the modern Soldier. The current load-bearing equipment, designed with male physical characteristics in mind, is called the Modular Lightweight Load-carrying Equipment (MOLLE) rucksack, which is comprised of a plastic frame and various detachable pouches that can be adjusted to distribute weight for the user's comfort. However, this design can cause discomfort or injury to women, who have different structural features than men. As women are accepted into more combat roles, it is necessary to take into account the physical differences of the female Soldier

Differences in the skeletal and muscular systems influence how males and females carry backpacks and other loads. The pelvis of the female is wider and lower in the body, allowing her to carry more weight in the hips. The female bones are also smaller and less dense than male bones. Males also have greater upper body strength due to greater muscle mass in the torso and shoulders. Due to these differences, females prefer to carry loads differently than males.

Many studies have been conducted on the effects of backpack loads on females. These studies have used various loads or torso angles to observe how these changes affect the load carriage of rucksacks. By varying the conditions, researchers are able to measure muscle activity, center of pressure, and load distribution. These tests have confirmed that females carrying heavy loads are more susceptible to injury and wearing a hip belt is beneficial for weight distribution. However, not all female Soldiers choose to wear the hip belt provided on the MOLLE.

The amount of load that a Soldier carries in his or her rucksack has been steadily increasing throughout history, and the manner in which this load is distributed in the backpack greatly influences the energy expenditure of the Soldier, as well as his or her performance in the field. The most practical way to carry load is as close to the center of

mass (COM) of the body as possible. In order to maintain COM of the body, Soldiers can use a double pack that evenly distributes the weight in the back and front of the body, but this design has limitations. To compensate for these limitations, modifications to the backpack, such as hip belts and shoulder straps, have been designed. These additions allow for more efficient distribution of load to maintain the COM of the body. However, it is difficult for women to appreciate the benefits of these modifications as they were originally designed based on the physical characteristics of men. Often times, women cannot perform as well as men in training and in combat due to their lower upper body and torso strength. Consequently, their COM is different than men, and they prefer to carry loads closer to their hips. Improper fit of the hip belt may cause discomfort or musculoskeletal problems (Ling et. al, 2004). This discomfort and injury among female Soldiers drives the growing need to develop modifications for the MOLLE.

Chapter 2: Literature Review

2.1 Evolution of U.S. Army Load Carrying Equipment

A Soldier's individual combat equipment, the gear he is required to have on his person for mission success, has always been an essential part of the of the infantry man's burden. This individual combat equipment has been referred to by many names over the course of military history and has evolved over time to better meet the needs and demands of the American Soldier. The Soldier's most common term for this equipment, from World War I to present, is "web gear." Today, it can also be referred to as load carrying equipment (LCE) or load bearing equipment (LBE). Regardless of the name, a Soldier's gear is absolutely essential to survival and mission success. Once issued, this gear becomes part of the Soldier. It does not escape his person, and if doffed, always remains within arms reach.

Since the introduction of the first modern load carrying equipment system, the development of US Army load carrying equipment has taken off. The military has its own employees that work solely on the development of new equipment for Soldiers. Many of the major changes in load carrying impact have been implemented for the adoption of new weapon systems and the necessity to carry their ammunition. There are several factors that have a direct impact on the development of new load carrying equipment including materials used, physiological, or "comfort," factor, and the trade-off between lightweight and durability. The search for the indefinable "light load" may never end, as improvements are always to be made. A balance must be found in designing lightweight gear that does not sacrifice durability. Lightweight gear permits Soldiers greater efficiency by allowing a greater freedom of movement. New designs of load carrying equipment seek to improve agility and comfort, but weight is ultimately the key factor leading the design (Rottman, 1989).

2.1.1 MLCE

The M1967 modernized load carrying equipment, or MLCE, was designed specifically for use in the Vietnam War. The MLCE was the first generation of modernized load carrying system adopted by the Army. The MLCE had essentially the

components of the previous design, but substituted nylon for cotton, and aluminum and plastic in place of steel and brass hardware wherever possible. The design of the 1967 MLCE tropical rucksack was influenced by the indigenous rucksack of the Special Forces-advised Civilian Irregular Defense Group (CIDG) in Vietnam. Captured North Vietnamese Army rucksacks were sent to counter-insurgency to be used as models in the early 1960s. The MLCE rucksack issued to the US Army was created using these Vietnamese rucksacks as a model (Rottman, 1989).

The MLCE model had three large cargo packets and equipment loops attached to the side and the back. The rucksack pockets were sewn only on the sides to allow a machete to be attached to a loop and positioned under the pocket. The main pouch of the rucksack was fashioned with a drawstring. Likewise, the three rubberized fabric waterproof liners were also fashioned with a drawstring. The top flap of the rucksack was secured by two straps and contained a thin rubberized fabric-lined pocket. The fabric, made of nylon, was lightweight and durable, which was one of the main qualities that led to the US Army's consideration of the MLCE for Army-wide adoption. The rucksack was supported by a flat metal riveted frame. Some Soldiers experienced discomfort with the frame as some tended to bow outward, causing the frame to rub against the wearer's back. Additionally, the padded shoulder straps were detachable, with the left strap having a quick-release device (Rottman, 1989).

2.1.2 ALICE

Following the MLCE, the US Army adopted the ALICE system in 1974. ALICE stands for All-purpose Lightweight Individual Carrying Equipment. Although the MLCE had been popular during its use, it was not capable of carrying complete mission loads. This was a problem which the ALICE pack sought to eliminate. This new system included a medium and large combat field pack as well as a frame that could support both packs. The ALICE pack was similar to the MLCE rucksack and could be used with or without the frame.

The ALICE pack was popular during its time in use, but there was still possibility for improvements on certain aspects of the system. In a Field End Analysis (FEA) conducted in 1995, nearly 1,850 Soldiers and Marines from eight military specialties –

combat infantrymen, combat engineers, medics, communications, chemical, mechanic, and other support specialties – answered a questionnaire about their ALICE system (Sampson, 2001). The following design deficiencies of the ALICE system are a reflection of their responses:

- Does not accommodate loads of all squad positions, such as the Radio Telephone Operator (RTO), Grenadier, Automatic Machine Gunner (AMG), or Medic, etc.
- Not easily tailored for changing missions
- Load rests mainly on the shoulders
- Design has a need for more padding
- Does not have a quick drop/release mechanism for the main rucksack
- Rifle cannot be fired while lying in the prone position with the load

In addition to the survey mentioned above, the FEA also conducted two “muddy boot” panels at Fort Benning, Georgia in September of 1994. Each panel discussed the need for a new load-carrying system that would address the limitations of the ALICE system (Sampson, 2001). There were several key features and improvements that the new system would implement as shown in the list below.

- Increase system capacity to slightly greater than ALICE
- Modular: to tailor for squad positions and missions
- Increase durability: must pass 55kg drop test
- Compatible to other equipment/gear (body armor, weapons, other CIE)
- Compatible with airborne operations
- Water repellent: provide drainage in pouches
- Frame support: stable under heavy loads and heat flow
- Load distribution/stability: comfortable, low energy expenditure
- Lightweight packs and frames
- Quick release mechanism for main rucksack

With these suggestions in mind, a new load carrying system was developed for the Soldier and Marine (Rottman, 1989).

2.1.3 Current Model: MOLLE

The modular lightweight load-bearing equipment, or MOLLE, was first used by the United States Marine Corps, and then was adopted by the US Army in 1997 (Halberstadt, 2006). The MOLLE system was designed to enhance the survivability and lethality of the modern Soldier and Marine, and provides far more load-carrying capabilities than the ALICE system. The manufacturer of the MOLLE system is Specialty Defense Systems out of Dunmore, Pennsylvania (Modular Lightweight, n.d.).

MOLLE I

The first generation MOLLE system, MOLLE I, is a fully integrated, modular load bearing system that consists of a load bearing vest (LBV) and butt pack, a main rucksack with two sustainment pouches, a sleeping bag compartment, and a plastic external frame to which everything attaches. A patrol pack, which is separate from the main rucksack, can be attached to the system for added load carrying capability. The main pack has a volume of approximately 3,000 cubic inches and has a front pocket designed to house a claymore mine. The two sustainment pouches have a volume of about 500 cubic inches and can attach to either side of the main pack. The sleep system carrier is attached directly below the main pack and is oriented parallel to the frame for easy access to the top flap. The patrol pack volume is approximately 1,200 cubic inches and attaches to the top of the main pack for additional load carrying capability (MOLLE II Molded Waistbelt, n.d.).

The most revolutionary modification of the MOLLE system is its method of additional pouch attachment. The MOLLE system was designed to give Soldiers the ability to tailor their equipment to their personal needs by allowing various configurations through modular attachment. The system of attachment is known as the pouch attachment ladder system (PALS), which was patented by Natick Soldier Systems Center, the U.S. Army and Marine Corps' research facility for gear centered in Natick, MA. PALS gives the individual Soldier control of his load by allowing him the flexibility to alter the amount and arrangement of his individual equipment (Halberstadt, 2006). PALS uses an inter-weaving method to attach pouches to heavy-duty nylon grid of webbing on load-bearing platforms such as the LBV and main rucksack. Figure 1 below depicts PALS.

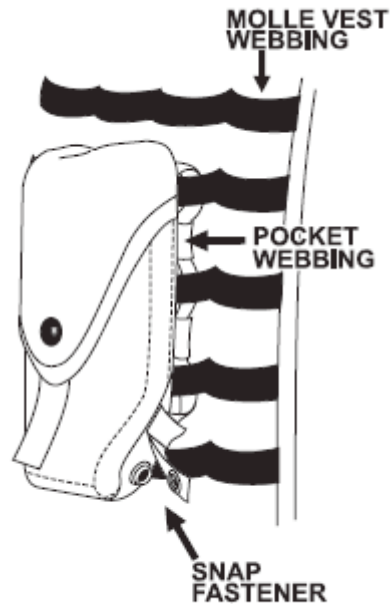


Figure 1: Pouch Attachment Ladder System

The LBV of the MOLLE I system is equipped with a removable insert that attaches the vest to the belt. Figure 2 below shows a schematic taken from the MOLLE Care and Use Manual explaining how the vest connects to the rucksack frame. In this model, the belt of the LBV is dually purposed as the hip belt of the rucksack for a fully integrated system. Despite the intent to improve load distribution and secure the rucksack as close to the body as possible to reduce load carriage injuries, this design led to numerous back injuries due to the ball missing the socket interface and impacting user's body when attempting to don the rucksack. Not only was this integration injurious, but also the plastic frame was found to be very fragile and could not withstand training and combat operating conditions. Many soldiers identified that when the fully loaded rucksack was dropped from overhead, the frame broke on impact with the ground. Consequently, a newer model with a more durable frame was requested.

The belt is equipped with a removable insert that has a female connector into which the frame joins. The female connection socket can be adjusted up or down to size for torso lengths.

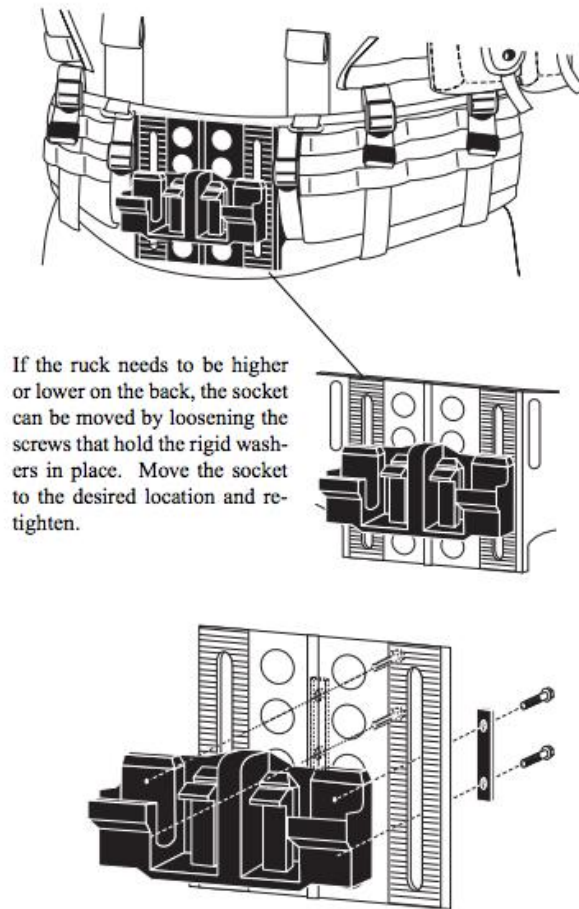


Figure 2: Hip Belt Connector to Ruck Frame

MOLLE II

Taking into account the limitations of the MOLLE I system, a second generation of the MOLLE system, MOLLE II, was developed. The MOLLE II has many of the same key features as the MOLLE I, such as PALS; however, the integrated LBV and rucksack hip belt has been eliminated. The belt of the LBV is now a separate entity from the hip belt attached to the frame of the main rucksack. Modifications present in the MOLLE II system include a more durable plastic frame, a large main rucksack, shoulder straps, and molded hip belt, an assault pack, two sustainment pouches that attach to the main

rucksack, a hip pack, and a fighting load carrier (FLC). Figure 3 below shows the components of the MOLLE II system.

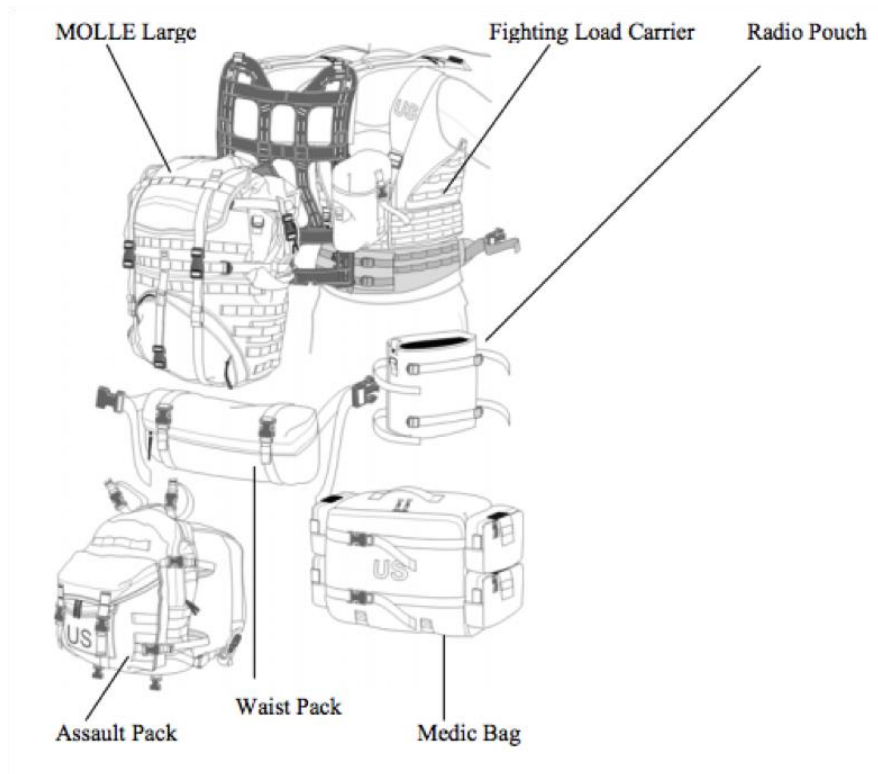


Figure 3: Components of the MOLLE II System

The large rucksack has an internally subdivided upper and lower compartment. The upper compartment has an internal volume of 2,900 cubic inches and the lower compartment has a capacity of 830 inches, which is able to house readily available mission items, including the sleeping bag system that originally attached to the frame in its own pouch in the MOLLE I model. Moreover, the large rucksack is capable of holding 120 pounds. The assault pack of the MOLLE II model, which replaced the patrol pack of the MOLLE I model, now has an internal volume of about 1,525 cubic inches in the main compartment, and 825 cubic inches in the large front pocket. The waist pack, which replaced the butt pack, can hold about 350 cubic inches of volume (MOLLE II Molded Waistbelt, n.d.). The FLC is similar to the LBV, except it is now outfitted with its own hip belt and front zipper to secure it to the Soldier's body. Additionally, the molded hip belt is designed to be permanently fixed to the frame via four 1-inch straps and buckles,

and distribute the load of the rucksack from the shoulders to the hips. Figure 4 below illustrates the molded hip belt design of the MOLLE II model.

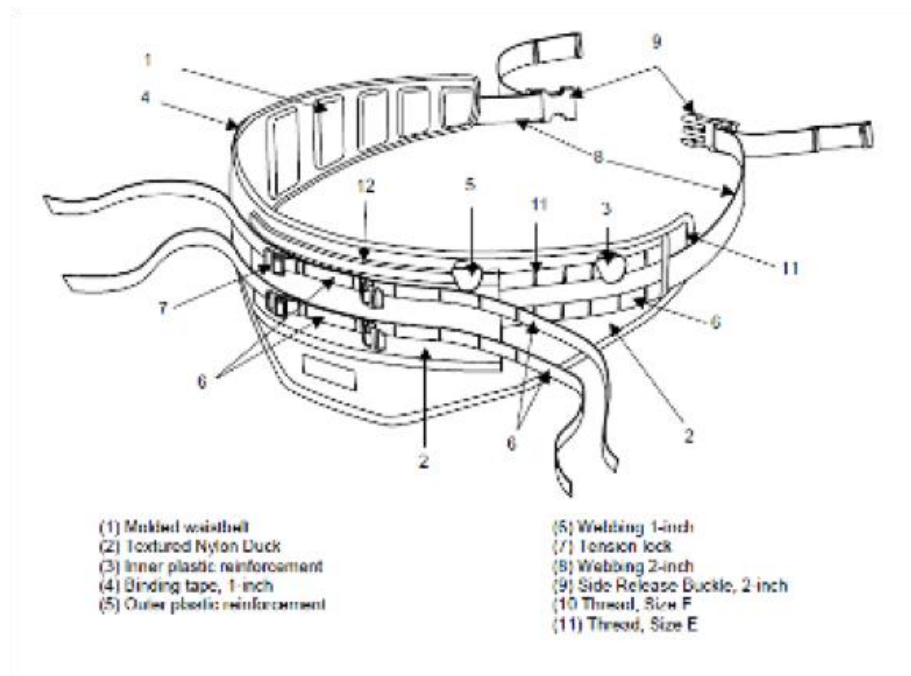


Figure 4: MOLLE II Molded Hip Belt

The following description of the molded hip belt was taken from CIE Hub: Load Bearing Equipment: (MOLLE II Molded Waistbelt, n.d.).

The molded waist belt is constructed of a molded foam pattern, covered in textured nylon duck, conforming to MIL-C-43734 (2), an inner plastic reinforcement and edged with 1-inch binding tape conforming to MIL-T-5038 (4). An outer reinforcement covered with textured nylon duck (2) is sewn to the rear of the belt and onto the inner plastic reinforcement (3). Two rear mounting straps of 1-inch-wide webbing conforming to MIL-T-5038 (6) are sewn onto the outer plastic reinforcement (5). Two attachment straps of the same material are sewn to the center of the rear mounting straps (6) to secure two each 1-inch tension locks (Duraflex PN 5425) (7). In addition, two lengths of 1-inch webbing are sewn to each side of the belt for equipment attachment. Two lengths of 2-inch-wide webbing conforming to MIL-W-17337 (8) are sewn to the outer ends of the inner

plastic reinforcement (3). Male and female ends of a 2-inch side release buckle (Duraflex PN 5432) (9) are attached to the 2-inch webbing belt (8). The waist belt is constructed using Size F Thread conforming to V-T-295 (10). Bartacking and binding tape attachment requires Size E Thread (11).

The MOLLE system has several strengths, including:

- Reliable and durable quick release mechanism on shoulder straps
- Modular pouches (PALS webbing)
- Packing flexibility
- Improved load distribution compared to ALICE

Despite its strengths, the MOLLE system also has some limitations. The deficiencies listed below are complaints from infantry Soldiers of the Army's 82nd Airborne Division, which were compiled in a study conducted on dismounted operations in Afghanistan in April and May of 2003 titled *The Modern Warrior's Combat Load*.

- The plastic frame of the MOLLE is too fragile
- The main cargo pouch of the rucksack is too small
- The stitching needs to be sewn with stronger thread
- The hip belt is difficult to wear under the interceptor body armor (IBA)
- The shoulder straps are too wide for smaller Soldiers under 200lbs
- The frame does not ride well with IBA

Furthermore, the MOLLE system was designed with male physical characteristics in mind and does not take into account the physical differences of the female. Thus, many female Soldiers find discomfort with the hip belt and suffer more load carriage injuries than their male counterparts.

2.2 Male vs. Female Anatomy Affecting Load Carriage

There are many anatomical differences between males and females that affect the way that the rucksack is carried and the distribution of the load carried. These differences include both skeletal differences and muscular differences.

2.2.1 Skeletal Differences

The female skeleton is not only smaller than males in general, but there are differences in the shapes of the bones. The largest difference is in the pelvis; the female pelvis is wider and smaller in height (Delavier, 2003). The difference in pelvis shape changes the location of the center of mass in females and can also cause uncomfortable rubbing of the current MOLLE hip belt on the hips during standard Army training. The lumbar curve in the spine is also greater in females, which causes tilting of the pelvis, changing the center of mass. Furthermore, the female spine has lower compression tolerances when load is applied (Friedl, 2005). The smaller female ribcage also affects the carriage of rucksacks due to the location of the shoulder straps (Delavier, 2003).

2.2.2 Muscular Differences

The muscular difference between males and females tends to be in the upper body. “In standard [military] tests of upper body strength, only the strongest women reach the lower end of the male distribution of strength capacities” (Friedl, 2005). The difference in muscle in the shoulders also has an effect on the ability to carry heavy loads, because the shoulder straps are designed for the broader shoulders of the male compared to the narrow shoulders of the female (Delavier, 2003).

2.3 Load Distribution

The amount of load that a Soldier carries in his rucksack has been steadily increasing throughout history, and the manner in which this load is distributed in the backpack greatly influences the energy expenditure of the Soldier as well as his performance in the field. The hypothesis that has been widely accepted is that items lighter in weight should be placed at the bottom of the backpack, while items that are heavier in weight should be placed at the top so that stability can be achieved. As can be seen in Figure 5 below, loads placed higher in the pack result in lower energy cost, and loads placed lower in the pack result in higher energy cost.

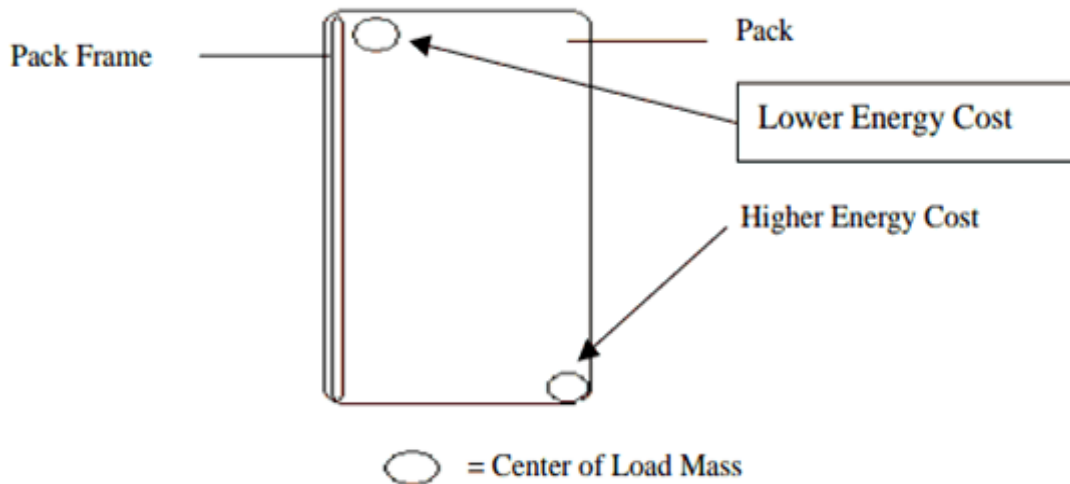


Figure 5: Placement of Load in the Backpack

Some previous studies have shown that when the load is placed higher in the pack, this can cause the body to sway and consequently disrupt posture of the Soldier (Liu, 2007). The use of treadmills in studies have shown that on flat terrain, it is more beneficial to place items high in the pack because this makes it easier to maintain the body in an upright position. On uneven terrain, an even distribution of the load allows the body to remain stable (Knapik et. al, 1996).

The most practical way to carry load is as close to the center of mass (COM) of the body as possible. When the location of the COM is high and close to the body, there will be less reaction forces exerted on the limbs as well as a decrease in metabolic cost (LaFiandra et. al, 2003). When the COM is higher, this means that when the Soldier makes a forward motion, the COM will be moved over the fulcrum, which reduces the muscles that are required to hold the load (Southard and Mirka, 2007).

There are various ways to evenly distribute the carried load so that the COM of the body is maintained. Soldiers have the option of wearing a double pack, which evenly distributes the weight in the back and the front of the body. The double pack produces less forward lean of the Soldier; the displacement of the COM is also smaller as a result of the even distribution of weight (Lloyd and Cooke, 2011). Although there are advantages of the double pack, it does have certain limitations. For example, it can inhibit movement of the Soldier, limit field of vision in front of the body and be difficult to doff in a combat situation. These limitations of the double pack have allowed for

modifications of the backpack. Hip belts and shoulder straps have been shown to efficiently distribute the load in order to maintain COM of the body. One study used a framed backpack with a hip belt to prove that 30% of the vertical force of a backpack is transferred to the hips. There will be more pressure on the shoulders if a hip belt is not used by a Soldier (Southard and Mirka, 2007). Shoulder straps have also been used to relocate the load to the hips or the shoulders. When the shoulder straps are looser, there is a greater amount of load placed on the hips. On the other hand, when the shoulder straps are tighter, there is a greater amount of load placed on the shoulders (Knapik, 2000).

Although these additions to the MOLLE can be beneficial for redistribution of load, women do not reap the benefits because they were originally designed based on the physical characteristics of men. Due to their anatomy, women may have problems with the fit of the pack or shoulder strap as well as the position of the hip belt. One study found that with the MOLLE, male Soldiers could efficiently shift 30% of carried weight from their shoulders to their hips and legs. Often times, women cannot perform as well as men in training and in combat due to their lower upper body and torso strength. As a result, their COM is different than men, and they prefer to carry loads closer to their hips. Women may also have a wider pelvis, which means that the MOLLE hip belt may not fit properly around the hip. If the hip belt is not tight or is positioned in the wrong location, it may not sufficiently transfer weight from the shoulders to the hips. This can result in discomfort in the hip or pelvis (Ling et. al, 2004). Overall, women are more likely to experience musculoskeletal problems. One study even found that in basic training, female recruits are twice as likely to be injured as male recruits (Heller et. al, 2009). There is a growing need to develop modifications for the MOLLE that could be used specifically by women in order to reduce discomfort and injury.

2.4 Commercial Backpacks for Females

Currently, the largest commercial use for backpacks that can hold a load or serve a purpose similar to that of a rucksack is the hiking backpack. Understanding the alterations and specifications of a hiking backpack made for women allowed the design team to determine what features have been successful in commercially available products and how those features may be modified and applied to a military rucksack for women.

Hiking backpacks are usually chosen based on the length of a trip, the type of trip the backpack is being used for and the user's body type. If the trip is for a shorter period of time, then the capacity of the pack can be smaller and the weight of the pack will be lighter. If the pack is being used for hiking in the winter, it will need to be slightly more durable than hiking in the summer. Increasing the durability of the pack often leads to an increase in the weight of the pack. Hiking backpacks are not very adjustable which makes torso length the main body measurement taken to choose the correct backpack. Backpacks for women are typically shorter and narrower than men's backpacks due to torso shape and length (Wood, 2013).

When commercial backpacks are compared to the MOLLE rucksack there were a number of observations made about the benefits and drawbacks of the MOLLE. The commercial backpack was much easier to move around in and maneuver through an obstacle course because it was closer to the body. The commercial backpack did not get in the way of firing weapons or stick out beyond the body. On the other hand, the MOLLE pack was much more durable and standardized. The MOLLE also accommodated all of the equipment that needed to be carried (LaFiandra, 2003). Overall the commercial backpacks are easier to handle and more comfortable.

2.5 Previous Studies

In a study conducted at New York University, the effects of the MOLLE on women were observed both while they were walking and on a simulated march. They also observed the upper and lower body strength of the women and how that affected their load carriage. This study was approved by the New York University Committee on Activities Involving Human Subjects. The chosen test subjects were seven healthy, active women between the ages of 18 and 30 who were screened for back or leg problems. The women were required to carry a rucksack with varying weights (no load, 20 lbs, 30 lbs, 40 lbs, and 50 lbs) to perform a trial to assess the strength of their muscles. They walked on a 40 foot pressure sensitive mat three times at 4.827 km/hr to measure gait. Following this, the subjects participated in a simulated march; this consisted of a two minute warm up, 56 minutes of marching, and a two minute cool down. At the time increments 0, 10, 20, 30, 40, 50 and 58 minutes, heart rate, discomfort and perceived exertion were

measured. Once the march was completed, subjects participated in a follow-up gait analysis (Ling, 2004).

While testing, only one participant was unable to finish all six sessions. Three participants required modified hip belts to ensure appropriate weight distribution. The female that was unable to complete all of the trials required a modified hip belt and could not complete the 40 lb load march. She experienced pain over her iliac crests and anterior superior iliac spines. It was observed that as the load increased, the discomfort of the rucksack increased. With a load of 40 or 50 pounds, discomfort was experienced in the anterior superior iliac spines, iliac crests and upper back (Ling, 2004).

The overall result was that, though the hip belt had to be modified for three of the participants, the MOLLE fit women effectively. When the hip belt adequately fit the pelvis, there was less movement of the back in the vertical direction. Furthermore, the participants did not appear to have significant shoulder discomfort, but they did have upper back and neck pain. To maintain an appropriate center of mass, women appeared to hunch forward. It did appear that the MOLLE was effective in distributing the load around the female's hips, though alterations were needed (Ling, 2004).

In a second study, 43 females between the ages of 18 and 25 were used to observe postural sway as the result of wearing a military backpack. Subjects stood on a force plate in a marked location without a load and then with an 18.1 kilogram rucksack that was loaded with rocks and linen. They were asked to cross their arms and look at a marked location 4.7 meters away from the force plate. While standing on the force plate, data was collected to measure center of pressure. In this study, path length, area of motion and medial-lateral and anterior-posterior excursions were measured (Heller, 2009).

The results of the study showed that the path length of the COP increased by 64% when subjects were wearing the rucksack. Both excursions increased when the backpack was worn, and the area of COP increased by 229% when the rucksack was worn. These changes in center of pressure result in postural sway, which poses a higher risk of falls for women (Heller, 2009).

In a third study, different harnessing mechanisms were evaluated at various angles. Participants were asked to wear a backpack with 18.2 kilograms of evenly distributed weight. Two backpack designs were used: basic style, which resembles a

regular backpack, and advanced style, which had stiffness rods and a hip belt structured similar to that of a hiking backpack. To determine the different effects of each of these backpacks, the study measured muscle activation level and comfort of each backpack. This study used fifteen participants (twelve men, three women) who ranged from 21 to 55 years old. Surface EMG was used to observe the muscle activation. The participants were asked to cross their arms and bend to the desired angle (15, 30, 45, or 60 degrees) while the EMG collected data. This same procedure was repeated again for the second backpack. Three subjective surveys were given out after the tests to measure the participants' comfort with each design and to compare the designs (Southard, 2006).

Results of this study showed that at 15 and 30 degrees, the advanced harness showed a decrease in muscle activity of the erector spinae and trapezius muscles than that of the basic harness. This is due to the fact that when bending, the weight of the pack is distributed across the back. Participants felt that the advanced harness was more comfortable than the basic harness (Southard, 2006).

As shown in these studies, hip belts are a very helpful addition to the design of any backpack, including the MOLLE. Women are more at risk for falls while carrying a heavy rucksack on their back due to the changes in center of pressure (Heller, 2009). This could be prevented if the center of pressure was maintained as close to the Soldier's center of mass as possible. Soldiers may face conditions where they wear the rucksack while standing at various degrees of torso bending. A previously discussed study showed that wearing a hip belt is more effective than only wearing the shoulder straps (Southard, 2006). However, not all women find the hip belt to be comfortable, so some may choose to forgo wearing it. In addition, with the amount of equipment that Soldiers must carry and the IBA they are required to wear, the hip belt may not fit comfortably or effectively around their hip, resulting in less effective weight distribution. If female Soldiers choose not to wear the hip belt, they will not experience the benefits that it provides. Therefore, a more effective and comfortable hip belt is needed to reduce potential injuries that women face from carrying the load in these packs.

2.6 Patents

The following patents were examined in order to develop a better understanding of current hip belt designs and hip belt aspects.

2.6.1 Shockproof Quick-Release Fastener for an End Fitting of a Safety Belt

(Lundgren & Sterner, 2011)

While developing functions, the team determined that the hip belt should include a quick release mechanism, which the current hip belt design lacks. Safety belts are an example of an effective fastener that has a quick release mechanism. This particular design consists of two frame plates, an insert plate and a piece to lock the insert plate between the two frames. This device no longer needs a specific two-pronged tool to release the buckle, allowing for a simpler quick release. It proves to be more shockproof than previously used safety belt buckles and will not release in the case of a car accident.

2.6.2 Modular Load Carrying Equipment

(Carlson, 1996)

This modular load carrying equipment was designed to carry heavy loads and to be used in conjunction with a “multifunctional, soldier-centered, computer enhanced warfare system.” The design has storage modules mounted on a flexible frame, which have the ability to be easily detached from the frame without doffing the frame to extend the user’s range of motion and level of comfort. The pack frame has an integrated adjustment mechanism to increase or decrease the shoulder straps, rib-cage straps, and distance between hip belt and pack frame to adapt to the size of the user’s torso and hip without doffing the pack. This particular modular load carrying equipment has not been adopted by the military.

2.6.3 Quick-Release Weight Distribution and Connection System

(Milligan & Stokes, 2013)

This hip belt was designed to distribute load in items such as a rucksack, body armor, or a tactical vest. It features a quick-release mechanism to doff it quickly in combat situations. The interconnection member of the hip belt connects the rucksack and

the hip belt to redistribute the load. Redistribution of the load is achieved when the interconnection member is inserted into a sleeve system of the hip belt. The invention allows for quick release, which the designers quantitatively defined as between 0.1 and 2 seconds. The quick disconnecting load-bearing component and interconnection member are attached to the hip belt, which does not require the belt itself to be removed. All components of this weight distribution system can be made from a variety of materials, as the designer did not choose a particular one for the design. However, the interconnection member is constructed of at least one inner stiffening material and a flexible material on the outside. In order to accommodate various body types, the hip belt was designed to be adjustable in length to make it adaptable to size of user.

2.6.4 Adaptive Fit Waist Belt and Backpack Having Such a Waist Belt

(Eveleigh & Hurn, 2006)

This waist belt was designed to best accommodate the users body shape. The belt has two contact points to the backpack for each side, one to the bottom of the pack and one low/mid pack. The upper strap can be tightened to adjust the angle of the belt in order for the belt to be worn over the top of the hips instead of flat around the hips. Ideally this means a greater upward angle for females and a more horizontal angle for males. The belt is not removable but remains stationary on the pack. This belt was designed for hiking backpacks.

Chapter 3: Project Strategy

3.1 Initial Client Statement

The stakeholders of the design were identified so that their needs could be considered during the design process. They were broken down into three groups: the designers, clients and users. The project team of biomedical engineers from Worcester Polytechnic Institute was the designer. The client is the United States Army who would buy this product to mass produce for Soldiers. In particular, female Soldiers of the United States Armed Forces would be the user because they demonstrate the greatest need for a modified hip belt. By identifying these stakeholders, the team was able to develop an initial client statement:

To modify the current design of the Modular Lightweight Load-carrying Equipment (MOLLE) rucksack for the female Soldier that considers the female anatomy and its physical differences. The design should still enable the average combat load. The rucksack should reduce the number of back injuries in Soldiers without interfering with other tactical equipment, while complying with the United States Army standards. The rucksack should allow for Soldiers to complete all necessary tasks that would occur in the field.

3.2 Design Objectives

Through the development of the client statement, the team established the following objectives that were ranked according to significance:

1. **Effective in load distribution.** This design should be equal to or better in effective load distribution from the shoulders to the hips compared to the current model.
2. **Durable.** Soldiers in the military are faced with many conditions, so the design of this hip belt must be durable to endure these conditions.
3. **Comfortable.** This design should be comfortable for the user to wear for extended periods of time.

4. **Flexible.** The design should be flexible so that it does not inhibit the movement of the Soldier due to the material or shape of the hip belt. Additionally the hip belt should be compatible with other equipment.
5. **Adjustable.** The hip belt should be adjustable so as to fit a range of sizes to account for the differences in dimensions from person to person.
6. **Standardized.** It is important that all Soldiers use standardized equipment to allow for maximum efficiency during training and combat operations. Soldiers are issued standardized equipment to simplify training and equipment knowledge. Therefore, the Army must mass-produce their equipment and gear, so the design of the hip belt must allow for similar production.
7. **Lightweight.** As these rucksacks can weigh over 100 pounds, the hip belt should not add a considerable amount of weight to the rucksack.

In order to avoid designer biases, three female Army Reserve Officer Training Corps (ROTC) Cadets and one female Army Captain were asked to rank the objectives based on user preference. The average of these rankings is shown in the pairwise comparison chart in Table 1.

Table 1: Pairwise Comparison Chart

PCC	Flexible	Adjustable	Standardized	Lightweight	Durable	Effective in load	Comfortable	TOTAL
Flexible	***	0.5	1	1	0	0	0	2.5
Adjustable	0.5	***	1	1	0	0	0	2.5
Standardized	0	0	***	1	0	0	0	1
Lightweight	0	0	0	***	0	0	0	0
Durable	1	1	1	1	***	0	1	5
Effective	1	1	1	1	1	***	1	6
Comfortable	1	1	1	1	0	0	***	4

The main objective of this project was to ensure the design is effective. The hip belt must effectively distribute the weight of the rucksack to the user's hips to alleviate the pressure experienced on the user's shoulders. The efficiency of the design was of the greatest importance; if the design is not effective, many of the other objectives would be negligible.

The objective that was ranked second was durable. This was because Soldiers face various conditions that may result in tear of a non-durable material. If the materials rip or break, they do not have the ability to be effective

Comfortable was ranked following durable. If the hip belt was uncomfortable to wear, Soldiers may choose not to wear it, and they would consequently not benefit from its intended use, to be effective in load distribution.

Following comfortable, flexible and adjustable were given the same ranking. The design must be flexible so that it does not inhibit the movement of the Soldier. Additionally, the design must be adjustable to fit the various dimensions of Soldiers. If the design cannot be properly adjusted, the rucksack will not be able to effectively distribute the load.

Standardized was ranked after flexible and adjustable. Everything in the Army is mass-produced to ensure that the equipment is universal. The Army would not create different hip belts to suit each Soldier, as this would limit the ability to interchange equipment. However, for the purpose of this project, an effective design was most important. Once the design was proven to be effective, standardization was then taken into consideration.

The lowest ranked objective was lightweight. Since rucksacks already weigh a considerable amount when fully loaded, the weight of the hip belt is negligible in comparison.

3.3 Constraints

As the team developed their objectives and revised client statement, they also developed constraints for their project.

1. **1-inch wide straps compatible with MOLLE frame.** The current design of the MOLLE frame allows for the attachment of the various pouches and straps

- through the use of 1-inch wide straps. To keep the hip belt compatible with the current frame, it must be attached through these straps.
2. **Support 120 pound load.** Rucksacks can weigh up to 120 pounds. If the hip belt effectively distributes the weight appropriately, the weight of the rucksack may be supported mainly by the hip belt.
 3. **Under \$20 consumer price.** Each part of the MOLLE can be bought separately. The current prices of the MOLLE hip belt are around \$20, so this design should be similar in price.

3.4 Revised Client Statement

After evaluation of the most important objectives and constraints of the design and collaboration with the client and user, the team was able to refine the initial client statement:

To redesign the hip belt of the current Modular Lightweight Load-carrying Equipment (MOLLE) rucksack for the female Soldier that considers the female anatomy and its physical differences. The design should still enable the average combat load and comply with United States Army standards. Redesigning the hip belt should allow the load to be evenly distributed according to the center of mass of the body. The rucksack should allow for Soldiers to complete all necessary tasks that would occur in the field.

3.5 Project Approach

In order to provide direction for the completion of this project, the team determined necessary steps towards developing, implementing, and testing a successful design. Although the team has set milestones to achieve along the way, these steps served as a basic outline of fundamental tasks to keep the team on the right course and headed for success.

3.5.1 Design Testing

Design testing played a major role in the design process. The team went through a process of design development and testing prior to prototyping. The team drew several schematic drawings of their alternative designs and final design. Due to the fact that the

hip belt was be composed of fabric rather than metals or plastics, the team also developed sewing patterns based off the team's modifications of prior models.

Once design alternatives were determined, the team proceeded to select the most appropriate fabric materials for constructing the new hip belt. The team chose materials based on resources available to them at Natick Soldier Systems Center, as well as materials that already comply with U.S. Army regulations. When selecting materials, the team kept the following in mind: which materials would provide the most comfort while supporting a 120-pound load and withstanding the stresses of a load under combat operations. Ideally, the chosen materials would outrank the current model in these areas.

Originally, the design team planned to use finite element analysis to theoretically test the final design through computer simulation. However, a major challenge that the team faced was lack in accuracy that a computer simulation would provide in assessing the success of the design since it was be composed of fabric material and tested on a variety of females with various heights, weights, and dimensions. Consequently, the team decided to take on a test and revise approach. Design and testing was therefore an iterative process. Since the design could not be tested through simulation, it required a feedback loop as a method of revision. Thus, the team produced and tested various versions of design prototypes.

3.5.2 Subject Testing

After a prototype was developed, the team moved on to subject testing. One challenge that the team faced was receiving approval from the Institutional Review Board (IRB) to conduct testing on human subjects. The team sought IRB approval in order to understand and comply with the ethical guidelines and governing requirements for research that involves human test subjects. IRB approval granted the team ability to further evaluate the success of the overall design of the new hip belt.

Initially, the team conducted subject testing on themselves. Once successful, the team selected ten female volunteers to participate in a series of physical tests. In order to measure success of the design, the team developed several tests and questions that determined heart rate, exertion comfort, and effective load distribution. These tests were performed outdoors on a one mile obstacle course around the WPI campus.

The team evaluated heart rate and rate of exertion to determine energy expenditure and the physiological stresses that were placed on the subjects under various loads with the current model compared to the team's design. Various methods of testing were proposed for potential evaluation of the success criteria. The team used a heart rate monitor as a means of measuring heart rate. Additionally, the team determined the rate of perceived exertion (RPE) of each subject through a questionnaire using the Borg scale that also addressed the issue of comfort. Furthermore, the team determined load distribution in one of four ways. Force plates were used to determine center of pressure. This method allowed the team to properly assess the distribution of the load on the female subject.

Piezoelectric sensors were looked into as a method to measure pressure in certain locations of the back, hips, and waist to determine where most of the pressure was exerted when carrying the load. Likewise, pressure transducers were also considered to be placed under the shoulder straps of the rucksack to evaluate the pressure of the load placed on the shoulders as opposed to the hips. Ultimately, the team decided to use pressure film along the hip, back and shoulders to measure the pressure distribution under the hip belt.

These methods were used to determine success of the new design. Success of the team's design was achieved when their design outperformed the current model in those areas.

3.5.3 Management

The team created a work breakdown structure that can be seen in Figure 6. After conducting background research, the team developed and revised the client statement. Using the revised client statement, the team formed the objectives, constraints and functions of the design. The project approach was established, which included the technical, financial and management aspects of the project, in order to track the budget and schedule. This background research allowed the team to develop alternative designs. Drawings were created for each alternative design, and from these alternative designs, the team chose a final design to prototype. The design was created using sewing patterns drawn by the team. The success of this prototype was tested using human subjects

performing a series of tests. Ten females were tested for heart rate, muscle activity and load distribution without the load, with the current system and with the design modified by the team. After these tests, the subjects were asked to complete a rating of perceived exertion. Four test subjects were then used to measure center of pressure under various conditions and distribution of weight through pressure film. The data was analyzed in order to ensure the success of the modified design. Again, since design and testing was an iterative process, the belt could not be tested through simulation, and thus required a feedback loop as a method of revision. The project was finalized with the completion of the paper and presentation.

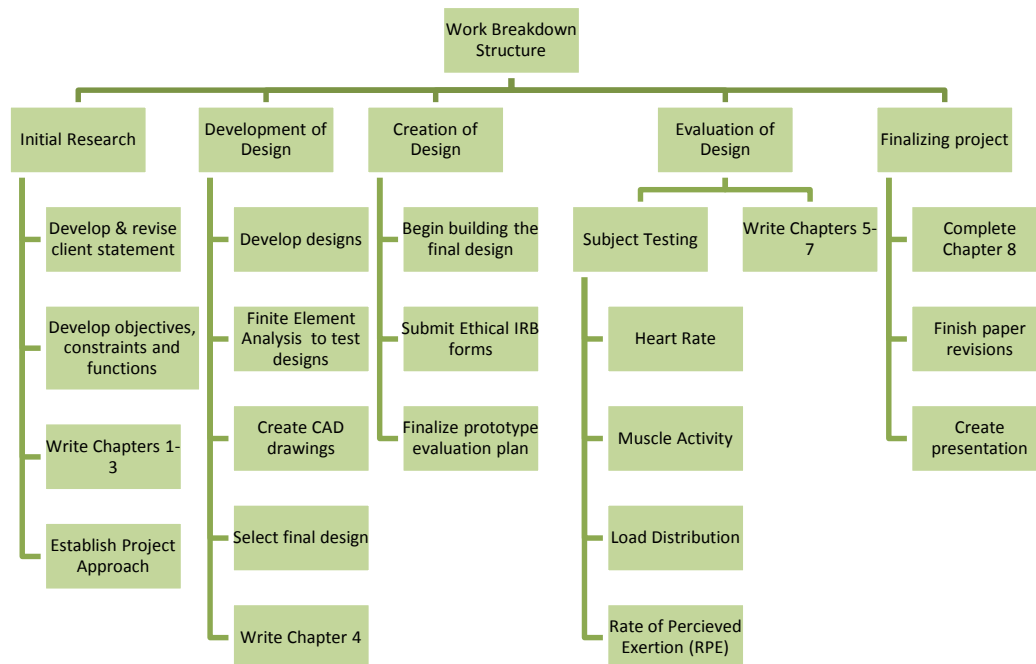


Figure 6: Work Breakdown Structure

The team developed the Gantt chart that can be seen below in Figure 7 to track their progress throughout the course of the project. In Phase 1, A term, the team conducted all of the necessary background research in order to create design alternatives. In Phase 2, B term, the design alternatives were tested so that the final prototype could be finalized by the end of the term, and the final design be manufactured. Phase 3, C term, consisted of evaluation of the final design using human subject testing. Force plate and pressure film testing were also conducted. These results were then analyzed to draw

conclusions from the data. The final paper and presentation were completed by the end of Phase 4, D term.



Figure 7: Gantt Chart

3.5.4 Finances

Finances were considered for each of the stakeholders. The user, female Soldiers, would receive this product for their service. Therefore, they would not have any financial claims to the project. The client, the US Army, would be interested in the overall cost that can be seen in Table 2 below. The table shows the cost per belt, which used a range of numbers in consideration of the possible materials that could have been used for the design. The cost to assemble the hip belt was estimated to be less than five dollars; however, this assembly price was ultimately determined by the final design. This financial breakdown proved that the cost of the hip belt would not be higher than the price of the current hip belt.

Table 2: Financial Breakdown for Client

Material	Unit	Cost/Unit	Cost/Belt
Fabric	60" x 36"	\$11-15	\$3.67-\$5
Fastening System	10	\$4.60 - \$7.90	\$2.30-\$3.95
Padding	60" x 36"	\$15-\$20	\$5-\$6.67
Assembly			<\$5
Total Manufacturing Cost			\$15.97 - \$20.62
Consumer Price:			\$20

The finances of the designers of the project team were also considered. Each team member was allotted approximately \$156, bringing the total budget for the project to approximately \$600. This money was used for the creation of prototypes, testing, and other smaller finances in order to complete the project.

Chapter 4: Design Alternatives

During the design process, the team analyzed the needs, functions, and constraints, which were then used to develop design alternatives. Various aspects of the design alternatives were considered before the team decided on their final design. The selection of the final design was based on many factors, including initial material testing and female hip and waist measurements.

4.1 Needs analysis

After talking to Richard Landry, a physical scientist and one of the lead engineers for the MOLLE system at Natick Soldier Systems Center, the team developed certain requirements for the hip belt that would meet military standards. The first requirement was that the hip belt must use American made materials. It also must withstand temperatures ranging from -40 °F to 140 ° F. This accounts for the wide variety of weather conditions that the Soldiers may face. Any materials, including the foam padding inside the hip belt, must be resistant to oils because some types of foam disintegrate after exposure to various oils. Finally, it must meet all military specifications. In order for the final design to be successful, it must satisfy all of these requirements as well as the objectives established by the team.

Ideally, this hip belt should be one size fits all so that the military can use one standardized hip belt for all female Soldiers. Although it is not the primary goal of the project, ideally the hip belt would be used by both men and women. Then all the current MOLLE hip belts could be replaced with the new design.

4.2 Functions

The team developed the following functions for the design:

- **Release quickly**

The design should incorporate a quick release buckle for securing the belt around the hips. The quick release buckle should not hinder the Soldier from doffing the

pack. In combat, a slower release time could pose a safety risk for the Soldier. The Soldier should be able to doff the pack in two seconds.

- **Distribute load evenly around the hips**

The design must show an improvement in distributing the load around the wearer's hips, thereby increasing comfort. Comfort level will be measured based on the rate of perceived exertion and compared to the current model. Pressure sensitive film will be used to measure load distribution at the hips and shoulders.

- **Bring the rucksack closer to the body**

The hip belt must allow for the rucksack to be moved closer to the body in order to help distribute the weight. For each participant in the testing phase, the distance from their back to the rucksack frame will be measured. The team's design must allow this distance to be equal to or less than the distance that the current model affords.

- **Allow freedom of movement**

Fourth, the hip belt should allow for freedom of movement. Wearing the hip belt should not prevent a Soldier's ability to bend or move. If the hip belt inhibits movement, the soldier may choose not to wear the belt. During the testing phase, a range of motion test will be implemented to compare the degree of freedom of the current model to that of the team's design.

- **Reduce injury**

Finally, the last function of the design is to reduce injury. Although this is not within the scope of the project, the goal for the future is to help reduce any injuries that wearing extremely heavy rucksacks cause.

The team compiled a functions-means chart (Table 3) to determine various ways to accomplish their design.

Table 3: Function Means Chart

Functions	Means		
Releases quickly	Side release buckle	Front release buckle	Seatbelt style
Distributes load	Shape of belt	Straps to attach to frame	
Backpack to body	Straps from belt to backpack	Shape of belt	
Freedom of movement	Flexible fabric	Shape of belt	Flexible foam

Using this chart, various design ideas were discussed and developed. Various buckles are available and are quick in their release. The current model uses a front release buckle for the hip belt, but a side release buckle for the sternum strap. The team considered various types of buckles, such as seat belts, that could be used for the design.

The way that the belt is designed can change how the load is distributed. The current model wraps around the hips with indentations close to the location of the hip bones. However, an altered shape may allow the belt to contour around the hips and effectively distribute the load.

The shape of the belt could also bring the backpack closer to the body. Also, straps could be added to the MOLLE frame to ensure that the rucksack is as close to the body as possible.

The shape of the belt, as well as the fabric or foam, can allow or inhibit freedom of movement; differences in fabric or foam could cause the belt to be more stiff or conformable.

4.2.1 Specifications:

- Must weigh under 5 lbs
To ensure that the hip belt is lightweight, the design should stay under 5 pounds.
- Must fit the 1st to 99th percentile of female hips

This will allow females of various sizes to wear the hip belt with effective load distribution. 1977 data states the 1st to 99th percentile of women have a hip circumference ranging from 81.7 – 112.2 cm. The team's hip belt must fit this range.

- Must use 1" straps to connect to MOLLE frame

This is required for the hip belt to remain compatible with any MOLLE frame that is in use.

4.3 Alternative Designs

Using the objectives, constraints, functions and specifications previously determined, the team developed a number of alternative designs as possible solutions.

4.3.1 Fastener Alternatives

The method of clasping the hip belt around the soldier was considered for many different design alternatives. The mechanism by which the hip belt connects around the person must be simple enough to be easily closed or opened. It also needs to be durable enough that it will not be easily broken upon use.

A hook and eye closure system (Figure 8A) would be simple, cost effective and would not be broken easily. However, it would not be the easiest to open or close around the soldier in a short amount of time. A twisting closure (Figure 8B) or threaded hook closure (Figure 8C) would also be cost effective and easy to undo. However, these closures are difficult to fasten back together because the interlocking parts must align.

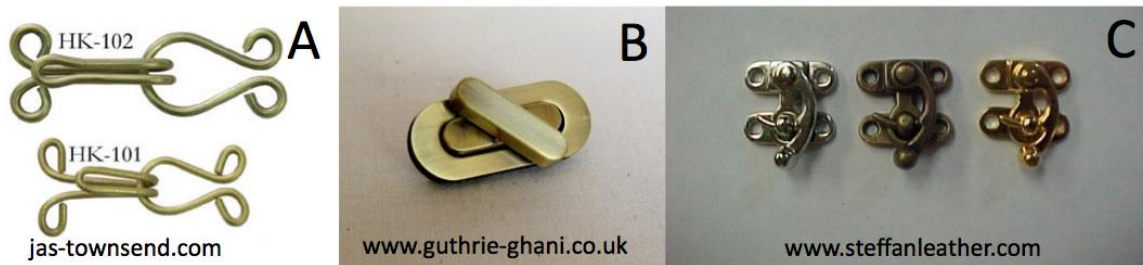


Figure 8: A) Hook and Eye, B) Twist Closure, C) Threaded Hook Closure

Another design idea was to use a seatbelt model for the closure system (Figure 9). Seatbelts are simple to both open and close quickly. They are durable and rather cost effective. The disadvantage of using a seatbelt system would be the bulky size and heavy weight.



Figure 9: Seatbelt Closure

There are two types of buckles that are currently used by the military that were considered for design alternatives, the front release (Figure 10A) and side release buckles (Figure 10B). Both are cost effective and can endure a large load. The side release buckle is much more difficult to release than the front release buckle. The front release buckle has been known to sometimes unlatch when Soldiers go into the prone position due to the ground pressing on the buckle. Both buckles are military approved for materials.

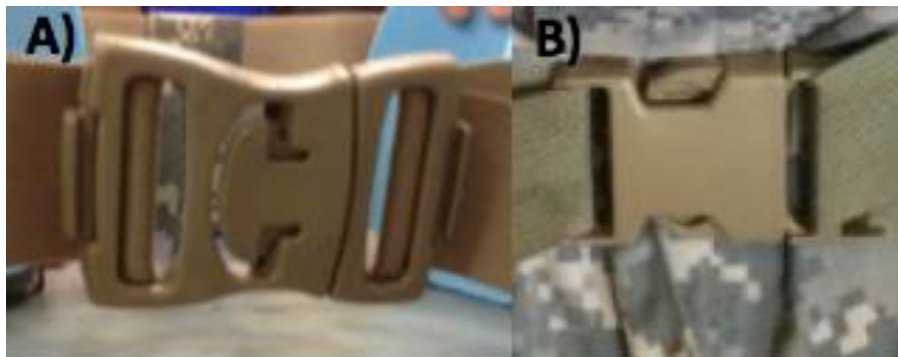


Figure 10: A) Front Release Buckle, B) Side Release Buckle

4.3.2 Tightening Alternatives

Another design aspect that was considered was the mechanism in which the belt is tightened around the body. In the current model, the Soldier must pull the straps sideways, away from the body, in order to tighten the belt around the hips. A “pull-forward” method of tightening would allow the individual to use his or her bicep muscles to tighten the straps, which would be much easier to adjust than the current “pull-sideways” method.

One design alternative was a system that would adjust the circumference of the belt using one strap (Figure 11). The buckle would still remain in the front of the belt. However, the strap would only be looped through the buckle and then be laced through the length of the belt to the sides where a tightening mechanism (buckle) would allow for the strap to be pulled forward.

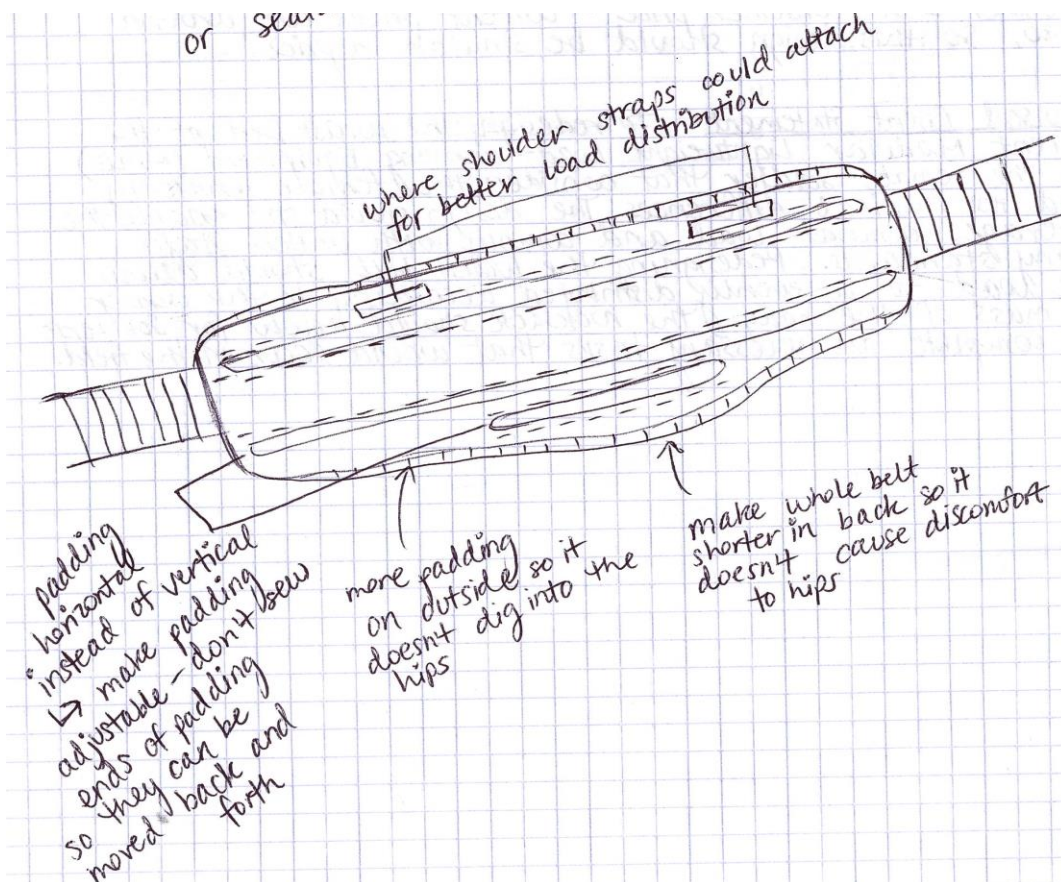


Figure 11: One Strap Tightening System

A second mechanism for tightening the circumference of the belt uses offset attachment of the straps (Figure 12). This would allow for the top and the bottom of the belt to be tightened to different tensions to better customize the belt from soldier to soldier. The offset strap system would attach the tightening strap to the top of the belt, which would then be threaded through the tension system on the buckle. The strap would then be threaded back through a tensionlock allowing the strap to be pulled forward for tightening. The tension lock would be attached to the belt below the strap attachment site. The offset strap mechanism would use a one inch strap and smaller fasteners, which would cause the belt to be less cumbersome.

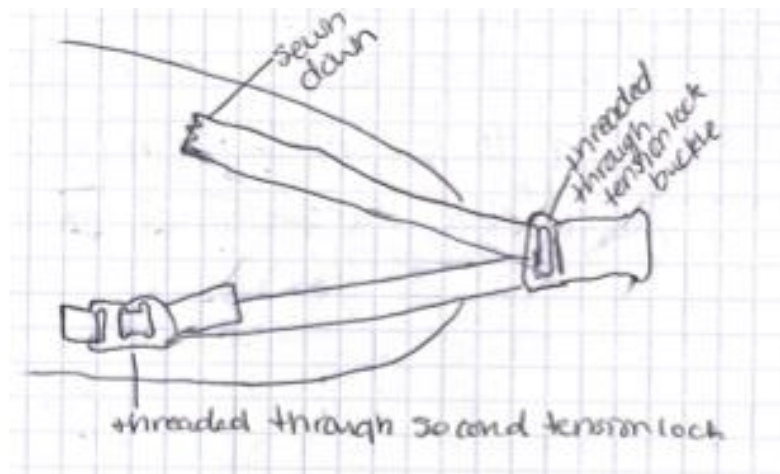


Figure 12: Offset Attachment Strap Tightening System

4.3.3 Padding Alternatives

Padding was a major design concern that directed the development of many different design alternatives. Each design considered the correct amount of padding that would allow for maximum comfort without sacrificing other objectives or constraints.

The first design alternative that was considered was solid horizontal padding (Figure 13). This used strips of closed and open cell foam along the horizontal of the belt in order to wrap around the curvature of the hip. The shape of the belt would also rise around the hips in order to support the top of the hips and allow for the proper canting of the belt. Manufacturing this belt would be feasible, because it is similar to the manufacturing that is used to produce the current belt.

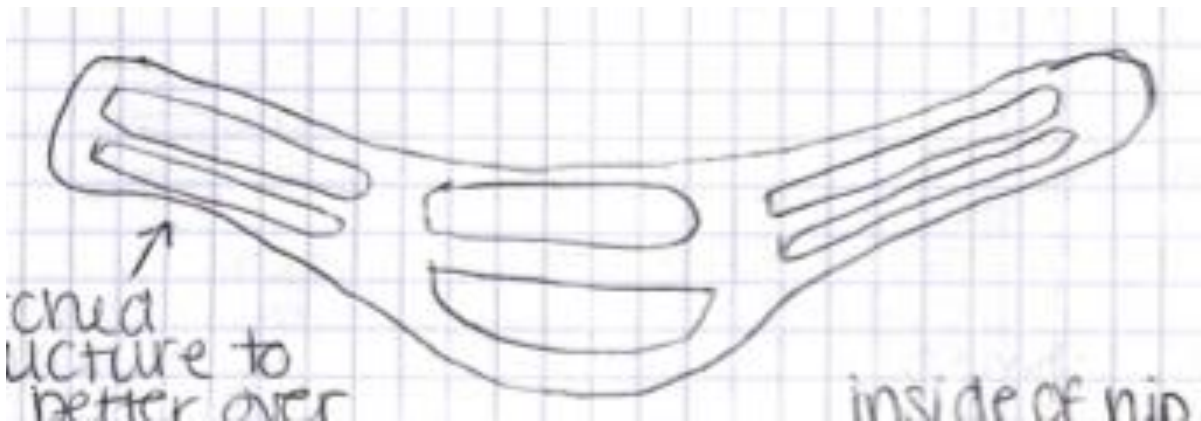


Figure 13: Horizontal Padding

A second design used elastic around the edges of the belt in order to “hug” the hips properly (Figure 14). The elastic portion would run along the top and bottom of the belt pulling the edges of the belt closer to the body and providing canting/wrapping around the hips.

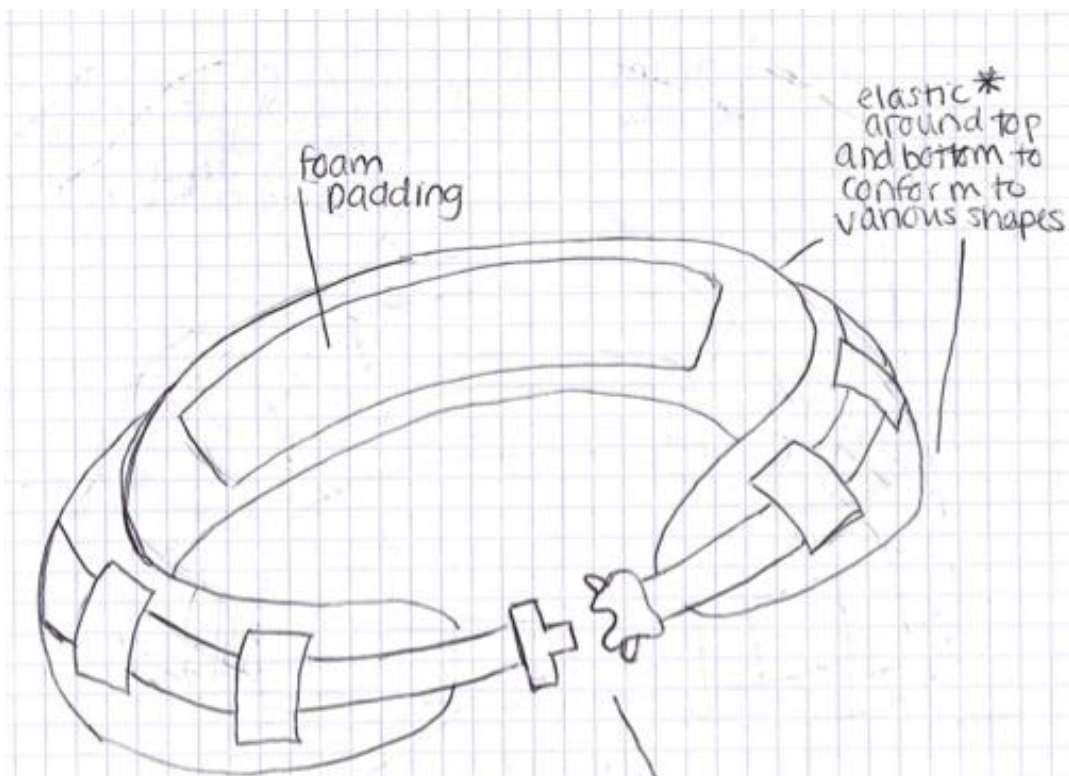


Figure 14: Elastic Edging

The third design used moveable padding that would be attached along webbing (Figure 15). The padding would slide along the webbing in order to be customized for each soldier. A removable padding system of the design used the already utilized PALS webbing, where each pad that could be removed would attach in a method similar to attaching an exterior pocket to the belt. This would use snaps to securely fasten the padding. For both the movable and removable padding systems, one solid pad for each hip and many smaller pads were considered.

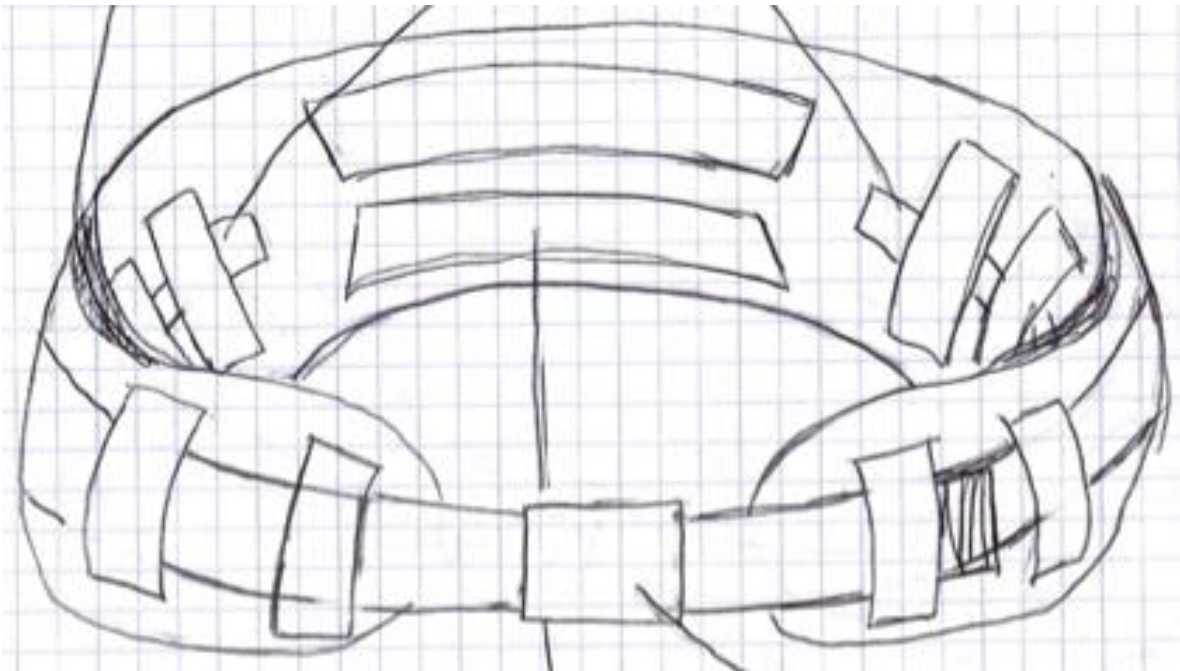


Figure 15: Webbing Attached Padding

Lastly, split padding was designed that created a space for the hip bone to settle while still conforming to the top and side of the hips (Figure 16). This would allow for better ventilation as well as the ability for the padding to hinge around the hipbone.

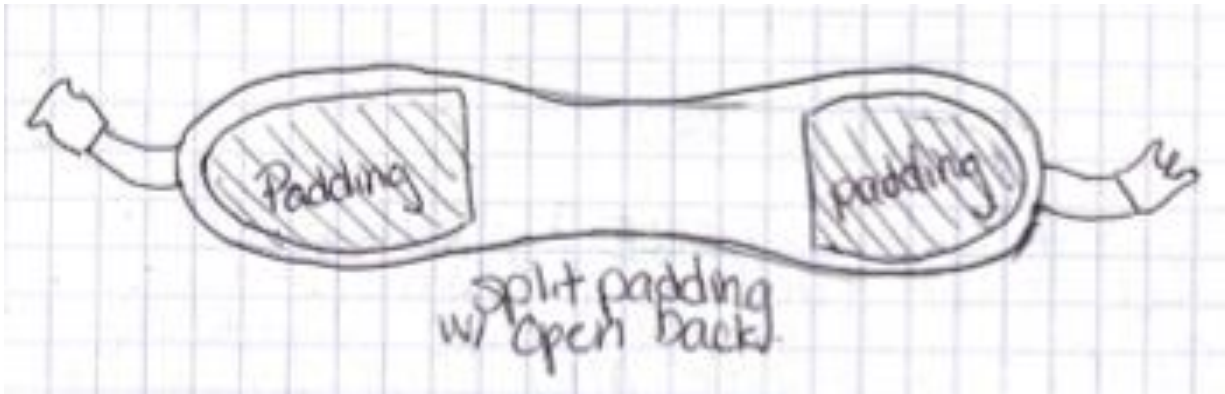


Figure 16: Split Padding

In each of the padding designs, the team considered adding a pad to the back of the belt. This padding would be attached by Velcro to allow for removal. Due to the ability to detach the back padding, there could be multiple options for inclined shape of the back padding.

4.3.4 Additional Design Aspects

An additional design alternative aspect that the team formulated was having a set of additional straps coming from the side of the belt to attach to the frame (Figure 17). This would allow for a better connection and support between the hip belt and the load. The current attachment in the back of the belt would still be used as a standard method of attachment.

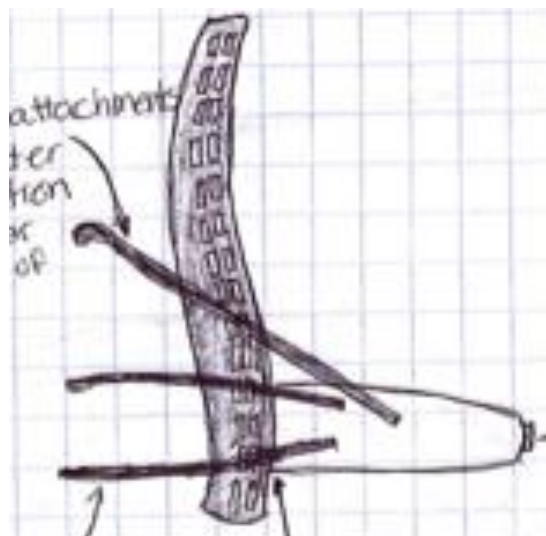


Figure 17: Additional Straps for Frame

4.4 Final Selection Matrix

In order to evaluate each of the design alternatives, the project group ranked the design alternatives based on how they met the objectives, functions, specifications and constraints as seen in Tables 4-7.

Table 4: Fastener Design

	Hook and eye	Twist closure	Threaded hook	Seatbelt buckle	Side pinch buckle	Front pinch buckle
C:Compatible with MOLLE Frame	Y	Y	Y	Y	Y	Y
C: Support 100 lb. load	N	N	N	Y	Y	Y
C: Under \$20 Consumer Price	Y	Y	Y	N	Y	Y
O: Durable	-	-	-	-	Y	Y
O: Comfortable	-	-	-	-	Y	Y
O: Flexible	-	-	-	-	Y	Y
O: Adjustable	-	-	-	-	Y	Y
O: Standardized	-	-	-	-	Y	Y
O: Lightweight	-	-	-	-	Y	Y
O: Effective in Loading	-	-	-	-	Y	Y

Table 5: Tightening Design

	One Strap Tightening	Offset Attached Strap Tightening
C: Compatible with MOLLE Frame	Y	Y
C: Support 100 lb. load	Y	Y
C: Under \$20 Consumer Price	Y	Y
O: Durable	N	Y
O: Comfortable	Y	Y
O: Flexible	N	Y
O: Adjustable	Y	Y
O: Standardized	Y	Y
O: Lightweight	Y	Y
O: Effective in Loading	Y	Y

Table 6: Padding Design

	Horizontal Padding	Elastic Edging	Adjustable Padding	Removable Padding	Split padding	Back Padding
C:Compatible with MOLLE Frame	Y	Y	Y	Y	Y	Y
C: Support 100 lb. load	Y	Y	Y	Y	Y	Y
C: Under \$20 Consumer Price	Y	Y	Y	Y	Y	Y
O: Durable	Y	N	Y	Y	Y	Y
O: Comfortable	Y	N	Y	Y	Y	Y
O: Flexible	N	Y	Y	Y	Y	Y
O: Adjustable	N	N	Y	Y	Y	Y
O: Standardized	Y	N	Y	N	Y	Y
O: Lightweight	Y	Y	Y	Y	Y	Y
O: Effective in Loading	X	X	X	X	X	X

Table 7: Additional Design Aspects

	Additional Support Straps
C: Compatible with MOLLE Frame	Y
C: Support 100 lb. load	Y
C: Under \$20 Consumer Price	Y
O: Durable	Y
O: Comfortable	Y
O: Flexible	Y
O: Adjustable	Y
O: Standardized	Y
O: Lightweight	Y
O: Effective in Loading	Y

4.5 Conceptual Design

The team brainstormed several ideas for a hip belt design that would fulfill the objectives and still remain within the constraints. Prior to determining what materials were to be used for the final design, the team first had to develop the design concept and build a prototype. Before constructing a prototype the team first met with Richard Landry. The team was able to speak with Mr. Landry and several of his colleagues during a visit to Natick Soldier Systems Center. From this visit, the team was able to learn many of the military specifications that they were unable to find in their literature research. Natick Soldier Systems Center was very supportive of the team's project, and provided the team with several materials to start on a basic prototype.

4.5.1 Initial prototype

Based on the alternative designs, the team developed the initial prototype seen below in Figure 18.



Figure 18: Initial Prototype - a) Front View b) Back View c) Over Head View d) Inside View

When developing this prototype, the team wanted to address the issues with the current hip belt. The current model does a poor job of contouring the hip and the heat pressed compression molding process used sacrifices most of the hip belt's comfort with the vacuum tight seal on the closed cell foam. The team wanted to address this issue of comfort first, because regardless of how effective the hip belt is in load distribution, no Soldier will wear it if it is uncomfortable. The team wanted to create a design that would avoid hitting major pressure points on the hips that would cause discomfort. When looking at the pelvic girdle, these main areas of contact pressure, especially on females,

include the anterior superior iliac spines, the top of the iliac crests, and the posterior superior iliac spines (PSIS). These anatomical structures are highlighted in the lateral view of the pelvic girdle shown in Figure 19.

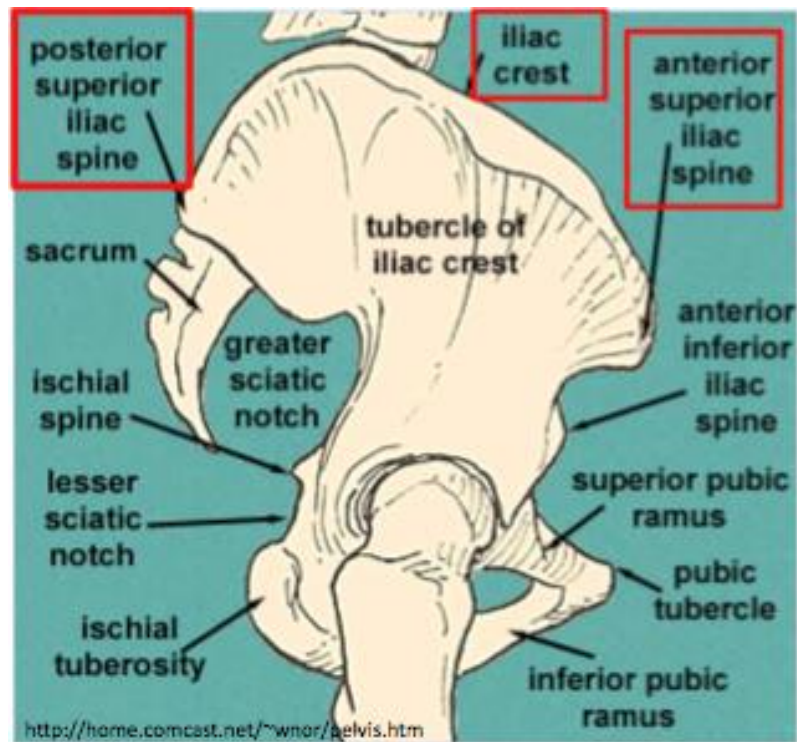


Figure 19: Anatomic Features of Pelvic Girdle that Cause Pressure Problems with Current MOLLE Hip Belt

With this in mind, the team decided to create the adjustable padding shown in blue in Figure 18. The team had the idea to create the hip belt with closed cell foam to wrap around the hips and then an adjustable pad made of memory foam that would attach to the hip belt via Velcro. This would allow Soldiers to angle the adjustable pads in a way that was most suitable for them and allow for the best possible comfort. This feature would make the hip belt customizable, without sacrificing standardization by having to create multiple hip belts with padding attached at different angles.

After building the initial prototype and trying it on, the team felt that it was still missing some features, and although the memory foam was very comfortable, the team members noticed that there was some discomfort on the anterior superior iliac spines, perhaps due to a shortage in length of closed cell foam that wrapped around the hips. The

hip belt felt a bit over packed as well. Since comfort is a main objective, and this hip belt failed to meet that objective, the team could not accept this as a final design.

The team had to reconsider the design and determine how to achieve optimal comfort. The team thought about cutting out the inside of the removal padding to allow the padding to contour and cushion the hips more (Figure 20). Although the team admired this aspect of the current prototype, they did not feel it would work because the layer of closed cell foam behind the adjustable padding would still apply pressure to the iliac crest. This would cause more discomfort. Thus, the team decided to develop a new prototype based on the feedback they gained from the initial prototype..



Figure 20: Padding With Open Cut

4.5.2 Final prototype

After developing some ideas that incorporated the “cut out” idea, the team decided to construct a prototype based on the sketch below.

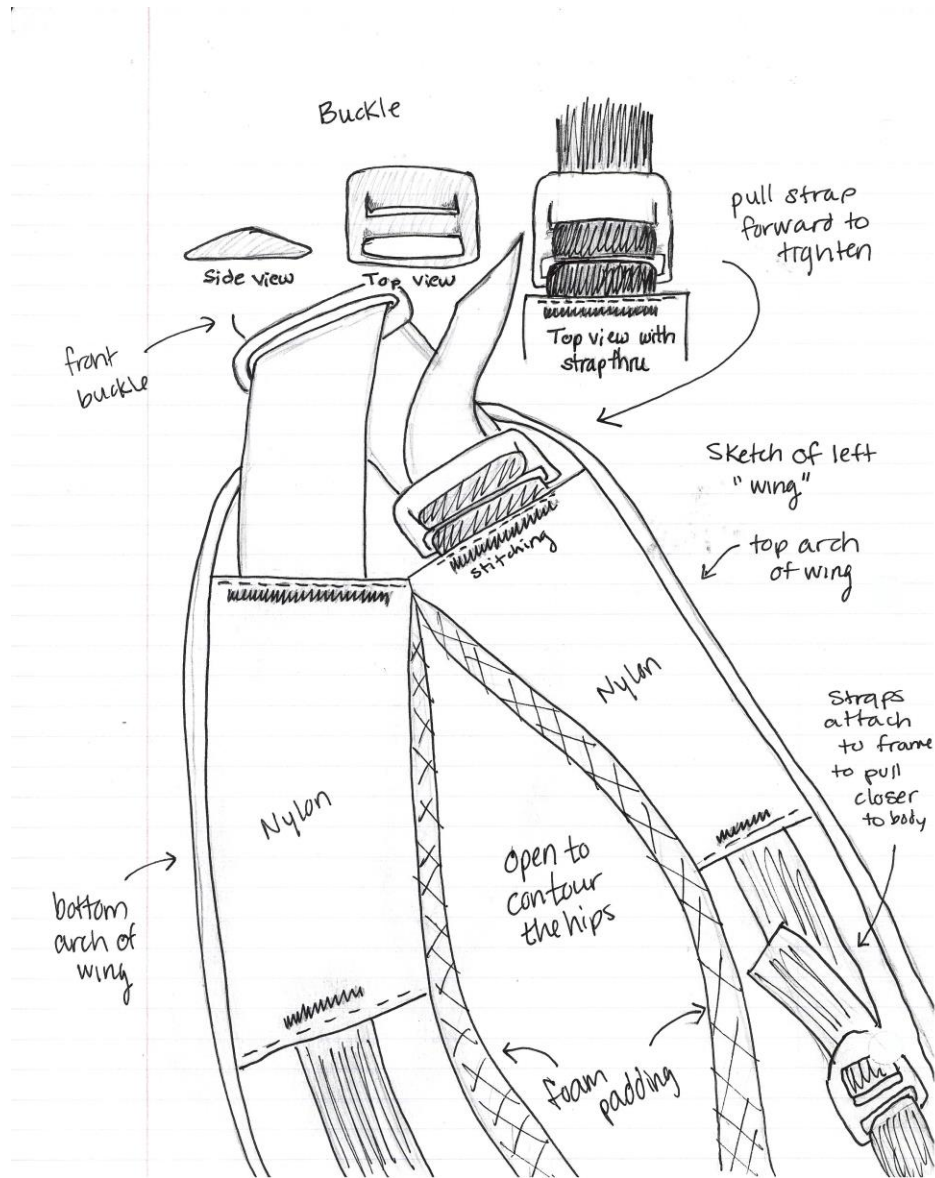


Figure 21: Prototype Sketch

This design requires that the hip belt be constructed in two “wings,” each composed of an extruded polyethylene, lined with nylon, and layered with closed cell foam, then sewn together to create an open center. This design not only contours the hips well, but also allows for added ventilation due to the “open” concept. This increased

ventilation would be a great selling point for Soldiers in the field who already who already wear layers of uniform and equipment that decreases ventilation. Additionally, this design has a dual tension system and a “pull-forward” method of tightening the straps. The team found that the “pull-forward” method of tightening allows individuals to use their bicep muscles to tighten the straps, which is much easier to adjust than the current “pull-sideways” method.

Finally, the team was able to build the final prototype. The result can be seen in Figure 22 below.

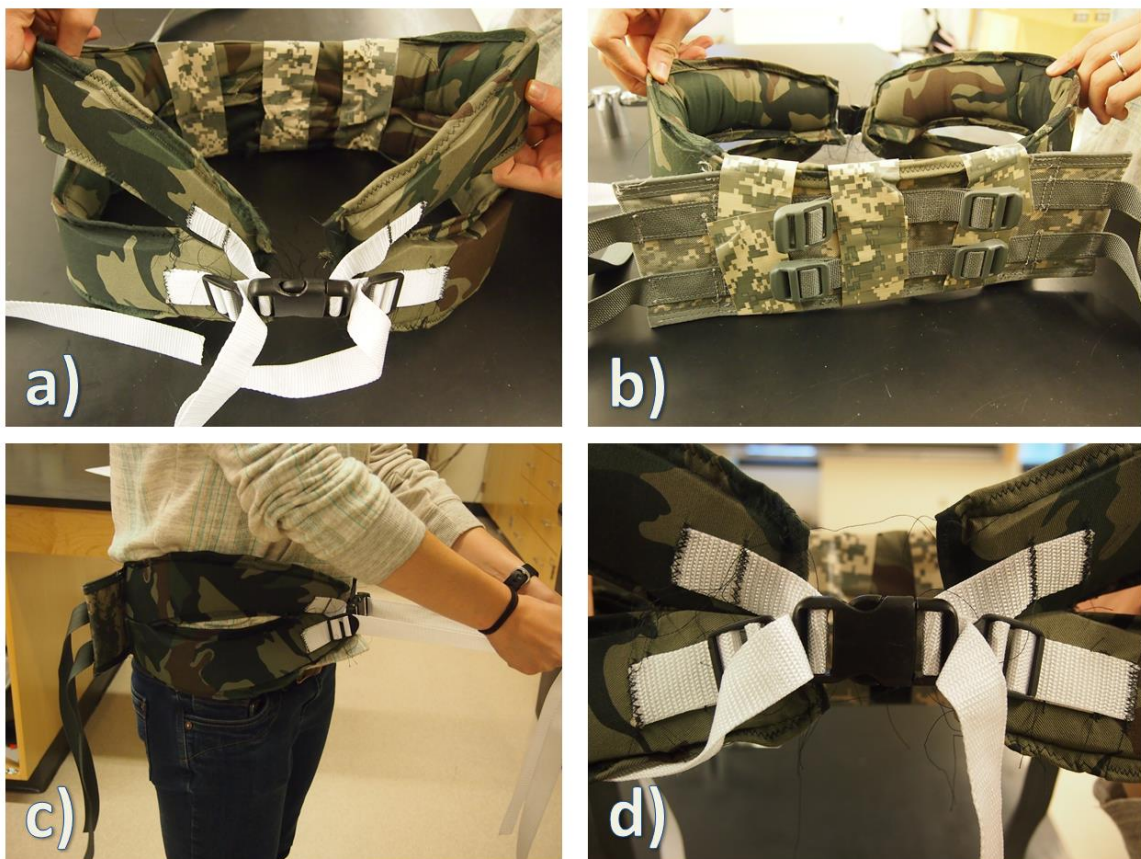


Figure 22: Final Prototype a) Front View b) Back View c) Side View d) Buckle View

Although rough, this prototype showed the basic concept of the design. After trying it on, the team agreed that this design provided the best comfort. The only modification that the team wished to make to this design was to add a removable padding along the back that could provide more cushioning against the PSIS. This padding would

be attached via Velcro. The padding will be enclosed by stitching rather than the current method of compression molding.

One drawback to this design is that it does not allow the nylon webbing to be placed on the outside of the hip belt, which would support the MOLLE attachment system. Although the current model does have this feature, Soldiers hardly use it. Thus, the team decided that this was a worthwhile sacrifice in order to achieve more comfort, ventilation, and lighter weight with less material.

4.5.3 Final Design

The team built a final prototype at Natick Soldier Systems Center on December 23, 2013. After trying to sew the open wings of the design, the team quickly realized that it would not be easy to manufacture this aspect of the design. Due to this manufacturing issue, the design was modified so that it consisted of two components. As seen in Figure 23, the first component is a “shell” composed of a layer of polyethylene plastic sandwiched between Cordura nylon fabric to provide shape, structure, and durability. Secondly, foam pads enclosed in spandex sleeves are attached to the shell making up the layer closest to the wearer’s body to provide comfort, support, and flexibility. The foam pads consist of three layers (starting closest to the body): nylon hex mesh, open cell foam, closed cell foam. The foam pads are attached to the shell via Velcro to allow the wearer to adjust the pads for comfort. This design attaches to the MOLLE system using the same mechanism as the current model. Additionally, there are two straps that attach the hip belt to the frame of the ruck via snap clips. The straps can be connected to various heights on the frame of the rucksack as well as adjusted to a different position with six snap clips available on the shell. This added feature allows the wearer to pull the MOLLE system closer to the body. The hip belt is secured around the wearer’s hips via a standard two-inch side-pinch release buckle and can be adjusted using the “pull-forward” method.

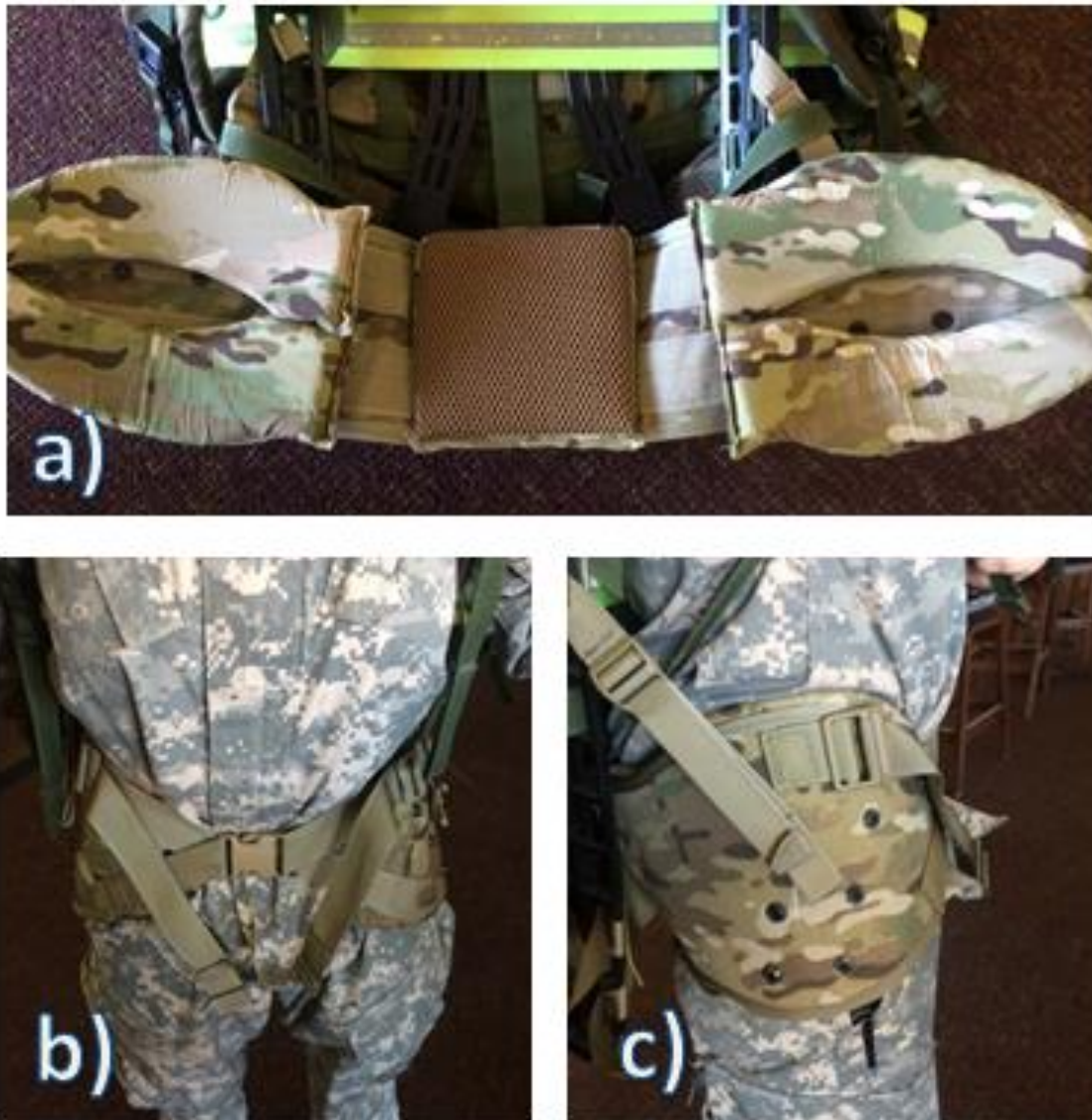


Figure 23: Final Design a) Inside View b) Front View c) Side View

After a few participants had completed part of the testing process, the team noticed several aspects of the design that could be improved. The team traveled to Natick Solider Systems Center on February 12, 2014 to modify the final design. The pull-forward method was effective, but the nylon straps at the top and bottom of the shell of the belt could not be evenly pulled. For example, when there was more tension on the top strap, the bottom strap buckled and became loose. To resolve this problem, the team decided that the top and bottom straps of the buckle should be joined together on the shell of the belt before being inserted through the front buckle. The modified final design can be seen in Figure 24. This would reduce the uneven tension of the straps and make it

more comfortable for the user. All other aspects of the design remained the same, and the team used this modified final design for the rest of the participants in the testing process.



Figure 24: Final Design with Modifications A) Front View B) Side View

4.6 Feasibility

The team had to conduct a feasibility study in order to determine the likelihood of project success. Factors such as materials, finances, time, resources available, and manpower were considered when examining achievability of a design. Both internal and external factors were taken into account. The team not only considered constraints within the premises of the group, such as project budget and timeline, but also external factors such as the demands of the client, competitors, and military regulations.

In terms of WPI requirements, the WPI budget of \$624 was more than enough to construct and test a final product. The team had instituted a project management system that allowed them to set deadlines and attainable goals. Natick Soldier Systems Center supplied the team with materials for the project that already meet military specifications. Additionally, Natick Soldier Systems Center allowed the team to utilize their facilities

and equipment to help finalize and manufacture the prototype. These added resources allowed the team to save both time and money on the project, as well as create a more complete and official prototype for testing.

There are many competitors in the commercial backpacking industry. However, due to military specifications, the military is not in this same market. The Army has been using the current hip belt since the implementation of the MOLLE II system nearly twenty years ago. Since then, it has yet to be redesigned. There have been issues regarding the hip belt, but the Army has felt that other issues were more important to address. Therefore, the team had no competitors, but Natick Soldier Systems Center agreed that a redesign of the hip belt was necessary and supported the team in their endeavors.

4.7 Preliminary Data

4.7.1 Compression Testing of Materials for Padding

The Instron Machine in Goddard Hall 207 was used by the team to analyze the materials that were chosen for the final design. The team used a compression test method to evaluate the amount of force that could be applied to a material or a combination of materials for the padding inside the hip belt. In order to provide a flat surface to test the material, a metal plate was positioned on top of a metal ring. The setup of this test can be seen in Figure 25 below.



Figure 25: Compression Testing Setup

In order to choose which material would be optimal for the padding of the modified design, the padding of the current MOLLE hip belt was the first material to be tested in compression. The Instron machine was run until “failure,” or until the metal head met the metal plate after being compressed through all of the material. The graph

below (Figure 26) shows the displacement as a function of force, allowing approximately 260 N of force before failure.

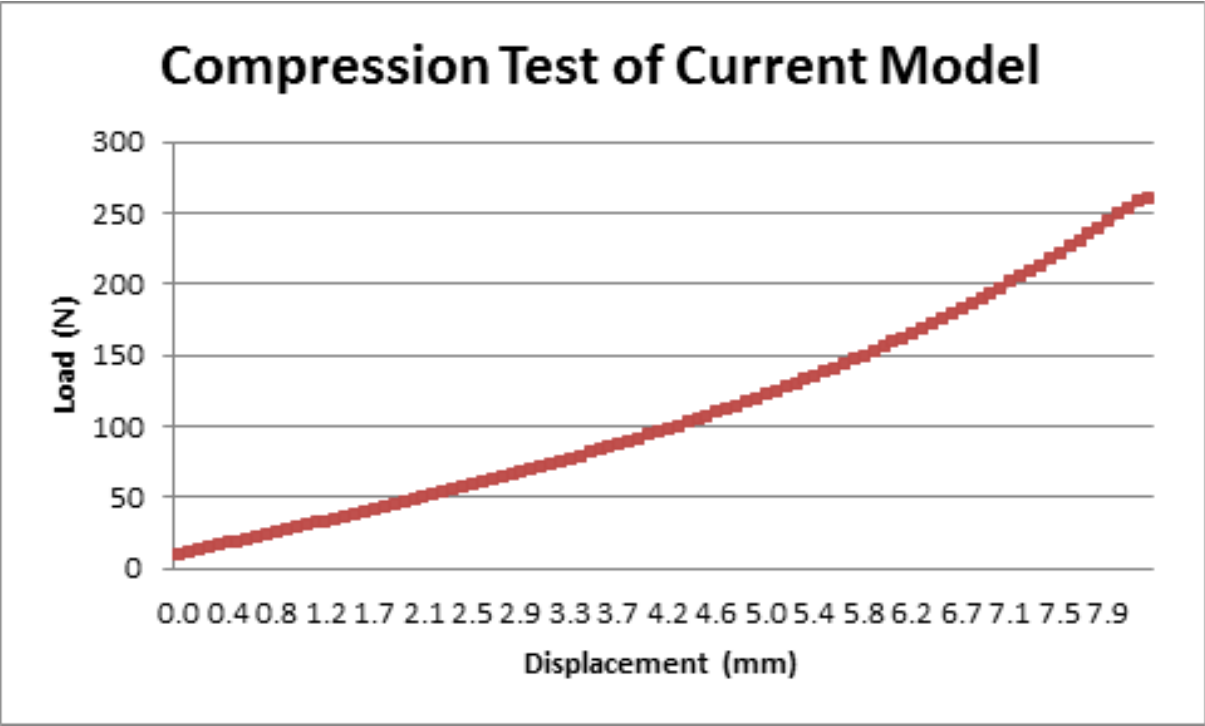


Figure 26: Compression Test of Current Model

4.7.2 Tension Testing of Buckles

After the compression tests of the materials were completed, a tension test was used to evaluate the strength of the buckles as they were pulled to failure (2 kN). The buckles were attached to the nylon straps that are currently used in the MOLLE hip belt (Figure 27).



Figure 27: Tension Testing Setup

As seen in Figure 28 below, the side snap buckle broke after being loaded with approximately 1.8 kN of force. The data for the tension testing of the two different buckle types was not recorded by the Instron machine, but the team was able to note the amount

of force that the sample could withstand before failure. The break occurred in the plastic bar that allowed for the attachment of the nylon straps.



Figure 28: Failure of Side Release Buckle

In contrast to the side snap buckle, the center snap buckle did not break in the same place. Rather, upon approximately 1.2 kN of force, the center snap released (Figure 29). The buckle could still be used, although the connection mechanism was not as effective. Although the center snap release buckle could still be used after the Instron

testing, it could not withstand as much force in tension as the side snap buckle; the team took this into consideration as they developed their prototype.



Figure 29: Failure of Center Release Buckle

4.7.3 Body Measurements

In order to form a design for the hip belt, the body measurements of women of various builds were considered. Using data from thirteen participants, the mean hip circumference was found to be 82.9 cm. The team analyzed the data to calculate the mean \pm two standard deviations, which would account for approximately 95% of the data. The range of values for hip circumference that would cover 95% of the data was found to be 70.7-95.1 cm. The team then compared these values to data published from Army reports in 1977 and 1988. There was no data for hip circumference in the data from 1988, but the values in the 1977 data that ranged from the 1st to the 99th percentiles were 81.7-112.2 cm. There is quite a discrepancy in the two data sets because the Army report measured hip circumference around the buttocks, whereas the team measured the hip circumference around the iliac crests.

The team also calculated that the range of values for hip circumference that would cover 95% of the data was 65.7-84.9 cm, with the mean at 75.3 cm. This measurement was found in the 1977 data, where the 1st to 99th percentile ranged from 59.0-92.4 cm; the value differed slightly in the 1988 data, ranging from 60.7-91.0 cm.

The participants were also used to obtain measurements that could not be found in the 1977 or 1988 data published by the Army. The mean distance between the posterior superior iliac spines (PSIS) was 10.8 cm, with 95% of the data ranging from 7.3-14.3 cm. The distance from the PSIS to the iliac crest was also measured, and the mean of this data was 16.2 cm, with 95% of the data ranging from 12.5-19.9 cm. These measurements and calculations can be seen in Table 8 below.

Table 8: Body Measurements

	Hip Circumference (cm)	Waist Circumference (cm)	Distance between PSIS (cm)	Distance from PSIS to iliac crest (cm)
	88.0	73.5	13.7	16.0
	82.5	75.5	10.5	14.0
	89.5	84.5	13.5	17.0
	83.0	80.0	12.5	15.5
	82.0	75.5	9.5	16.5
	89.5	78.0	10.0	20.0
	92.0	75.0	10.0	15.0
	79.5	72.0	10.0	16.0
	80.0	72.0	11.0	13.0
	68.0	81.5	12.5	17.0
	82.5	74.0	8.0	18.0
	80.5	71.0	9.0	15.0
	81.0	66.5	10.5	18.0
Average	82.9	75.3	10.8	16.2
SD	6.1	4.8	1.7	1.8
2 SD	12.2	9.6	3.5	3.7
Avg - 2 SD	70.7	65.7	7.3	12.5
Avg + 2 SD	95.1	84.9	14.3	19.9

To account for these measurements the wing of the belt is 16.5 inches, or 41.2 cm. This makes the total length of the hip belt provided by the two wings 82.4 cm. With the adjustable straps that clip in the front, the belt can accommodate a hip circumference of females in the 5th to 99th percentile. In addition to the circumference of the hip belt, the

length of the opening of each wing was taken into consideration based on measurements of the PSIS to the iliac crest. The length of the hole is 7 inches, or 17.8 cm, which accommodates the majority of females that were measured.

Chapter 5 Raw Data

The new and old hip belts were tested in various ways in order to compare the two. Ten female volunteers gave written informed consent to participate in an institutionally approved user test. Participants tested the hip belts on an obstacle course while their heart rate was monitored. The participants were then asked to fill out a rate of perceived exertion questionnaire and a survey asking for their opinions of the two hip belts. The data was collected and then analyzed in order to compare the different belts and determine if the team's new design met their objectives.

5.1 Obstacle Course

In order to test the hip belt, the team developed an “obstacle course” for study participants to complete. This obstacle course was exactly one mile long around the Worcester Polytechnic Institute (WPI) campus. Participants would complete it once with the current hip belt model and then again two days later with the team's newly designed hip belt, both of which were attached to a MOLLE large rucksack. Participants carried 30% of their bodyweight, up to 50 pounds. Following each iteration, participants were asked to rate their perceived exertion at different points throughout the course, as well as answer several survey questions about the hip belts.

A map displaying the course route in red can be seen in Figure 29 below. The white star labeled “1” indicates the start and finish of the course. Participants started along Institute Road outside of Daniel's Hall on WPI campus. They walked down Institute Road and took a left onto West Street and continued through campus. When participants reached the opposite side of campus, they took a left onto Salisbury Street until they arrived at Park Avenue, where they again took a left. Participants walked along Park Ave until they reached the WPI parking garage. At this point they sprinted the length of the garage and then returned to a walk when they reached the end of the garage. Passing the WPI football field on their left, they continued along Park Ave and turned onto Institute Road to complete the course in the same location that they had started. The participant's heart rate was recorded at one minute intervals during the test.

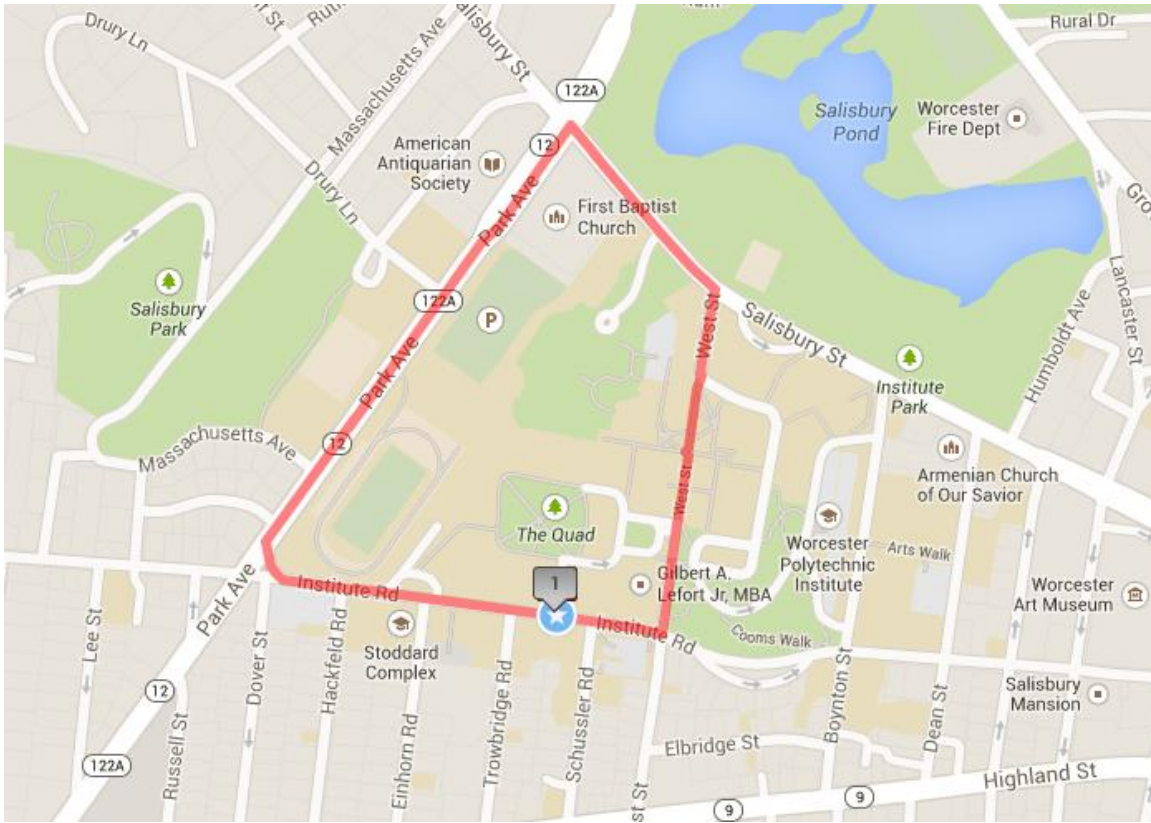


Figure 30: Obstacle Course Route Map

The following guidelines were given to participants from the approved IRB detailing the testing procedures:

Procedures to be followed: *If you are an ROTC cadet, please wear your uniform. If not, please wear sweatpants and sneakers. You will wear a rucksack that is loaded with 30% of your body weight, or 50 pounds, whichever is less, and will complete a series of tasks around campus. The whole course is approximately one mile long. During the testing you can adjust the belt to whatever you feel is most comfortable for you. Your heart rate will also be measured using a heart rate monitor at one minute intervals over the completion of the course. A study team member will accompany you.*

1. *Begin the course around campus at the ROTC office near Daniels Hall. You will begin the course walking down Institute Road. When*

you reach the corner of Institute Road and West Street, you will be asked to don and doff the rucksack three times.

- 2. You will then take a left up West Street towards the fountain on campus. When you reach Atwater Kent, you will be asked to get in the prone position.*
- 3. After you reach Goddard Hall, you will take a left on Salisbury Street towards Park Ave. At this point in the course, you will sprint the length of the parking garage.*
- 4. You will turn onto Institute Road at the corner of the track and finish the course in the same place you started.*
- 5. At the completion of the course, we will ask you to complete a survey that measures your rate of perceived exertion.*
- 6. You will receive an email from the team one day after the testing that will ask you about any injuries or discomfort that may have occurred as a result of the testing.*

For the full IRB including testing procedures and survey questions please refer to Appendix A.

Due to inclement weather conditions (snow, ice, rain, etc.), participants were asked to complete the donning and doffing of the rucksack inside the Army ROTC weight room in Daniel's Hall at the end of the course. This was also where they were asked to lie in the prone position.

Ten female participants were asked to complete the obstacle course. Seven of the ten participants were in ROTC programs on campus, four of which belong to the Army ROTC program and have had experience carrying a rucksack with the current model hip belt. The remaining three participants were student athletes. Table 9 below is an overview of the age, height, and weight of each participant.

Table 9: Overview of Study Participants

Participant #	Age (years)	Height (inches)	Weight (pounds)
1	18	63	145
2	22	66	175
3	21	66	130
4	20	68	147
5	21	64	122
6	21	67	125
7	20	64	175
8	21	66	130
9	21	66	130
10	19	65.5	140

Testing was done over a three week period, and each iteration was scheduled for a one hour block in order to allow time for explanation of the course and rucksack adjustments. The course took the average participant approximately 16 minutes to complete.

5.1.1 Rate of Perceived Exertion

After the course was completed, participants were asked to use a chart, as seen in Figure 31 below, to measure their rate of perceived exertion (RPE). The Borg Rating of Perceived Exertion is commonly used as a means to measure the intensity level of physical activity. Although it is a subjective measure, it can still provide the investigator with a fairly decent estimate of the actual heart rate of the participant during the study. This is because there is a high correlation between a perceived exertion rating multiplied by 10 and the actual heart rate during the physical activity. For example, the lowest rating on the chart is a 6, which is usually the average resting heart rate of a human at 60 beats per minute (bpm). A rating of 20 at maximal exertion would mean that the heart is working very hard, at approximately 200 bpm ("Perceived Exertion (Borg Rating of Perceived Exertion Scale)").

Rating of Perceived Exertion (RPE)	
6	No exertion at all
7	
8	Extremely light
9	
10	Very light
11	
12	Light
13	
14	Somewhat hard
15	
16	Hard (heavy)
17	
18	Vey hard
19	
20	Extremely hard
	Maximal exertion

Figure 31: Chart Used by Participants to Measure RPE

The ten participants were presented with four questions to evaluate their RPE throughout various parts of the course, and these results can be seen in Table 10 below. The data were analyzed using calculations to find mean and standard deviation of the old and new hip belt for each question. Furthermore, a paired t-test was performed in order to evaluate if the differences between the two belt conditions were statistically significant or by random occurrence. The results are considered to be statistically significant if the p value is less than 0.05.

Table 10: Results of RPE Survey Questions

Participant	Exertion up West St Hill		Exertion getting in prone		Exertion sprinting park ave		Exertion up Institute Rd.	
	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt
1	12	15	8	14	20	19	16	15
2	13	13	8	12	16	17	13	15
3	12	11	11	12	15	14	14	13
4	13	15	8	10	16	17	15	13
5	12	13	7	10	15	14	13	15
6	13	14	12	12	12	16	15	15
7	7	15	6	13	7	15	11	19
8	12	11	9	7	13	13	13	13
9	14	14	7	11	18	19	13	14
10	13	11.5	6.5	6.5	18.5	17.5	14.5	16.5
T- Test	0.225		0.021		0.259		0.247	
Average	12.1	13.25	8.25	10.75	15.05	16.15	13.75	14.85
STD	1.912	1.620	1.933	2.441	3.730	2.109	1.439	1.857

For the first question, participants were asked to rate their exertion walking up the West Street Hill at the beginning of the course. The average for the new belt (12.1 ± 1.91) was found to be lower than the average for the old belt (13.25 ± 1.62). Furthermore, the t-test provided a p value of 0.22, indicating that the differences between the two groups were not statistically significant and due to random occurrence.

The second question asked participants to rate their exertion getting into the prone position at the completion of the course. The average for the new belt (8.25 ± 1.93) was found to be lower than the average for the old belt (10.75 ± 2.44) indicating less exertion with the new belt. In contrast to the first question, the t-test indicated that these differences were statistically significant because the p value was 0.02. Overall, participants assigned this task the lowest RPE, according to the averages of all the questions.

The sprint along the parking garage on Park Avenue was the third question on the RPE survey. Once again, the average for the new belt (15.05 ± 3.73) was found to be lower than the average for the old belt (16.15 ± 2.11). The t-test results did not indicate that the results were statistically significant with a p value of 0.26. Using the average, the team saw that this task received the highest RPE, meaning that most participants felt that this task required the highest level of physical intensity.

Finally, the fourth question asked participants to rate their exertion walking up the Institute Road hill at the end of the course. As seen in the previous three questions, the average for the new belt (13.75 ± 1.44) was found to be lower than the average for the old

belt (14.85 ± 1.86). In addition, the t-test results did not indicate that the results were statistically significant with a p value of 0.25.

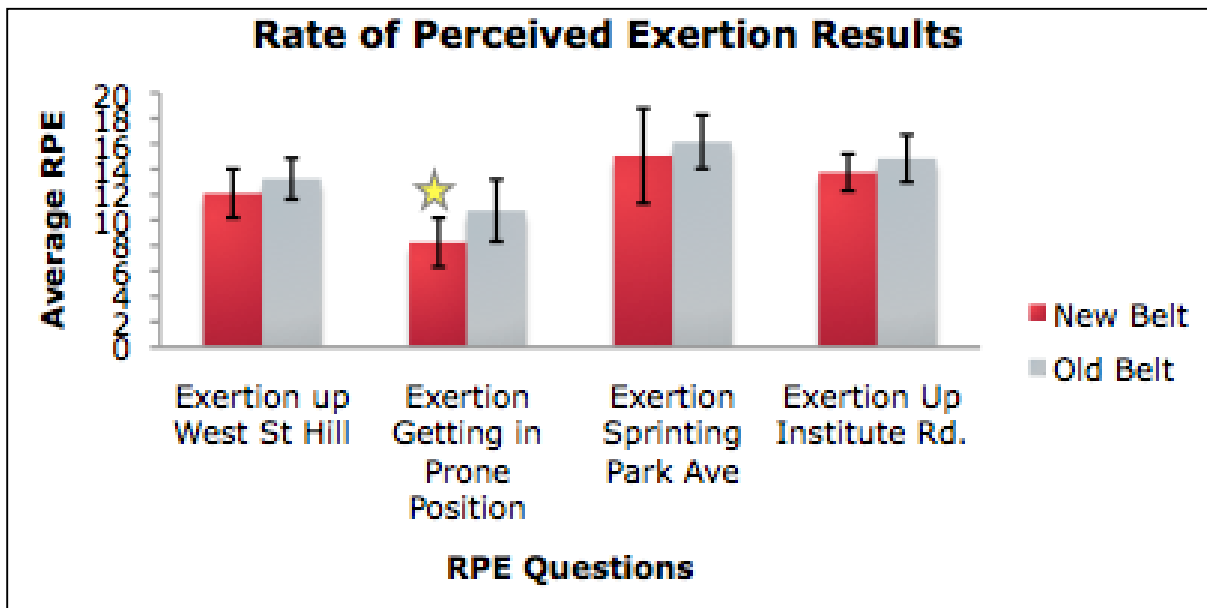


Figure 32: Rate of Perceived Exertion Results

5.1.2 User Survey

After completing two iterations of the obstacle course, once with the old hip belt and once with the new, participants were asked to complete a series of survey questions that were formulated by the team in order to assess the success of the design in achieving the objectives. The participants answered the questions using a scale from 1 to 10, with 1 being the worst and 10 being the best.

The first survey question addressed the willingness of the participant to wear the hip belt for extended periods of time. This question was important because the rucksacks are worn for many hours in the field. For this question, the new belt rated higher with an average score of 8.1 ± 1.45 than the old belt with an average score of 6.7 ± 2.21 . However, when this survey question was evaluated for significance using a t-test, the difference between the two belts was found to be insignificant ($p=0.138$). This means that even though females generally said they would be willing to wear the new hip belt rather than the old hip belt, there is no correlation between the given answers.

The following survey questioned the hip belt's effectiveness in distributing the

weight from the participant's shoulders to her hips. Weight distribution was the most important objective of the project design, so this question was asked to evaluate the ability of the design to achieve that objective. The average score for the new belt was 7.7 ± 1.42 , and the average score for the old belt was 5.8 ± 2.53 . This difference in score was also found to be insignificant when evaluated with a t-test ($p=0.118$).

After donning and doffing the pack three times, the participants were asked to evaluate the ease of donning and doffing the rucksack with the hip belt. For this question, the new belt scored better than the old belt, with an average score of 7.6 ± 1.08 for the new belt and 6.1 ± 1.60 for the old belt. This difference was found to be statistically significant when a t-test was performed ($p=0.048$).

The next survey question focused on the participant's comfort while wearing the hip belt. The results showed a large difference between the old belt and the new belt. The new belt received an average score of 8.3 ± 1.06 , while the old belt received an average score of 5.7 ± 1.89 . This large difference was found to be statistically significant when a t-test was performed ($p=0.010$).

A Soldier must be able to move easily while still wearing the belt in the field. This includes walking up and down inclines, running and getting into the prone position as performed in our obstacle course. Participants were asked to evaluate the flexibility in movement allowed by the hip belt. On average, the participants rated the new belt as being more flexible with a score of 7.6 ± 1.35 and the old belt with a score of 6.3 ± 1.50 . This question was also found to be significant when a t-test was performed ($p=0.013$).

The last survey question asked participants to rate the adjustability of the hip belts. Adjustability was an important objective of the design because it must have the ability to fit many different body types. On average, the new belt was rated better with a score of 8.2 ± 1.93 compared to the old belt with a rate of 5.4 ± 1.96 . This was found to be statistically significant with a t-test ($p=0.021$).

All of these survey questions and the average scores, standard deviation and t-test significant results can be seen in Table 11 and are shown in a graph in Figure 32 below. The survey question is found to be significant if the t-test result produces a p value of less than 0.05.

Table 11: Summary of Survey Results

Participant	Willingness to Wear for Extended Time		Effectiveness of Distributing Weight from		Ease of Donning and Doffing		Comfort		Flexibility in Movement		Adjustability	
	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt	New Belt	Old Belt
1	8	8	7	8	6	8	8	7	8	8	9	7
2	8	3	9	2	8	8	9	5	9	7	10	3
3	7	8	9	9	8	7	7	8	9	8	6	7
4	10	10	7	7	9	3	8	6	5	4	4	6
5	10	7	5	7	7	6	10	7	8	6	8	5
6	7	6	8	7	6	4	8	3	7	5	8	2
7	10	4	10	2	9	6	10	3	9	5	10	5
8	8	7	7	7	8	6	8	6	8	7	9	7
9	6	9	7	6	8	7	7	8	7	8	8	8
10	7	5	8	3	7	6	8	4	6	5	10	4
T- Test	0.138		0.118		0.048		0.01		0.013		0.021	
Average	8.1	6.7	7.7	5.8	7.6	6.1	8.3	5.7	7.6	6.3	8.2	5.4
STD	1.45	2.21	1.42	2.53	1.08	1.60	1.06	1.89	1.35	1.49	1.93	1.96

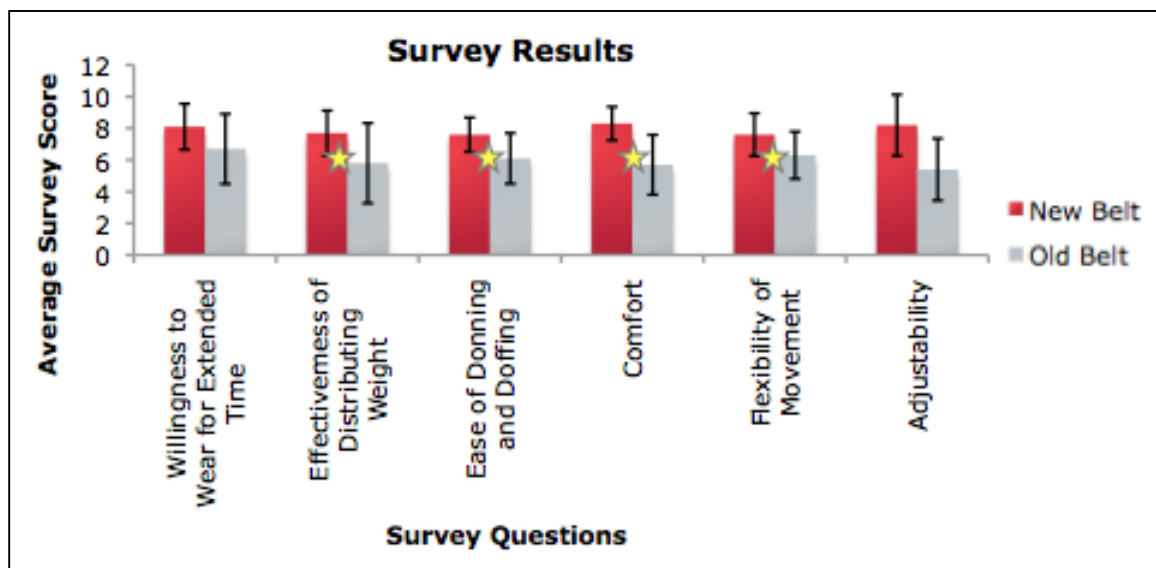


Figure 33: Results of Survey Questions

5.1.3 Heart Rate

The team used a heart rate monitor to measure the participants' heart rates every minute while undergoing the obstacle course. Heart rate was tested to determine if there were any significant changes in the users' heart rate while wearing the different hip belts. Below are two of the heart rate graphs for each participant of the study. The remaining heart rate graphs of all participants can be found in Appendix C. The blue line represents the heart rate from the old belt, and the green line represents the heart rate from the new belt. The red line at the bottom represents the elevation of the course. The sprint began at about 0.5 miles into the course.

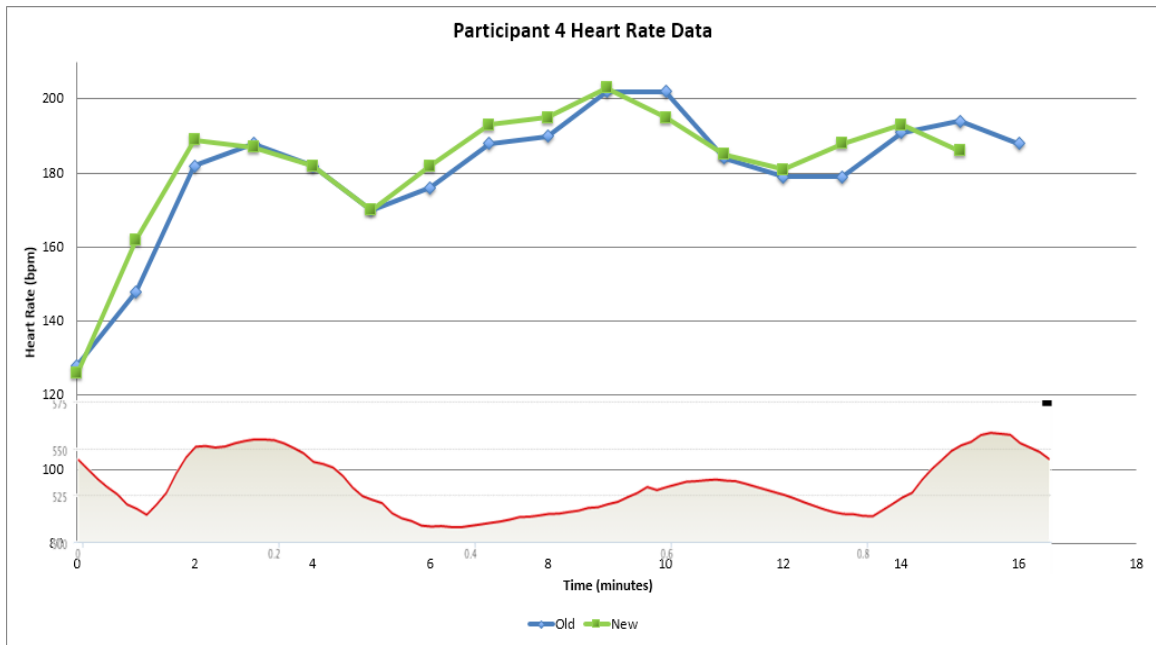


Figure 34: Participant 4 Heart Rate Data

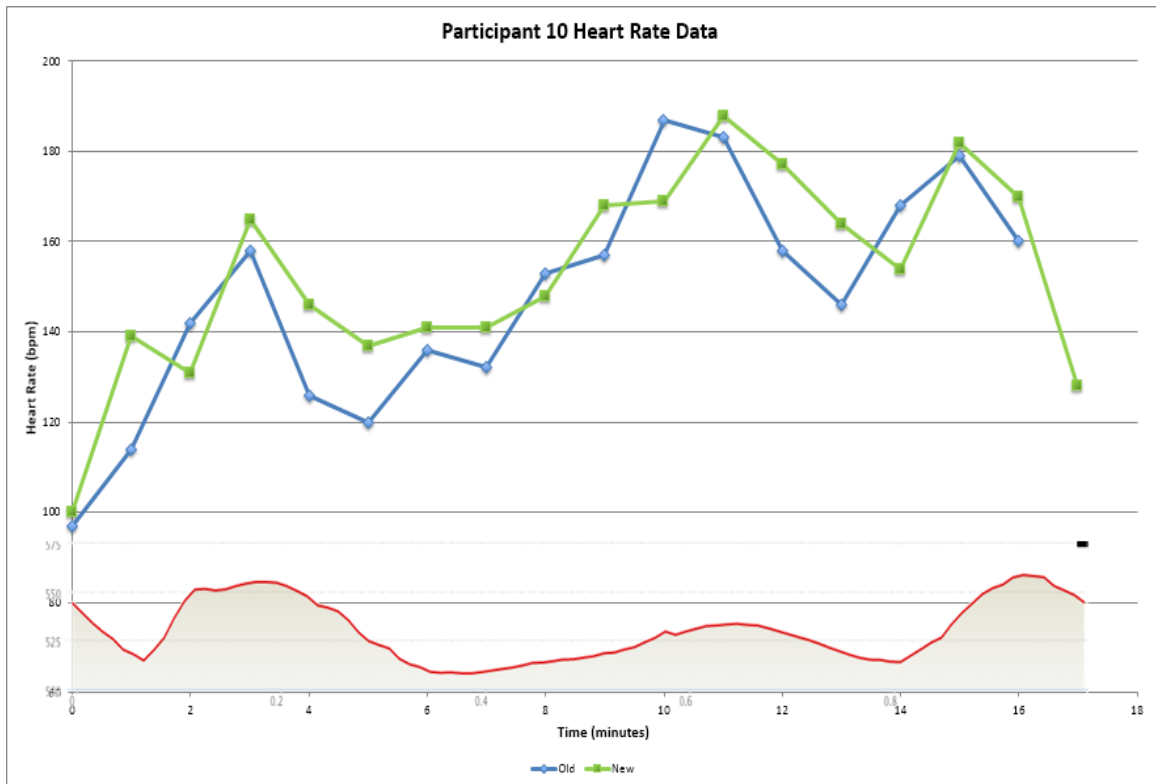


Figure 35: Participant 10 Heart Rate Data

5.2 Force Plate

Four participants between the ages of 21 and 22 with weight ranging from 130 to 170 lb and height ranging from 5'6" to 5'10" completed force plate testing for 10 seconds under each of the various conditions. Each person stood on the force plate without the rucksack on, with the rucksack but no hip belt, with the rucksack and the old hip belt and with the rucksack and the new hip belt. From the center of pressure (COP) data collected the path length of the COP was calculated for all ten seconds as shown in the Table 12 and Figure 36.

Table 12: COP Path Length (cm) for 10 Seconds under Various Conditions

	Subject 1	Subject 2	Subject 3	Subject 4	Average
Alone	0.1259	0.1288	0.1063	0.1442	0.1263
No Belt	0.1250	0.1736	0.1120	0.2348	0.1614
Old Belt	0.1573	0.1316	0.1225	0.1229	0.1336
New Belt	0.1179	0.1406	0.2216	0.1246	0.1512

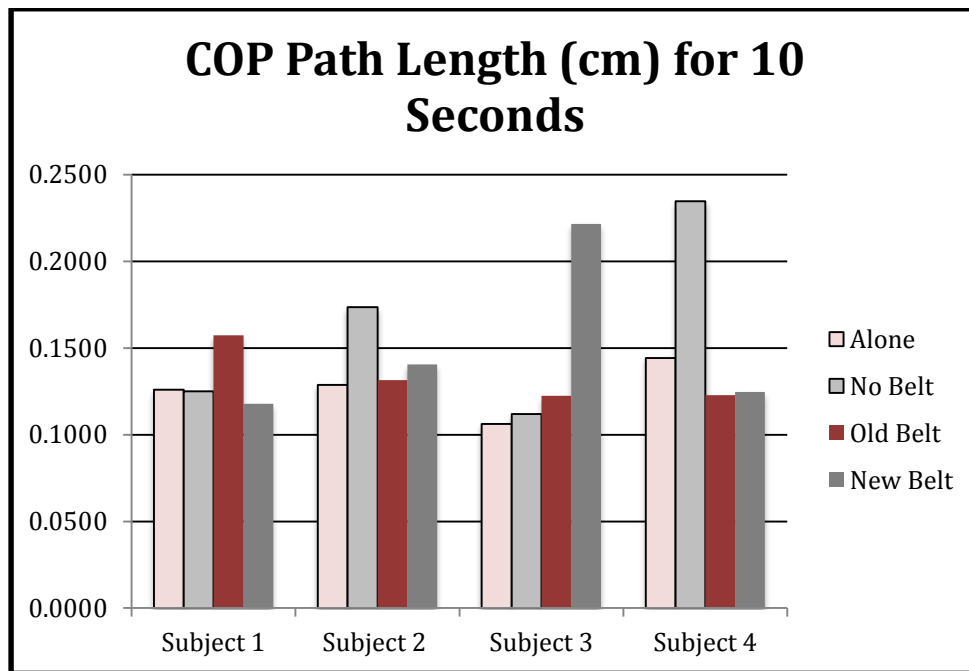


Figure 36: COP Path Length (cm) for 10 Seconds

After evaluating this data, it appeared as though there may be some error toward the end of the 10 seconds for some of the participants, which could be caused by stepping off the force plate too soon or becoming distracted and losing focus. In order to eliminate this error the path lengths were evaluated for the first five seconds of the testing as seen in Table 13 and Figure 37.

Table 13: COP Path Length (cm) for 5 Seconds Under Various Conditions

	Subject 1	Subject 2	Subject 3	Subject 4	Average
Alone	0.0707	0.0658	0.0620	0.0772	0.0689
No Belt	0.0665	0.0958	0.0543	0.1450	0.0904
Old belt	0.0835	0.0660	0.0688	0.0639	0.0705
New Belt	0.0637	0.0599	0.0599	0.0690	0.0631

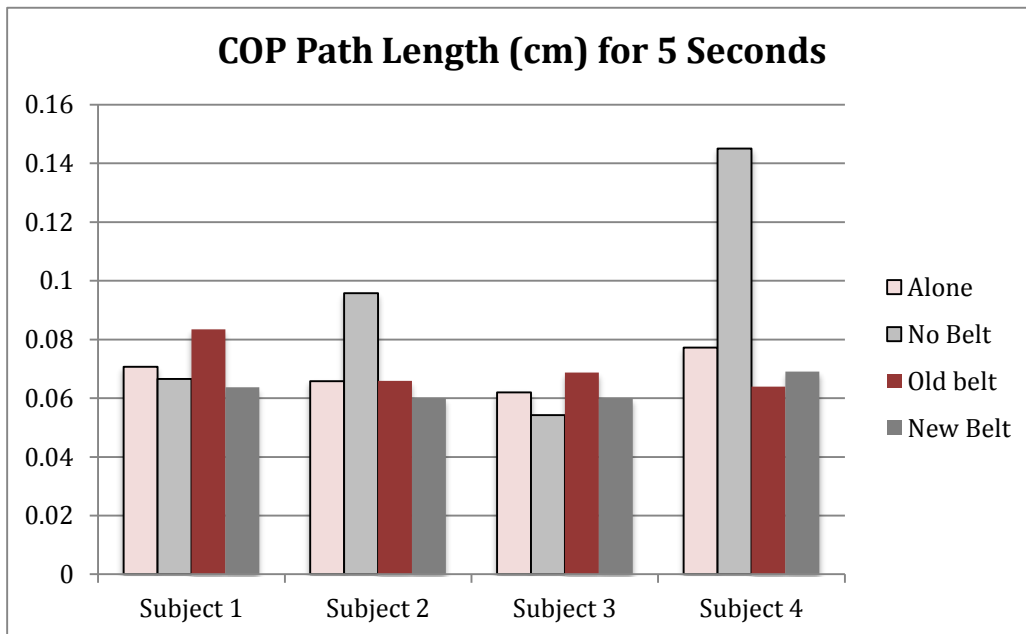


Figure 37: COP Path Length (cm) for 5 Seconds

The data was found to be inconclusive because there was no noticeable trend between conditions or subjects even after the error was reduced. The data was not evaluated for statistical significance by paired t-test because there were too many variables to evaluate, especially because there were no clear trends.

5.3 Pressure Film

To determine where the force of the rucksack was located, the team used Fuji pressure film located on key points on the body. The pressure film is composed of two sheets that, when placed on each other appropriately, show the pressure applied to that specific location due to small capsules of red dye breaking. There is a shiny side and a powdered side for each sheet. The pressure film works only when the powdered sides are in contact with each other.

The locations that the pressure film strips were placed were the shoulders, the posterior superior iliac spine on the back, and the iliac crests. The shoulders were selected to see if the weight was transferred to the hips for each hip belt. The posterior superior iliac spine was selected to determine the pressure on the back of the hips. The iliac crests were chosen because the team noticed there was a significant amount of pressure on these bones while wearing the current model.

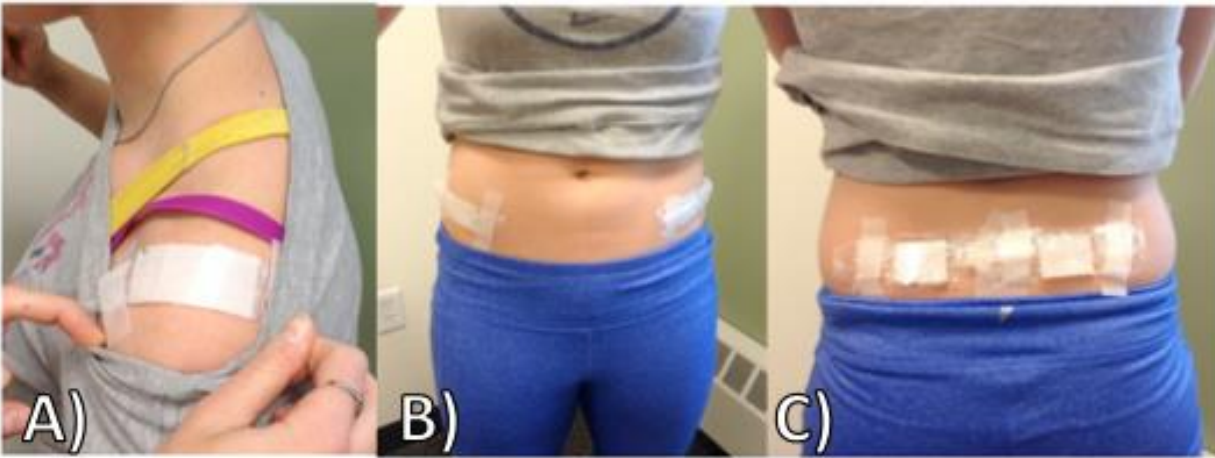


Figure 38: Placement of Pressure Film A) shoulders B) Superior Anterior Iliac Spine C) Superior Posterior Iliac Spine

One member of the team volunteered to wear the rucksack first. Another member drew four dots around each location that was to be tested to determine the size of each pressure film strip. The size of each strip is located in the table below.

Table 14: Pressure Film Size

Location	Length (in)	Width (in)
Iliac Crest	2.25	1
Posterior Iliac Spine	1.5	1
Shoulder	2.5	1

Four strips for each location were required for each team member (both left and right side for the new model and current belt). Each length was cut out and placed on each other appropriately. Each strip was delicately wrapped in plastic wrap to ensure that the two pieces would not move around or get wet.



Figure 39: Pressure Film Preparations

Once wrapped, one side of the pressure film was marked. The inside top corners were marked for the locations on the back and hips, while the inside anterior corner was marked on the shoulder strips. They were then taped to the team member's body in the confines of the previously marked dots. This was performed carefully to ensure that there were no unintentional pressure marks on the film.

Once the team member was fitted with the film taped to the specific locations, another team member placed the rucksack on the table and loosened the straps. When the

team member was ready, she would place the straps around her shoulders and hips, pick up the rucksack, tighten the straps and walk around wearing the rucksack for one minute. Once the minute was up, the rucksack was placed back on the table, and the straps were removed immediately. The pressure film was removed from the team member immediately. The two pieces were removed from each other to prevent any accidental staining and the dyed strips were taped onto a piece of paper labeled with the location of the film. Upon completion of the testing process, each paper was scanned into a computer (Appendix D) and the pressure films were set to 8-bit grayscale. Using ImageJ's histogram function, the pressure film was analyzed.

Using ImageJ software, the locations with the darkest gray were selected, signifying the most pressure. They were analyzed using the histogram function. The scale used was a 0 to 255 gray scale, with 0 being the darkest (black) and 255 being the lightest (white). The mean, standard deviation, minimum and maximum values were reported. The standard deviation represents the largest variation of pressure on the film, while a smaller standard deviation represents a more consistent pressure.

Below is a figure of one of the team member's pressure film placed over her iliac crest. The top two films represent the film while the current model belt was worn. The bottom two are the result of the modified hip belt being worn.

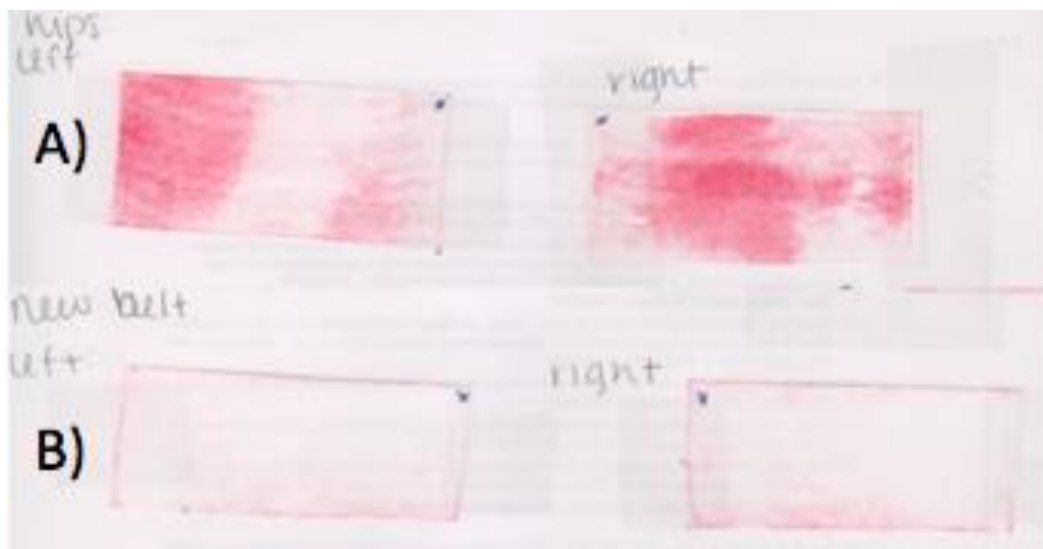


Figure 40: Pressure Film From Iliac Crest A) Old Belt B) New Belt

The histogram data was collected and the table below describes the results.

Table 15: Histogram Summary for Anterior Superior Iliac Spine

Old Belt	Left Hip	Right Hip
Mean	187.225	179.971
St Dev	18.3	20.169
Min	134	134
Max	235	232
New Belt	Left Hip	Right Hip
Mean	238.216	235.635
St Dev	2.521	2.656
Min	209	209
Max	243	241

Since 0 represents the darkest color, the smaller numbers indicate a higher pressure, and the larger numbers indicate a lower pressure. As seen by the “mean” on the table, the old belt resulted in more pressure for the user. The standard deviation is large as well, which signifies that there was more pressure on specific points than across the entire strip of film. The new belt mean increased by about 50 points, signaling that there is less pressure on the hips while wearing the new belt. The standard deviation is also much smaller, resulting in less concentrated pressure on the hips.

The following figure is one of the team member's data from her posterior superior iliac spine.

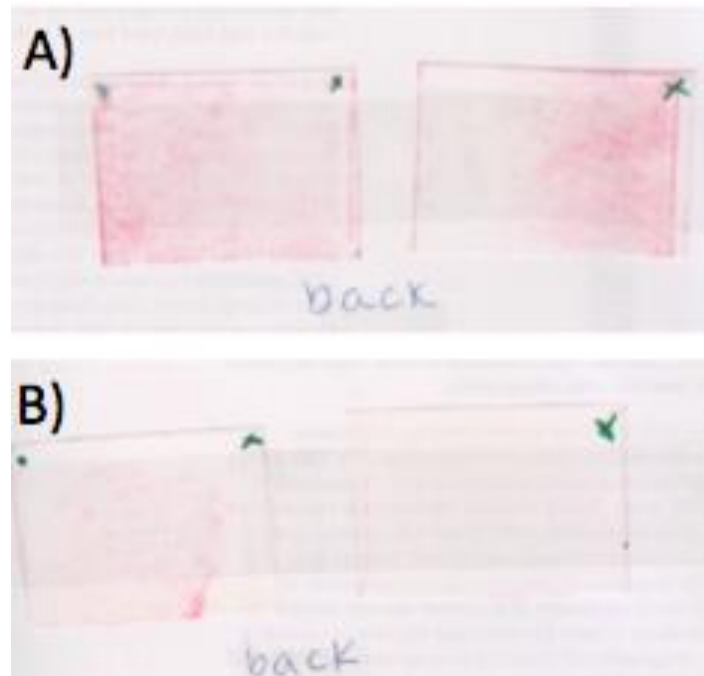


Figure 41: Pressure Film from Posterior Superior Iliac Spine A) Old Belt B) New Belt

Below is the histogram data for these results.

Table 16: Histogram Summary for Posterior Superior Iliac Spine

Old Belt	Left Back	Right Back
Mean	224.111	223.043
St Dev	6.36	9.364
Min	164	164
Max	235	241
New Belt	Left Back	Right Back
Mean	231.079	232.727
St Dev	4.175	3.356
Min	165	207
Max	242	242

As seen by the figure and the data, there was more pressure on the team member's back while she was wearing the old belt as opposed to the new belt. The standard deviation also decreases when the belts are switched, as seen in the previous table as well. Therefore, the overall point pressure decreases with the modified hip belt. The following figures represent the left and right shoulders of two separate team members.

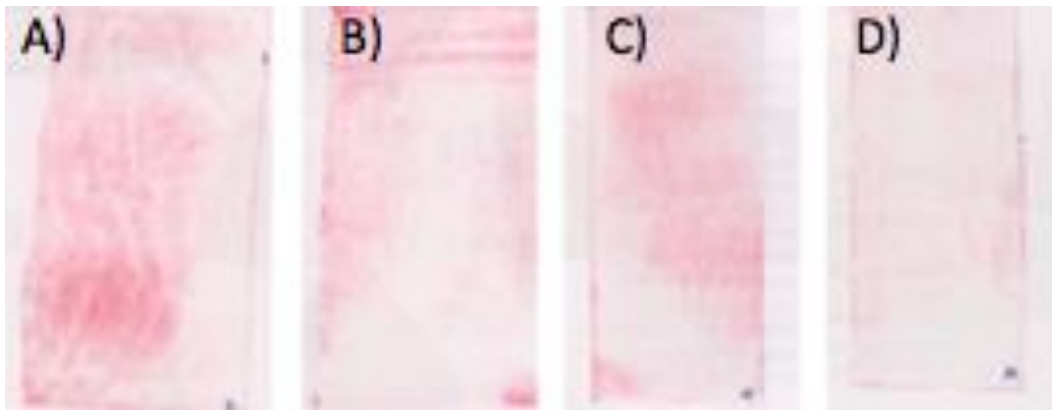


Figure 42: Pressure Film From Shoulders A, C) Old Belt B,D)New Belt

Table 17: Histogram Summary for Shoulders

Old Belt	Left Shoulder	Old Belt	Right Shoulder
Mean	217.207	Mean	221.999
St Dev	14.872	St Dev	8.797
Min	144	Min	167
Max	238	Max	235
New Belt	Left Shoulder	New Belt	Right Shoulder
Mean	228.61	Mean	224.479
St Dev	8.878	St Dev	12.212
Min	170	Min	158
Max	241	Max	244

Similarly with the previous data points, the averages increase when the new hip belt is worn, therefore reducing the amount of pressure on the shoulders.

Chapter 6: Discussion

6.1 Discussion of Results

From the results of the RPE survey, the team was able to conclude that participants preferred the modified design over the old belt. All of the averages for the new belt were lower than the old belt, meaning that participants felt that the new belt allowed them to perform better throughout the course without having to exert as much energy to complete each section. As previously mentioned, the only task that proved to hold statistical significance with a p value of 0.02 was the exertion required to get into the prone position. Based upon the responses of the participants as they were lying in this position on the ground, this could be due to the fact that the new belt had more padding, which proved to be more comfortable when the weight was placed on the back. Although there was a mutual feeling that the weight felt heavy on the back, none of the participants indicated that the belt was digging into their body while in this position. The other three RPE survey questions did not prove to be statistically significant. After listening to the comments of the participants after each task on the RPE survey as they were completing the course, this is most likely due to the fact that no matter how comfortable or effective the hip belt is, the participant always feels like she is exerting herself while walking up a hill or sprinting with a heavy rucksack.

From the data of the survey questions, the team was able to conclude that the new hip belt provides more comfort, maneuverability, flexibility of movement and adjustability when compared to the old belt. This means that the participants rated the new belt higher than the old belt when asked about ease of donning and doffing, comfort, flexibility of movement and adjustability. These survey questions were found to be statistically significant with a p value of less than 0.05. A participant who rated a higher degree of comfort expressed that there was a reduced degree of pressure on the hip bones as a result of more effective padding. Most participants rated ease of donning and doffing the belt higher because they noted that the buckle allowed them to quickly release and fasten the belt without additional help. In addition, almost all of the participants assigned a high score for flexibility in movement. During the testing, they expressed how they

found it easier to run, walk up and down inclines, and get into the prone position while wearing the new belt. Participants also mentioned that they felt the ruck was more stable on their back when wearing the new belt. Finally, a high rating for adjustability proved to be statistically significant, which indicates that the new belt was easy for participants to adjust and had the ability to accommodate many different body types. Participants said that it was easier to loosen the straps on the new belt compared to the old belt. In addition, participants had a positive response for the additional straps that connect the ruck to the belt. The questions addressing the willingness to wear the hip belt for an extended period of time and the distribution of weight were not found to be statistically significant; however, the results still indicated that the participants preferred the modified design over the old model. In particular, a few participants who mentioned they experienced back problems said that the new belt was more effective at distributing the weight from the shoulders than the old belt.

After looking at the heart rate data, it proved to be inconclusive. Some tests appear to have no change in the data, with nearly the same heart rate for both tests. For other tests, the change in heart rate is so dramatic that there is no belt that clearly results in more exertion. Participant #3 was required to wear two different heart rate monitors, resulting in a difference in the accuracy of the reading. There were also icy road conditions which inhibited the ability for the participants to run their quickest on the sprinting section of the course. After comparing the heart rate data to the rate of perceived exertion, there appeared to be no direct trend. In some cases, the RPE appeared to match up with the participant's heart rate. In general, the RPE was either higher or lower than the participant's heart rate.

Force plate testing proved to be inconclusive as well. It was expected that the person standing alone would have the lowest path length because the person is most stable and it would be easiest to balance without additional weight. The rucksack with no belt was expected to have the highest path length because there would be additional weight, which would not be stabilized by a hip belt and therefore would be farther away from the body and require more effort to maintain balance. It was expected that the modified hip belt would have a shorter path length than the current hip belt because the side straps and shape of the belt would create the most stability and proper distribution of

weight to the pack. Only one of the four participants had data that followed our expectations. The greatest difference between our expectations and the data collected occurred in the standing without the pack at all which had a greater path length than standing with the rucksack and the new belt.

After analyzing the data collected during the pressure film test, it is evident that the modified hip belt is not only effective in distributing the weight to the hips but also more effectively across the hips. This belt minimizes the pressure points on the iliac crest and posterior superior iliac spine. This is not only seen by the minimal amount of red dye on the film strips for the new belt, but also by the averages of the grayscale intensity. The increase in distributed weight is shown by the decrease of the standard deviation. Some results were not as significant as others; however, for each team member, there was an improvement in the modified belt compared to the current model in one way or another. These improvements include decreased overall pressure on the hips or shoulders, as well as consistent distribution of pressure among the three regions tested.

6.2 Testing Limitations

There were a few limitations that were encountered during the testing process. Many of these limitations involved using the rucksack. For example, the MOLLE large rucksack that was used for the tests was pre-packed and loaded in the way that the owner preferred. Furthermore, the straps and other components of the rucksack were attached to the frame the way that the owner constructed it for her own use. The women in this study did not adjust the location of any part of the rucksack on the frame to suit their body type, which may have resulted in a bit more discomfort than a custom rucksack would. If each testing participant had been experienced with rucking and knew how to adjust the hip belt for her own comfort, the outcome may have been different.

Another limitation in testing was the weather conditions. The obstacle course was performed outside in the month of February. This resulted in a variety of testing conditions, ranging from icy, wet, and dry sidewalks, as well as freezing cold to mild temperatures, and occasional snow. If each participant was able to complete their test in mild temperatures with clear and dry sidewalks, their total time and heart rate data may have different results.

The heart rate data also proved to have its own limitations. There were two heart rate monitors used in the process of testing. Usually, the same heart rate monitor was used for each participant's test, but on one test, two different heart rate monitors were used. Similar trends were observed using the two heart rate monitors, but the team noted that one heart rate monitor did prove to be more accurate.

6.3 Discussion of Impact of Hip Belt

After initial testing of the team's design and analysis of the raw data, the team had to consider the impact that their design would have on the economy, environment, society, politics, ethics, health and safety, sustainability, and manufacturing.

6.3.1 Economics

This project would not directly influence the economy of everyday living. If the Army did choose to produce this hip belt for Soldiers, it would be mass produced, meaning that manual labor would not be needed. If manual labor was necessary, then it may have allowed for the creation of more jobs, at least in the initial phase of production. However, the companies that manufacture the materials may benefit economically because the Army would need to obtain enough materials to make enough belts to replace the current hip belt design. After the first group of belts is made, the hip belt materials will only be needed from time to time as new Soldiers enter the Army. This means that these manufacturing companies likely would not see an economical boost after the initial production phase.

6.3.2 Environmental Impact

The new hip belt design would have no impact on the natural environment. As the current hip belt does not have any positive or negative impacts on the natural environment, the new design would also be neutral in its environmental impacts.

6.3.3 Social Influence

Following the manufacturing process and the initial release of the team's hip belt, a significant impact on the society will be noted. If the hip belt is accepted and implemented into the United States Army, the target user will be the female Soldier, thus

helping to promote females in the U.S. Army and military and potentially resulting in greater support of females in combat roles. Although targeted to female Soldiers, the hip belt will be available to both female and male Soldiers alike, giving them an option of a different hip belt that they did not previously have. Once implemented by the Army, the hip belt will also be available for commercial use by the individual owner, or sold in military surplus stores. The team's hip belt may also impact the commercial backpacking industry and compel those companies to reevaluate their models or adopt the design developed by the team.

6.3.4 Political Ramifications

In terms of the global market, the team's model could potentially have a small impact. Most nations have a military and most carry equipment in load carriage systems. Although the MOLLE system used by the U.S. is American made and not sold to foreign armies, those armies may choose to adopt a similar model for their own use. Within the U.S., a new hip belt for the MOLLE system would not cause any negative political ramifications. Since there is already a current model that is used by the Army, replacing it with a new and improved model, such as the team's design, would simply be a quality improvement. Since there are no ethical issues that would arise from the implementation of the team's hip belt, there are no foreseeable political debates.

6.3.5 Ethical concern

This project does not have any ethical concerns. This project aims to help Soldiers rather than the general public, by preventing injuries caused by wearing a heavy rucksack in the military. Any ethical issues that may have been brought up with the initial implementation of a hip belt have already been addressed in the current model.

6.3.6 Health and Safety Issues

This project aims to reduce the risk of injury of the MOLLE rucksack for female Soldiers. Therefore, the rucksack will be more stable on the Soldier's back, and reduce the risk of becoming off balance, falling, and fracturing a bone. It will also reduce the stresses on the female Soldier's shoulders, which could reduce the risk of back problems

later in life. It could also help male Soldiers in the same manner if they choose to wear it on their rucksack.

6.3.7 Manufacturability

Throughout the process of producing the prototype, the project team became very aware of the importance of manufacturability, especially since everything in the military needs to be mass-produced. Unlike the current MOLLE hip belt, which uses heat compression to secure padding into place, the new design only requires the use of a sewing machine and a bartack machine for stitching. The shape of the new design was optimized for stitching by ensuring that all the edges were simple and easy to maneuver around on a sewing machine. The shape of the padding was also designed to allow it to be easily inserted within the fabric sleeve. Additionally, we allowed for three-eighths of an inch seam allowance, which is standard for most patterns and reduces the likeliness of error. The ease of manufacturability of the design ensures that it has the ability to be mass produced.

6.3.8 Sustainability

The new design uses similar materials and amounts of energy as the old hip belt in terms of manufacturing. The sustainability of the design was not a component of the design criteria because the project team was more concerned with the functionality of the belt.

Chapter 7: Final Design and Validation

During the design process, the team analyzed the needs, functions, and constraints, which were then used in order to develop design alternatives. Various aspects of the design alternatives were considered using final selection matrices before the team decided on their final design. These aspects included fastener, tightening and padding alternatives as well as additional straps that could be attached to the frame. The team used these matrices in order to create an initial prototype. This hip belt was made of closed cell foam to wrap around the hips and an adjustable pad made of memory foam that would attach to the hip belt using Velcro, a feature that would allow the belt to be customizable. Although this model did address many of the issues with the current hip belt, there were still some key features missing from the design, as the team observed that there was still discomfort on the anterior superior iliac spines and the belt felt over packed. Therefore, the team reconsidered the design in order to incorporate more ways to achieve optimal comfort.

Taking these observations into consideration, the team developed a final prototype that consisted of two “wings,” each composed of an extruded polyethylene, lined with nylon, layered with closed cell foam and then sewn together to create an open center. The open center would allow for increased ventilation, an advantage for Soldiers in the field who are required to wear layers of uniform. In addition, this design had a dual tension system and a “pull-forward” method of tightening the straps, which is much easier to adjust than the current “pull-sideways” method. Although the design did accomplish many of the objectives of the project, the team would have liked to include a removable padding along the back to provide more cushioning against the posterior superior iliac spine (PSIS). Another drawback was that the open center of the prototype would not allow for the attachment of nylon webbing on the outside of the hip belt. Despite these minor drawbacks, the team brought this final prototype to Natick Labs to build the final design.

The team was able to construct their final design with the help of Richard Landry at Natick Soldier Systems Center at the end of December. After attempting to recreate the final prototype, the team discovered that it would be too difficult to sew the wings as one

piece with an open center. For ease of manufacturing, the team decided to modify the open center concept so that the belt would consist of two components: foam pads that could be sewn separately and attached to the “shell” of the hip belt. The “shell” is composed of a layer of polyethylene plastic sandwiched between Cordura nylon fabric to provide shape, structure, and durability. Secondly, foam pads enclosed in spandex sleeves are attached to the shell making up the layer closest to the wearer’s body to provide comfort, support, and flexibility. The foam pads consist of three layers (starting closest to the body): nylon hex mesh, open cell foam, closed cell foam. The foam pads are attached to the shell via Velcro to allow the wearer to adjust the pads for comfort. This design attaches to the MOLLE system using the same mechanism as the current model. Additionally, there are two straps that attached the hip belt to the frame of the ruck via snap clips. This added feature allows the wearer to pull the MOLLE system closer to the body. The hip belt is secured around the wearer’s hips via a standard two-inch side-pinch release buckle and can be adjusted using the “pull-forward” method. Additionally, an adjustable wedge piece was added to the back of the belt to allow for cushioning of the PSIS. The wedge shape was chosen because it is representative of the typical curvature of a female’s back.

Throughout the design process, the team used sewing patterns for precise measurements. These patterns allow the design to be reproduced in the future, whether for experimental or manufacturing purposes. All of these sewing patterns can be seen in Appendix B.

Multiple tests were conducted to compare the team’s modified hip belt to the current model. Ten female volunteers between the ages of 18 and 22 consented to participate in an “obstacle course” which consisted of a one-mile march/run with a rucksack, around WPI campus with each hip belt over various inclines. Participants carried 30% of their bodyweight up to 50 pounds. Afterwards, they were asked to rate their perceived exertion for each component of the obstacle course (up West St. getting in the prone position, sprinting Park Ave., up Institute Rd.), where “6” represented no exertion and “20” represented maximal exertion. The participants were also asked to fill out a survey rating the hip belt for the following: willingness to wear for extended time, distributing weight from shoulders to hips, ease of donning and doffing, comfort,

flexibility in movement, and adjustability, where “1” represented worst and “10” represented best.

The heart rate data was taken every minute using a chest strap heart rate monitor. This data was correlated with the elevation of the course. Although each participant’s heart rate data increased with increasing elevation and with the increase in pace, the data proved to be inconclusive. Some tests appeared to have no change in the data, with nearly the same heart rate for both hip belts. After comparing the heart rate data to the rate of perceived exertion, there appeared to be no direct trend.

From the results of the RPE survey, the team was able to conclude that participants preferred the modified design over the current belt. All of the averages for the modified belt were lower than the current belt, meaning that participants felt that the modified belt allowed them to perform better throughout the course without having to exert as much energy to complete each section. The differences between the two belts for willingness to wear the hip belt for an extended period of time and effectiveness of weight distribution were not found to be statistically significant when a paired t-test was performed. Ease of donning and doffing (new 7.6 ± 1.08 , old 6.1 ± 1.6 , $p=0.048$), comfort (new 8.3 ± 1.06 , old 5.7 ± 1.89 , $p=0.01$), flexibility in movement (new 7.6 ± 1.35 , old 6.3 ± 1.49 , $p=0.013$), and adjustability (new 8.2 ± 1.93 , old 5.4 ± 1.96 , $p=0.021$) were found to be statistically significant when a paired t-test was performed. The data from the survey questions demonstrated that the modified hip belt provided more comfort, maneuverability, flexibility of movement and adjustability when compared to the current belt. This means that the participants rated the modified belt higher than the current belt when asked about ease of donning and doffing, comfort, flexibility of movement and adjustability.

Force plate testing was conducted to measure the center of pressure (COP) and COP path length under four different conditions: without the rucksack, with no belt, with the old belt and with the new belt. COP was collected every 0.01667 seconds for 5 seconds. The path length was calculated by summing the distances between each COP point. Additionally, the team could not make any conclusions from the force plate data. While the data generally showed that the modified belt was more effective in allowing the subjects

to balance, there were not enough participants in the sample size and no definitive trends that could confirm improved balance with the modified belt.

Pressure film was used to test different contact pressures on the body. The film was placed at three locations on the body: iliac crest, posterior superior iliac spine, and shoulders. The subject then wore the rucksack with the current hip belt for one minute. Upon doffing the rucksack, the film indicated in red greatest areas of pressure. This process was repeated with the team's new design. The pressure film was then removed and analyzed using ImageJ to compare the intensities between the current and modified belt. This allowed us to look at the distribution of the pack and detect any pressure points against the hips and shoulders. The files were converted to 8-bit grayscale, with different gray values from 0 to 255 (0 being the darkest, with the most pressure). In general, the grayscale intensity averages for the new belt were indicative of less pressure for the three locations that were tested on the female body. If the pressure points on the new belt did prove to be more intense, they were paired with smaller standard deviations, meaning that the pressure was more evenly distributed throughout the film.

The team has designed a modified hip belt for the MOLLE system specific for female Soldiers. The new design provides increased comfort due to increased padding around the bone processes of the hip. Flexibility of movement is increased by allowing the user to have a full range of motion in completing various tasks. Addition of the pull forward mechanism allows for ease of adjustability and the side straps allow for better load distribution compared to the current model.

Chapter 8: Conclusion and Recommendations

The team has designed a modified hip belt for the MOLLE system specific for female Soldiers. The new design provides increased comfort due to increased padding around the bone processes of the hip. Flexibility of movement was increased by allowing the user to have a full range of motion in completing various tasks. Addition of the pull forward mechanism allows for ease of adjustability and the side straps allow for better load distribution compared to the current model.

After testing the final design and developing conclusions, the team came up with several recommendations and modifications that they would like to see happen in the future. Before the team's hip belt can be implemented into the United States Army, the team recommends that large-scale and long term studies be conducted on active duty female Soldiers in order obtain a larger pool of data for analysis. Secondly, the team suggests long term durability studies be conducted with the hip belt. Since the Army operates in a multitude of theaters, the hip belt must be tested for durability in a wide range of climates and environments, as well as for long periods of time in the field.

Additionally, the team feels that studies should also be conducted on male Soldiers. Although the team focused on females, they do feel that their hip belt design can be used universally for both males and females. The team has already gained initial feedback from two male Cadets from the WPI Army ROTC program who wore the hip belt on two different occasions. One wore it for a weekend long Field Training Exercise at Fort Devens, and the other wore it while rucking the Boston Marathon. Both gave positive feedback, stating that the team's hip belt was very comfortable and distributed the weight well.

In terms of modifications, the team feels the front buckle needs to be modified. Currently, the two-inch wide nylon straps attached to the front buckle exhibit a small amount of creep when wearing the hip belt for long periods of time because it is so smooth. To mediate this, the team feels the buckle should be modified with teeth, or a

rougher nylon strap should be used to increase friction between the buckle and strap to reduce the creep.

Furthermore, the team would like the hip belt to have fixed padding. The four inner pads are removable via Velcro, but the team would like them sewn in place to minimize the number of components that Soldiers would have to worry about.

Lastly, the team was successful in fitting the hip belt from the 5th to 99th percentile of females, but would like to do better. The team believes that with some slight size adjustments, the hip belt can be modified to fit the 1st to 99th percentile of females.

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Appendix A: Complete IRB Form

Study Protocol:

ROTC cadets are encouraged to wear their uniforms. All other participants should wear sweatpants and sneakers. The rucksack will be loaded with 30% of the participant's body weight, or 50 pounds, whichever is less, and she will complete a series of tasks around campus. The whole course is approximately one mile long. During the testing, she can adjust the belt to whatever she feels is most comfortable. The heart rate of the participant will also be measured using a heart rate monitor at one minute intervals over the completion of the course. A study team member will accompany the participant throughout the course. The participant will be asked to complete the course at two separate times, one using the current MOLLE hip belt and one using our modified design. There will be one day between the sessions. For example, if the first session is completed on a Monday, the second session will be completed on a Wednesday. If at any point during the session the participant is unable to continue due to pain, discomfort or injury, she is allowed to stop the testing process.

These are the instructions that will be given to the participant before starting the course.

1. Begin the course around campus at the ROTC office near Daniels Hall. You will begin the course walking down Institute Road. When you reach the corner of Institute Road and West Street, you will be asked to don and doff the rucksack three times.
2. You will then take a left up West Street towards the fountain on campus. When you reach Atwater Kent, you will be asked to get in the prone position.
3. After you reach Goddard Hall, you will take a left on Salisbury Street towards Park Ave. At this point in the course, you will sprint the length of the parking garage.
4. You will turn onto Institute Road at the corner of the track and finish the course in the same place you started.
5. At the completion of the course, we will ask you to complete a survey that measures your rate of perceived exertion.
6. You will receive an email from the team one day after the testing that will ask you about any injuries or discomfort that may have occurred as a result of the testing.

The following survey will be given to the participant after the course has been completed.

Please use the chart below to measure your rate of perceived exertion (RPE). This survey will be completed after each session, one using the current MOLLE design and one using our modified design. Please answer these questions to the best of your ability.

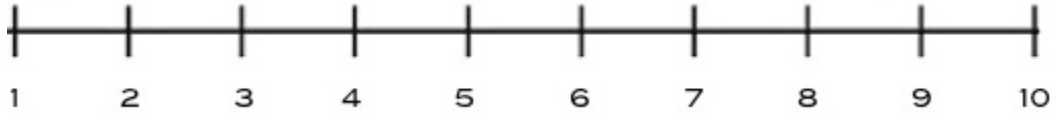
Rating of Perceived Exertion (RPE)	
6	No exertion at all
7	
	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Vey hard
18	
19	Extremely hard
20	Maximal exertion

1. Rate your exertion walking up the West Street Hill.
2. Rate your exertion getting into the prone position.
3. Rate your exertion sprinting along Park Avenue.
4. Rate your exertion walking up the Institute Road hill at the end of the course.

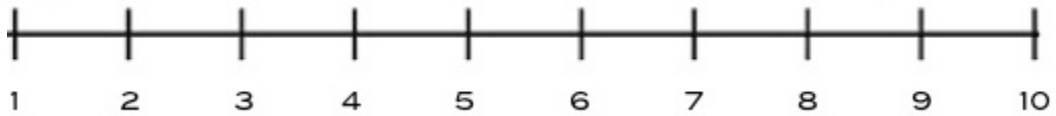
After both sessions have been completed, the participants will complete this survey evaluating their experience with the hip belt.

Please rate the following on a scale of 1 to 10 (1 being the worst, 10 being the best):

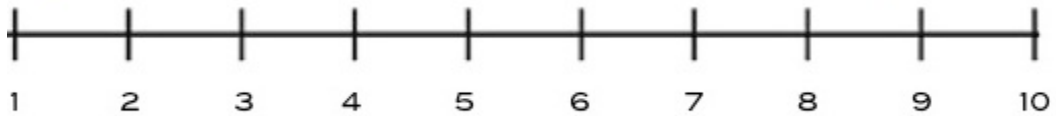
1. Willingness to wear the hip belt for extended periods of time?



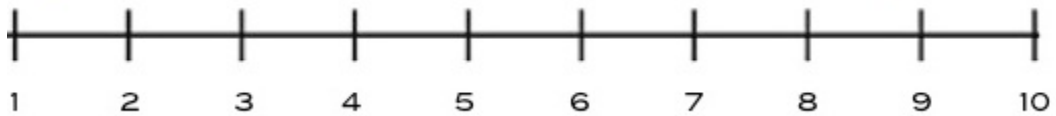
2. Effectiveness of distributing the weight from your shoulders to your hips?



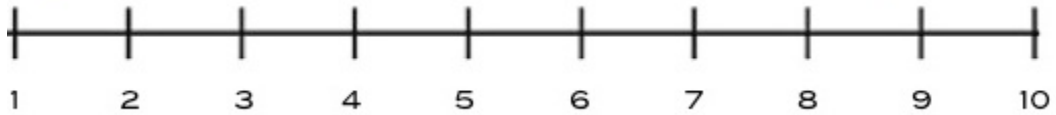
3. Ease of donning and doffing the rucksack with the hip belt?



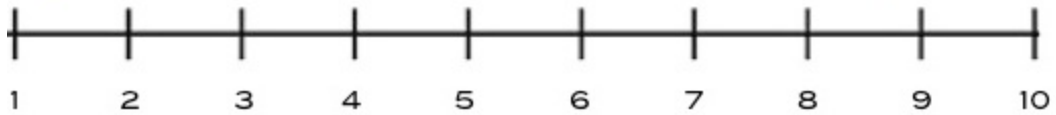
4. Comfort of the hip belt?



5. Flexibility in movement allowed by hip belt?



6. Adjustability of hip belt?



Informed Consent Agreement for Participation in a Research Study

Investigator: Karen L. Troy, PhD

Contact Information: Department of Biomedical Engineering
60 Prescott St
Worcester, MA 01605
Tel: 508-831-6093
Email: ktroy@wpi.edu

Title of Research Study: *Optimizing the MOLLE for the Female Soldier*

Sponsor: None

Introduction

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study: A Soldier's individual combat equipment, the gear he or she is required to have on person for mission success, has always been an essential part of the foot Soldier's burden. The current load-bearing equipment, designed with male physical characteristics in mind, is called the Modular Lightweight Load-carrying Equipment (MOLLE) rucksack. However, this design can cause discomfort or injury for women, who have different structural features than men. The purpose of this study is to compare the comfort of the hip belt that is currently being used by the Army to a modified design.

Procedures to be followed: If you are an ROTC cadet, please wear your uniform. If not, please wear sweatpants and sneakers. You will wear a rucksack that is loaded with 30% of your body weight, or 50 pounds, whichever is less, and will complete a series of tasks around campus. The whole course is approximately one mile long. During the testing, you can adjust the belt to whatever you feel is most comfortable for you. Your heart rate will also be measured using a heart rate monitor at one minute intervals over the completion of the course. A study team member will accompany you. You will be asked to complete the course at two separate times, one using the current MOLLE hip belt and one using our modified design. There will be one day between the sessions. For example, if you complete the first session on a Monday, your second session will be on a Wednesday. If at any point during the session you are unable to continue due to pain, discomfort or injury, you are allowed to stop the testing process.

1. Begin the course around campus at the ROTC office near Daniels Hall. You will begin the course walking down Institute Road. When you reach the corner of Institute Road and West Street, you will be asked to don and doff the rucksack three times.

2. You will then take a left up West Street towards the fountain on campus. When you reach Atwater Kent, you will be asked to get in the prone position.
3. After you reach Goddard Hall, you will take a left on Salisbury Street towards Park Ave. At this point in the course, you will sprint the length of the parking garage.
4. You will turn onto Institute Road at the corner of the track and finish the course in the same place you started.
5. At the completion of the course, we will ask you to complete a survey that measures your rate of perceived exertion.
6. You will receive an email from the team one day after the testing that will ask you about any injuries or discomfort that may have occurred as a result of the testing.

Risks to study participants: You may experience discomfort wearing the hip belt or back discomfort due to the amount of load in the rucksack. There is more chance for discomfort if you are not an ROTC cadet who is used to carrying more than the load used in this experiment.

Benefits to research participants and others: You probably will not directly benefit from this study, but a potential benefit of this study is the use of the hip belts in the future. If the modified design is successful, the Army may choose to have this design mass produced and standardized. This could not only directly benefit all women in the Army, but also men if they choose to wear the hip belt as well.

Record keeping and confidentiality: Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of injury: If you are injured during your participation in this study you may seek medical treatment through your regular care provider. No compensation will be provided. You do not give up any of your legal rights by signing this statement.

Cost/Payment: Upon completion of this study, you will be receiving a \$10 gift card. During the testing, you will also receive snacks and drinks.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: Karen Troy (information on the first page). In addition, you may contact the IRB Chair Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu and the University Compliance Officer Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu.

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be

entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Study Participant Signature

Date: _____

Study Participant Name (Please print)

Signature of Person who explained this study

Date: _____

WORCESTER POLYTECHNIC INSTITUTE

Worcester Polytechnic Institute
IRB# 1 HHS IRB # 00007374

17 December 2013
File: 13-241

**Re: IRB Expedited Review Approval: File 13-241 "Optimizing
the MOLLE for the Female Soldier"**

Dear Prof. Troy,

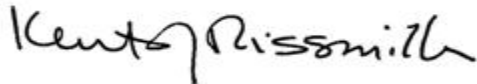
The WPI Institutional Review Committee (IRB) approves the above-referenced research activity, having conducted an expedited review according to the Code of Federal Regulations 45 (CFR46).

Consistent with 45 CFR 46.116 regarding the general requirements for informed consent, we remind you to only use the **attached stamped approved consent form** and to give a copy of the signed consent form to your subjects. You are also required to store the signed consent forms in a secure location and retain them for a period of at least three years following the conclusion of your study. You may also convert the completed consent forms into electronic documents (.pdf format) and forward them to the IRB Secretary for electronic storage.

The period covered by this approval is 17 December 2013 until 16 December 2014, unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific approval must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue.

Please contact the undersigned if you have any questions about the terms of this approval.

Sincerely,



Kent Rissmiller
WPI IRB Chair

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Appendix B: Sewing Patterns

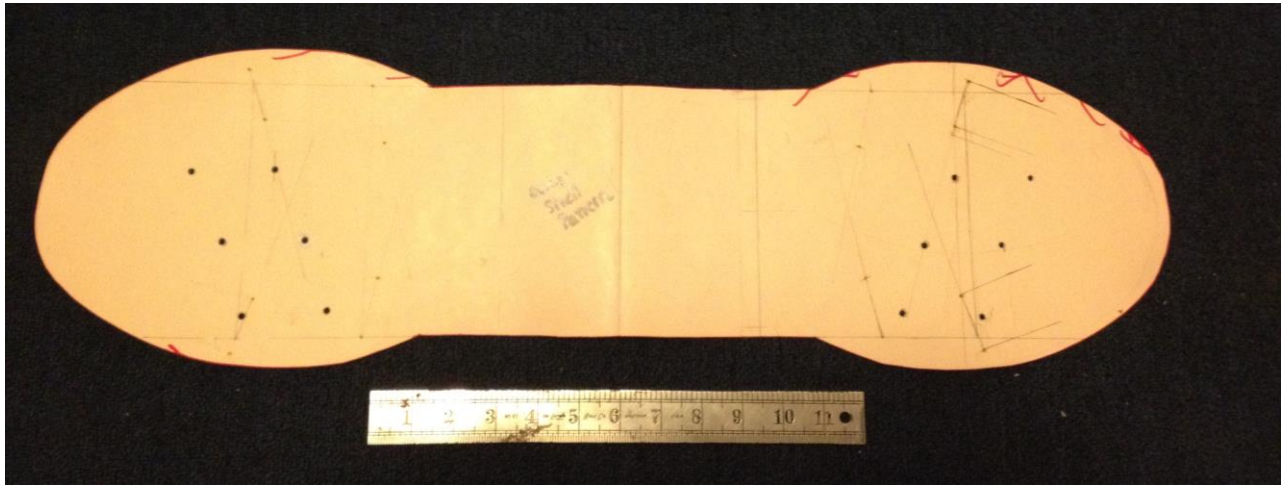


Figure 43: Shell Pattern

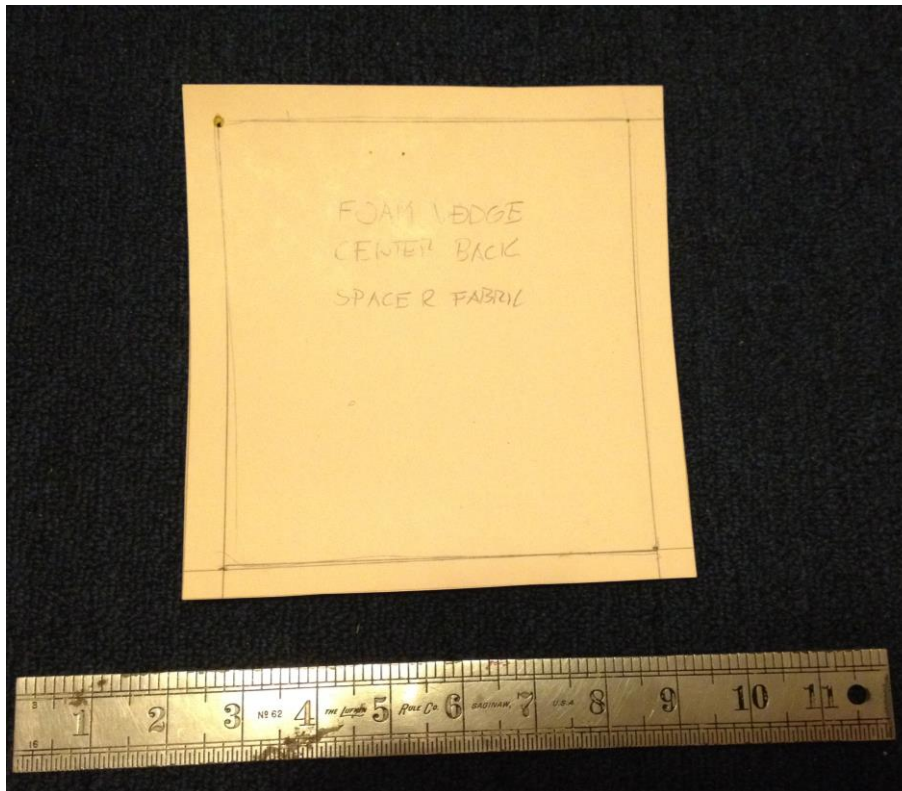


Figure 44: Back Padding Pattern (Mesh Part)

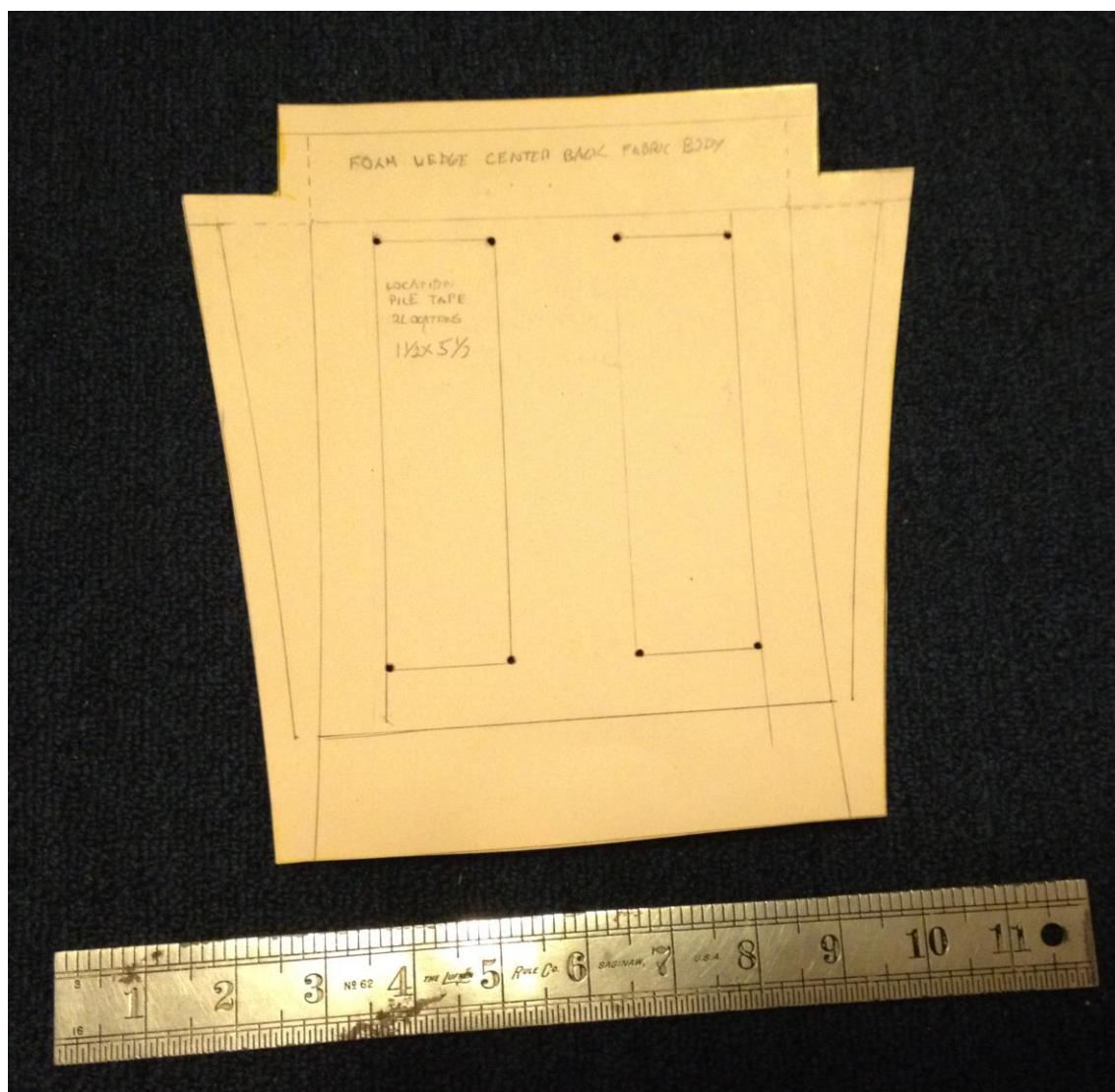


Figure 45: Back Padding Pattern (Codura Part)



Figure 46: Velcro Pattern for Padding Backing

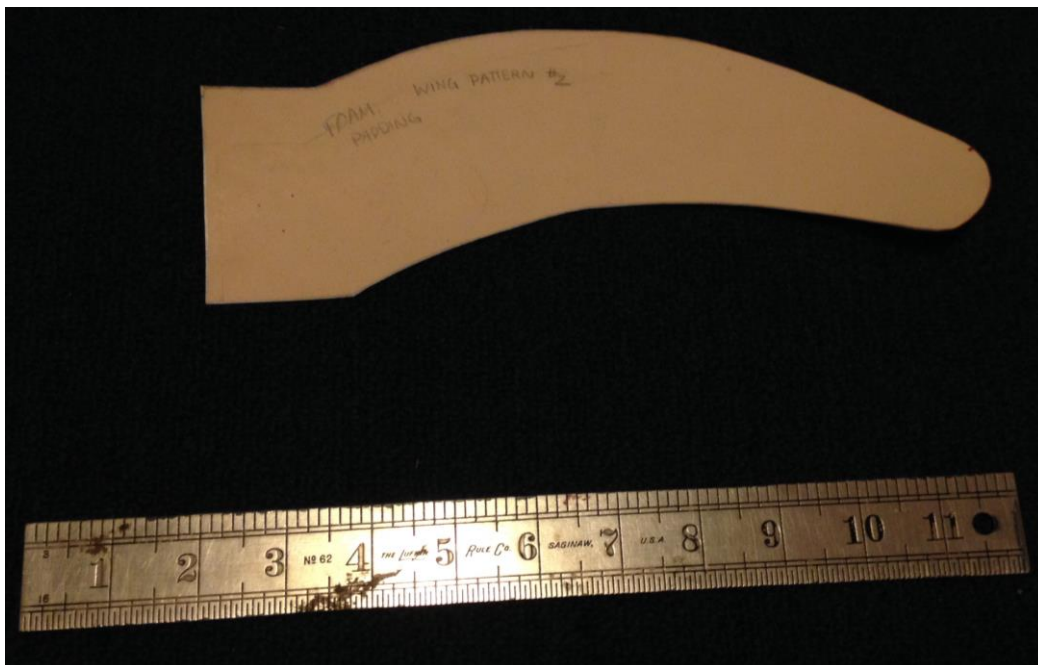


Figure 47: Padding Pattern



Figure 48: Padding Pattern for Fabric Cover

Appendix C: Heart Rate Data

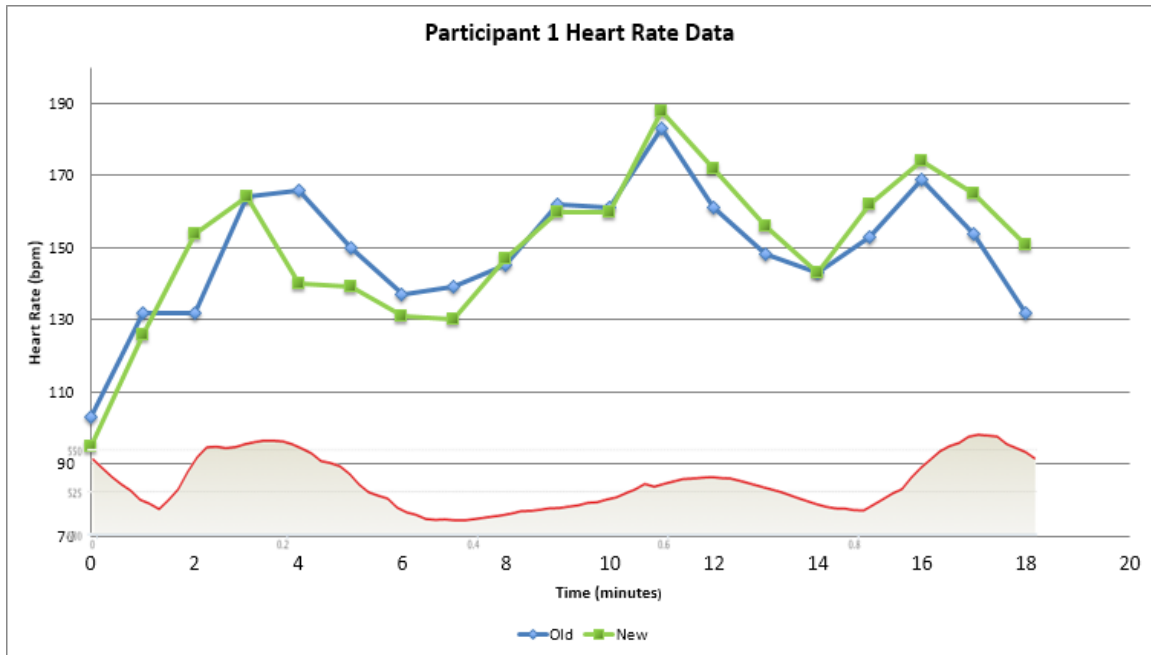


Figure 49: Participant 1 Heart Rate Data

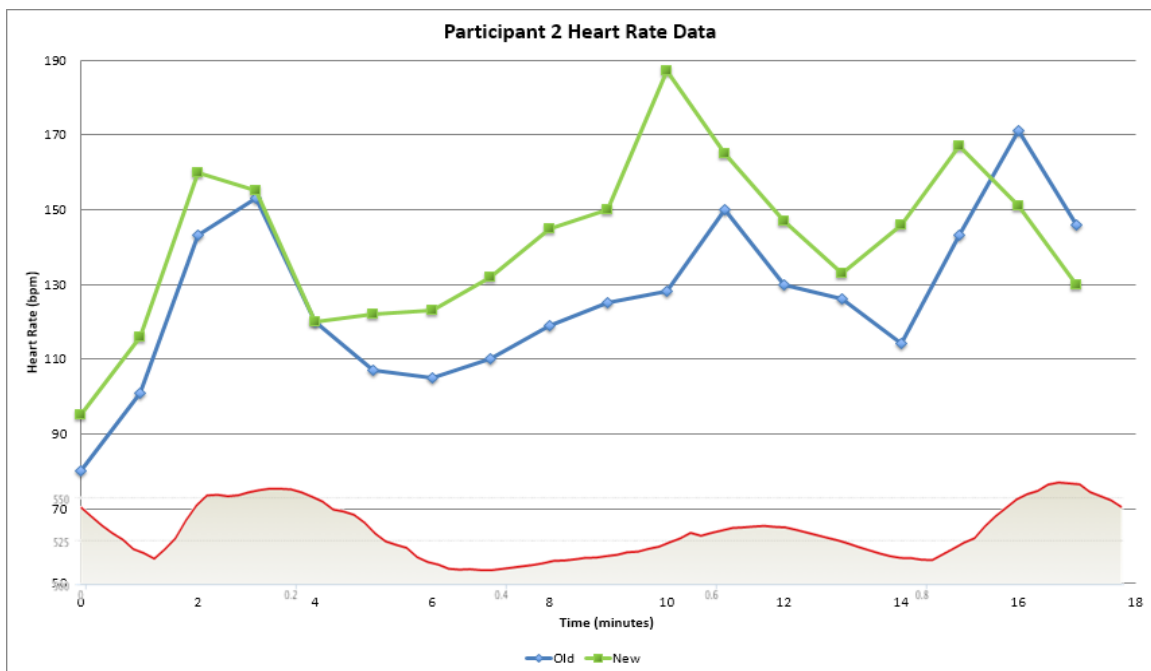


Figure 50: Participant 2 Heart Rate Data

Participant number 2 was required to wear two different heart rate monitors, which explain the variety in the data. The data trends are similar, but the accuracy in the data are different. The heart rate monitor also was not working as efficiently at 11 minutes for the second test, which resulted in the participant having to take her heart rate manually.

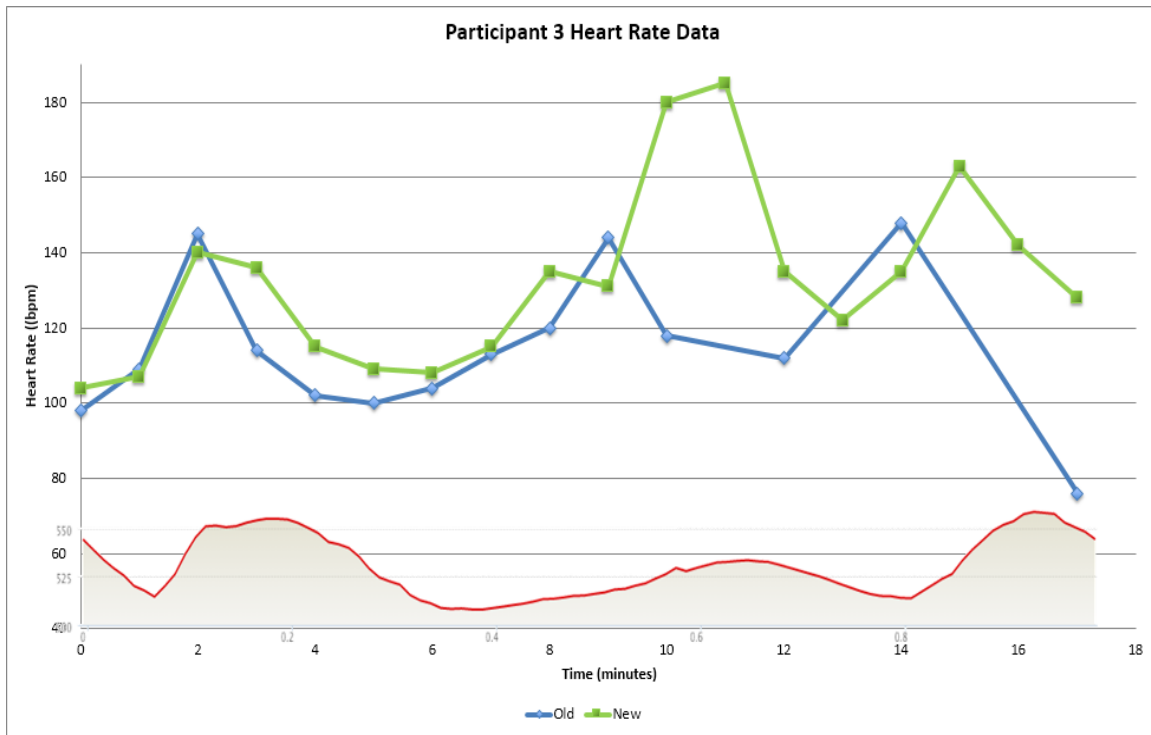


Figure 51: Participant 3 Heart Rate Data

During the second test (old hip belt) for participant #3, the heart rate monitor battery died. This resulted in the heart rate being taken manually in different locations: after the sprint, at the intersection of Park Ave and Institute Rd, and at the top of the hill on Institute Rd. Since the participant was required to stop walking while taking the heart rate, the old belt heart rate data is less than that of the new belt heart rate data.

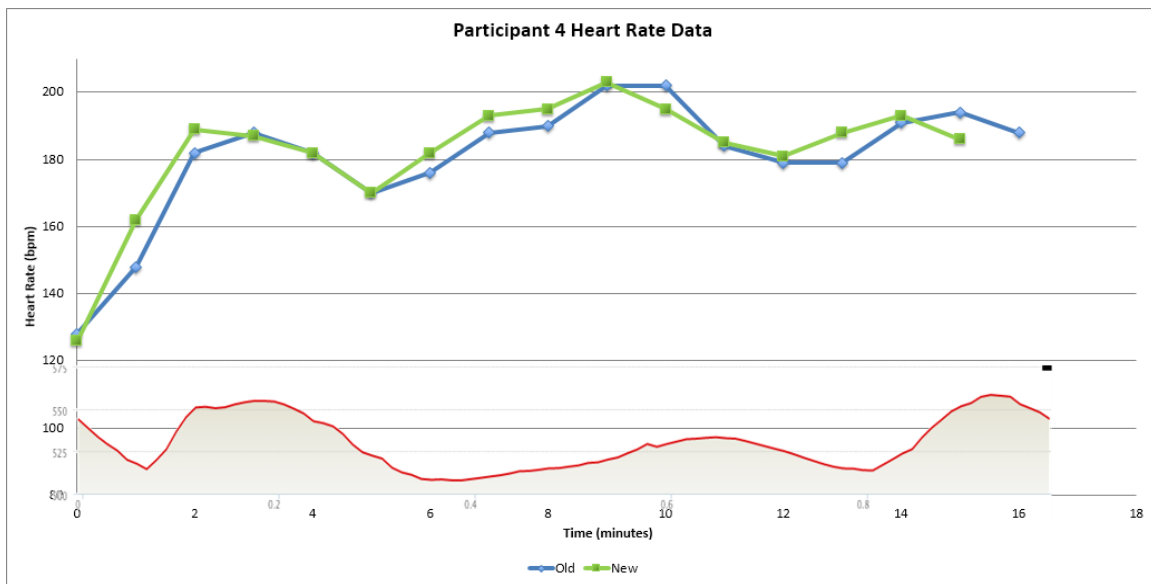


Figure 52: Participant 4 Heart Rate Data

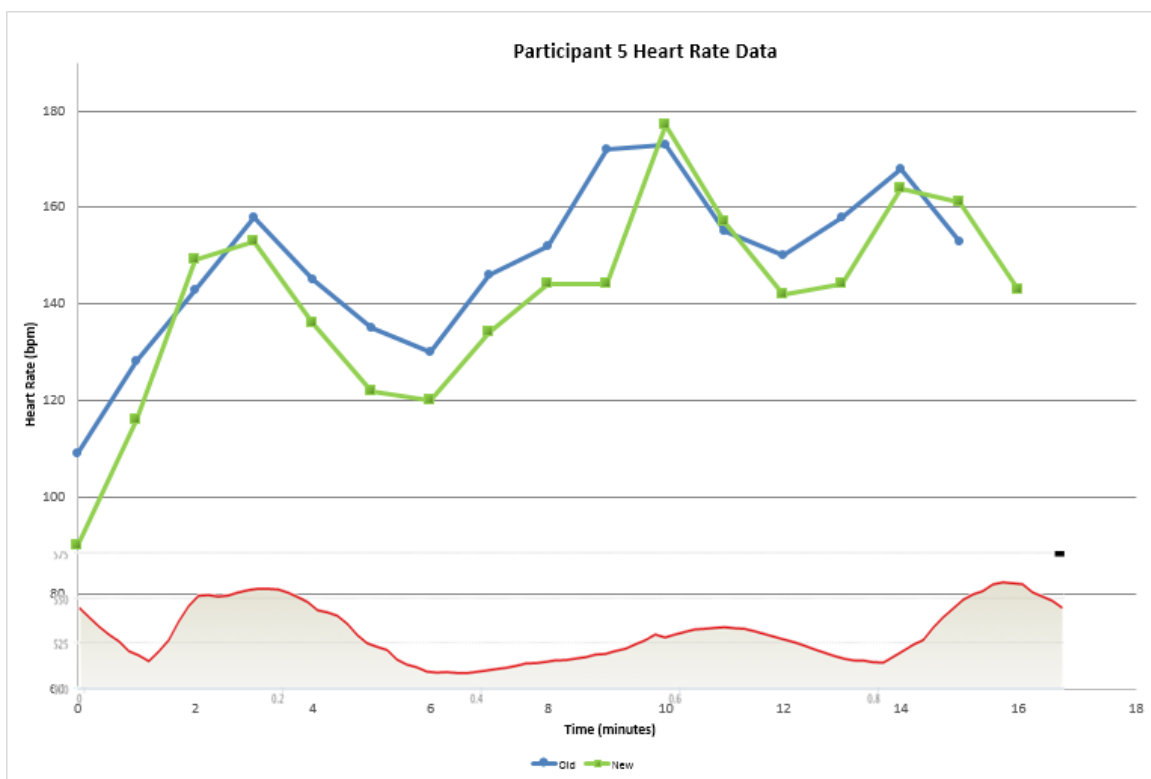


Figure 53: Participant 5 Heart Rate Data

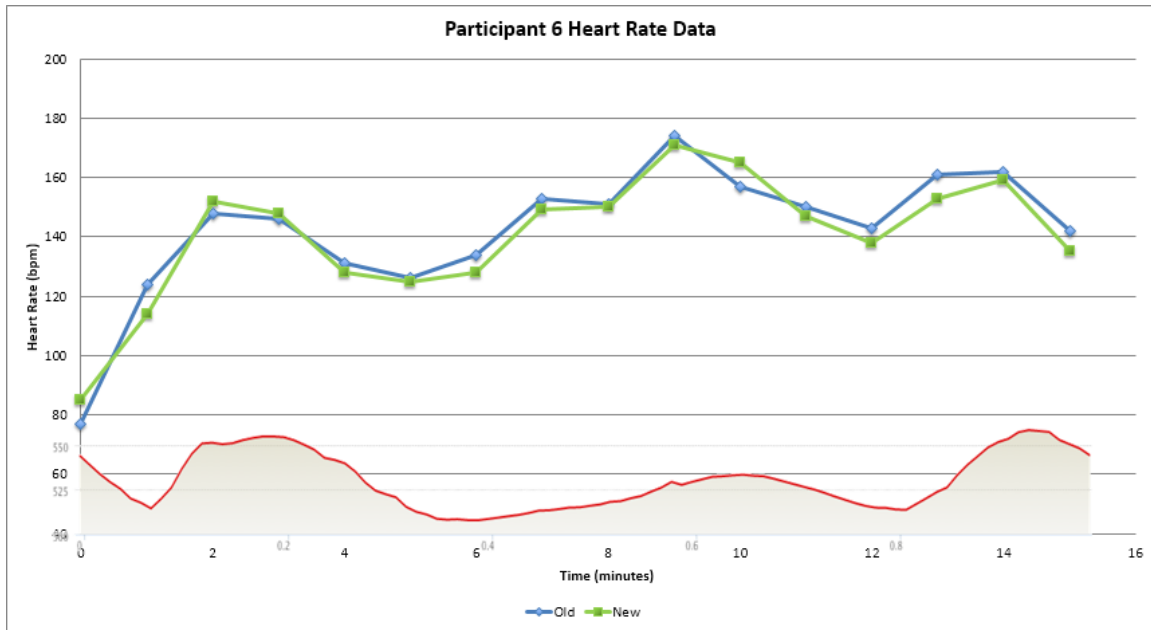


Figure 54: Participant 6 Heart Rate Data

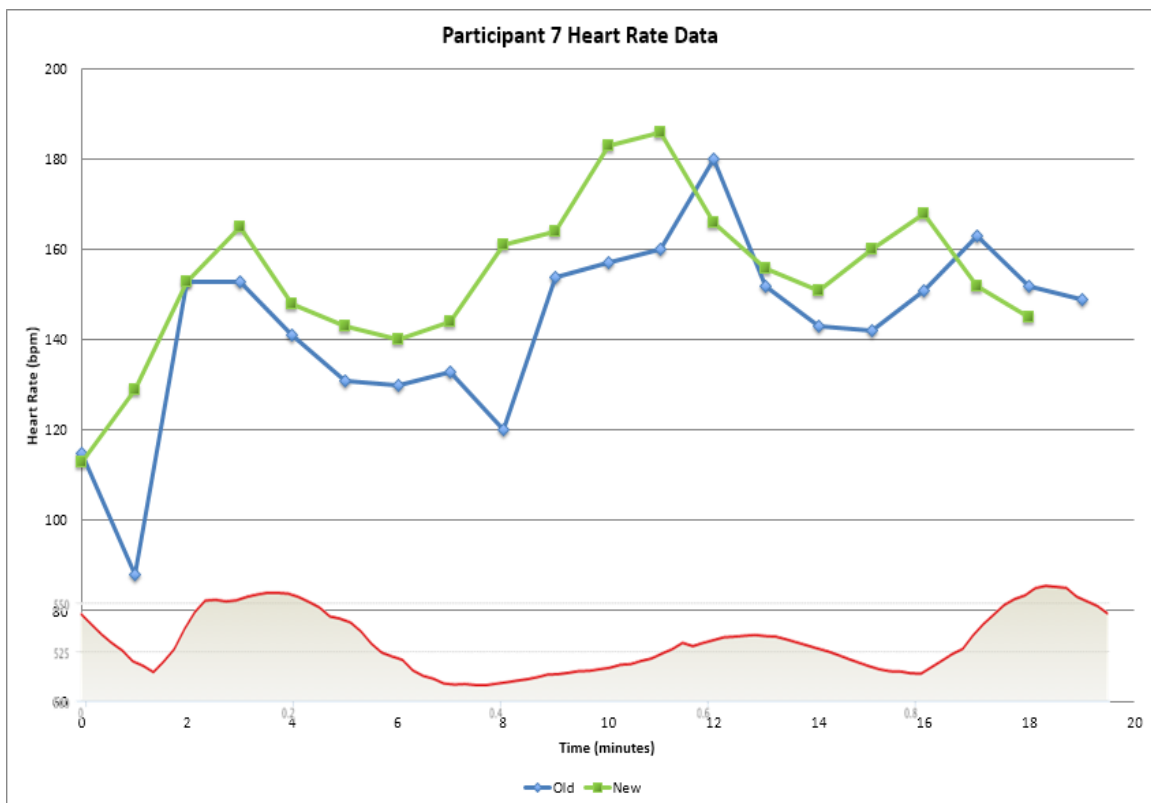


Figure 55: Participant 7 Heart Rate Data



Figure 56: Participant 8 Heart Rate Data

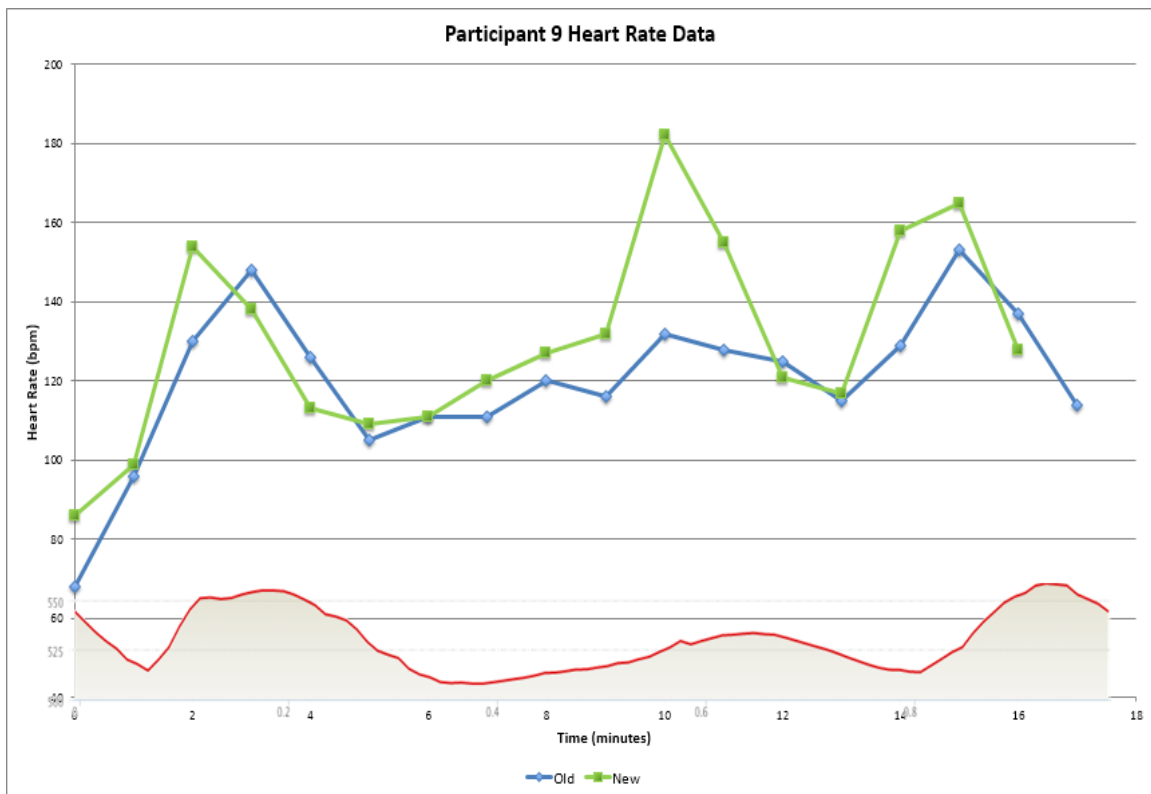


Figure 57: Participant 9 Heart Rate Data

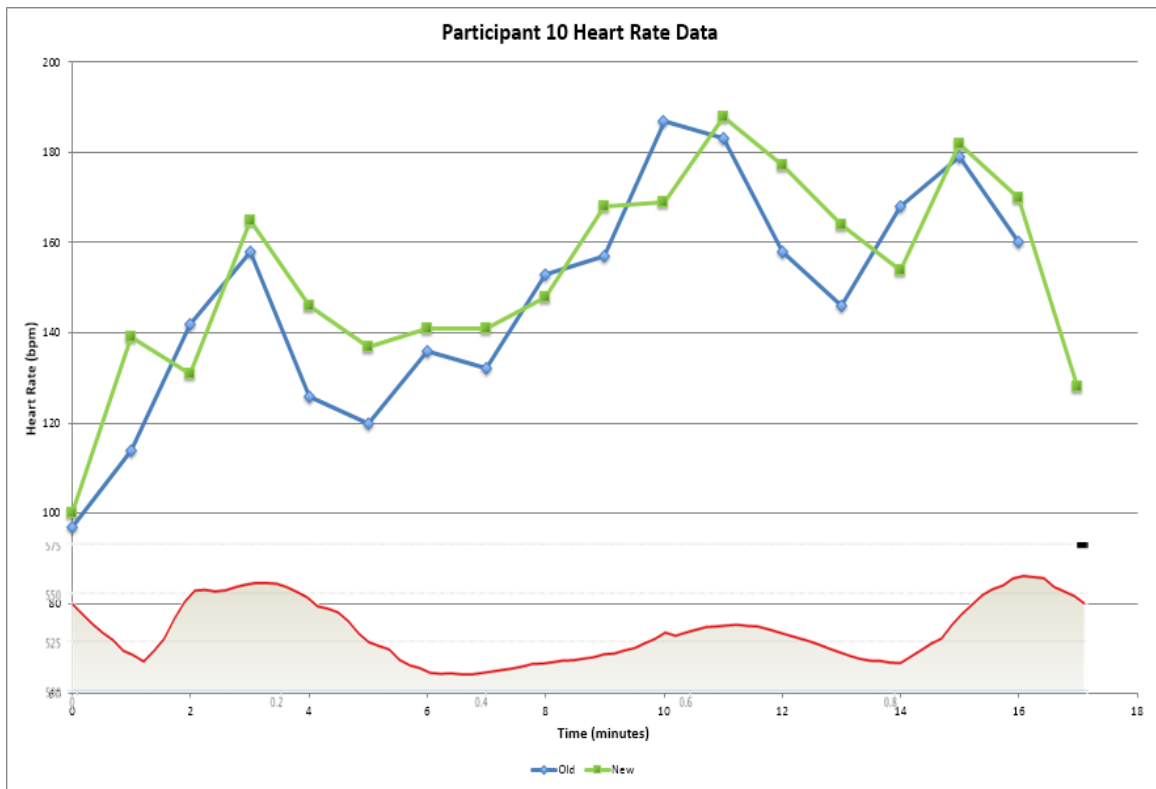


Figure 58: Participant 10 Heart Rate Data

Appendix D: Pressure Film

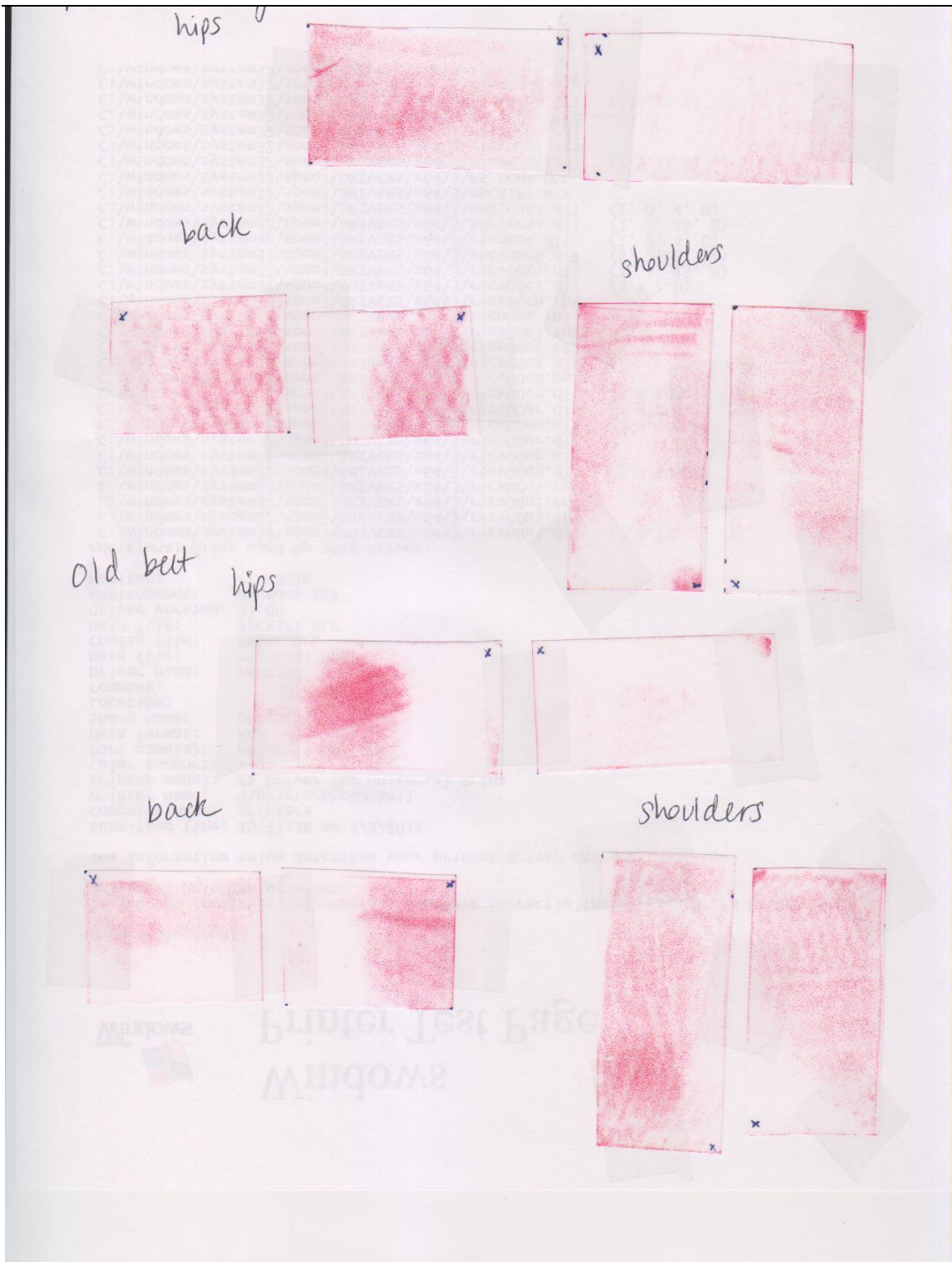


Figure 59: Participant 1 Pressure Film

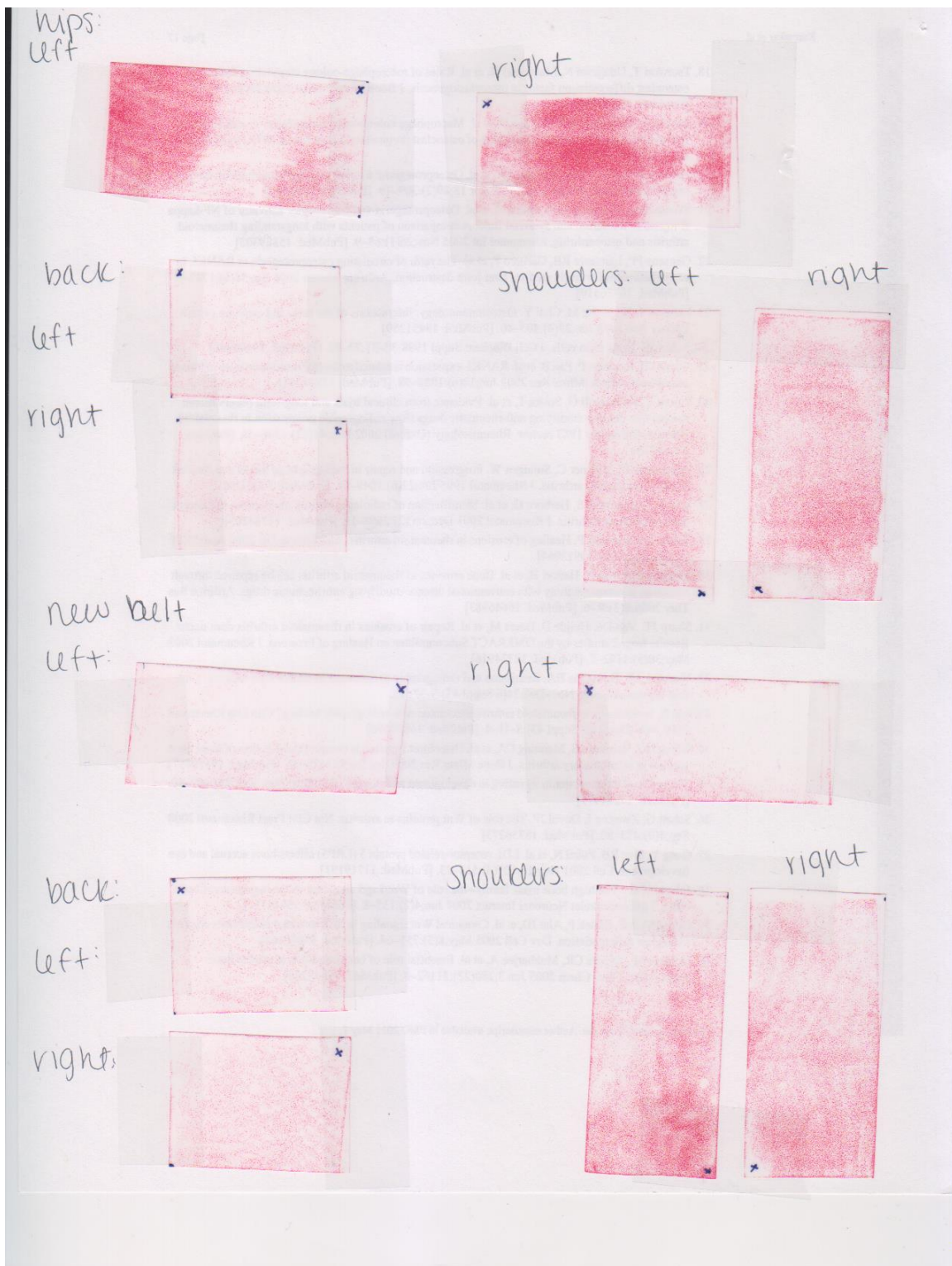


Figure 60: Participant 2 Pressure Film

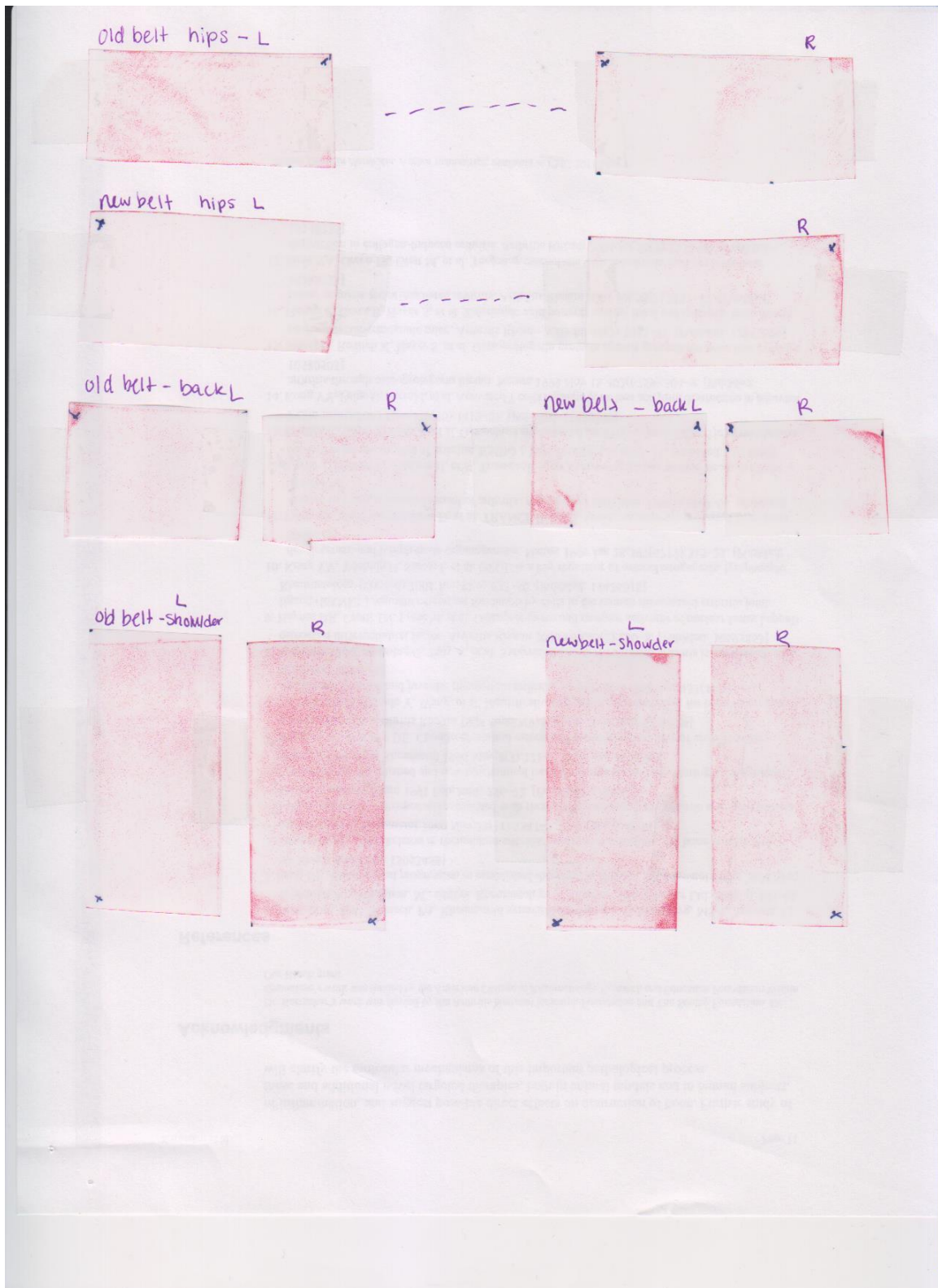


Figure 61: Participant 3 Pressure Film

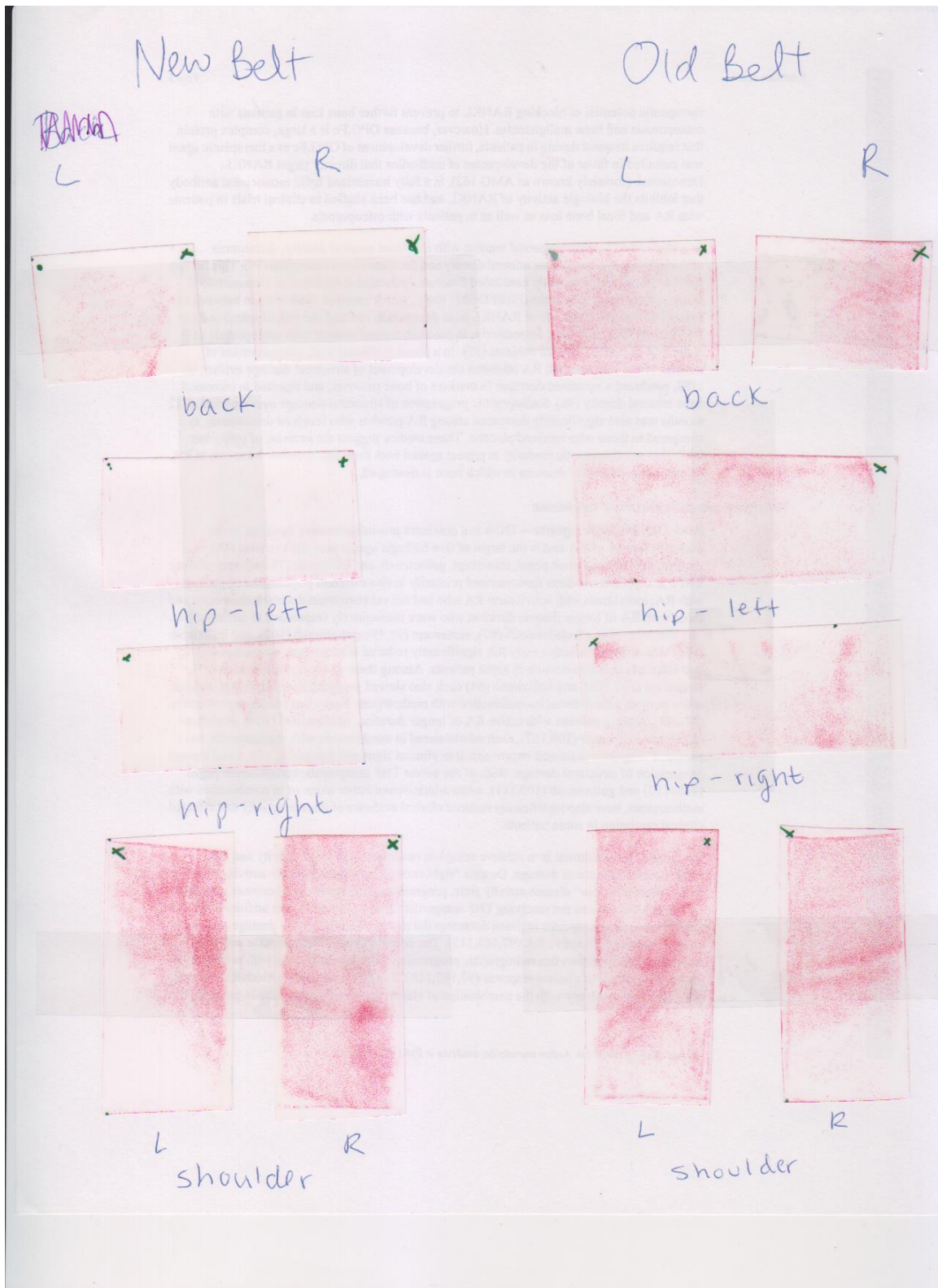




Figure 62: Participant 4 Pressure Film

Appendix E: Public Awareness

Students work with Natick researchers to create prototype female-friendly rucksack hip belt

April 30, 2014

By Clara Calderon, NSRDEC Public Affairs

 2  Like 16 people like this. Sign Up to see what your friends like.

Story Highlights

- "The reason that we focused on the hip belt was that women carry weight more effectively on their hips, while men carry weight more effectively on their shoulders."



NATICK, Mass. (April 30, 2014) -- An all-female team of four students from Worcester Polytechnic Institute recently developed a design to make the Army-issued rucksack hip belt more comfortable for female Soldiers.

The engineering students worked with one of the U.S. Army Natick Soldier Research, Development and Engineering Center's load carriage specialists over the course of the year to develop a prototype.

NSRDEC physical scientist Rich Landry had previously held a workshop for the Army ROTC cadets at WPI on how to correctly assemble Army load carriage components, including the rucksack.

Marlisa Overton, an Army ROTC cadet and senior biomedical engineer student, relied on her experiences carrying the rucksack and found that the current hip belt could use some adjustments that would prove beneficial for female Soldiers. She noticed not everyone would use the hip belt, and after further investigation, the team found that it was because of discomfort and lack of effective weight distribution. The hip belt was challenging to adjust and sometimes required another Soldier to pull the strap, or pulling it using an awkward forward motion.

The main change was to the hip belt itself but there are now also wedged cushions for the curve of the lower back. The newer design allows the female Soldier to pull the strap to the side. This means the Soldier can adjust it to make the rucksack fit just right.

To get a clearer perspective of what most Soldiers need to carry on the battlefield, Overton, and classmates Rachel Matty, Amy Babeu, Erin LaRoche-all senior engineering majors- first had to learn about Army equipment used in the field.

They added up the weights and bulk of the ammunition, weapons, communications equipment, water, food, environmental protective clothing and other gear that Soldiers need in combat. The great amount of gear and its weight makes it extremely important to design an efficient and comfortable load carriage system for all Soldiers to use. The weight of all these items, including wearing personal protection equipment (body armor, helmet and eyewear can add up quickly, no matter what your gender, frame size, height, or weight.

The students' new modifications to the rucksack hip belt allow a female Soldier to carry this equipment more efficiently and move with more ease and safety, as the weight is distributed off the shoulders and back, and onto the female Soldier's hips where it is more balanced and stable.

Overton, a senior cadet in the WPI ROTC program, will receive her commission in May as a second lieutenant and may someday see the results of the project in the future.

"The reason that we focused on the hip belt was that women carry weight more effectively on their hips, while men carry weight more effectively on their shoulders. Therefore, for the scope of this project we are only conducting tests on females. However, this belt could be adjusted for a male Soldier's use. We have a foam wedge which can be removed or repositioned for the user's preference. There are also 6 snaps that allow for attachment to straps to pull the rucksack closer to the user's body, which allows for adjustability from user to user," Overton said.

Team member Matty added "We tested the female rucksack (hip belt) on 10 females through an obstacle course. One subject, who previously had complained of back problems, instantly noticed a difference. She felt that she could wear it longer."

Babeu was able to prove conclusive results based on the feedback from the female Soldiers who ran the obstacle course. The Soldiers reported that perceived exertion was lowered, demonstrating the prototype's efficiency where it matters most, out in the field.

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NSRDEC's lead engineer for Load Bearing Equipment, John Kirk, felt that the idea was innovative. Kirk and his team believe in providing a stage for promising developers to create and develop their visions. LaRoche was grateful for NSRDEC's support and agreed that the effort was very rewarding, especially considering the productive environment which allowed them to try a variety of possibilities.

Team leader for NSRDEC's Clothing & Configuration Management Team, Fernanda Crivello said, "I was very excited that they had picked the female load bearing belt to work on, since we don't currently have one." She also added that she "had high hopes that they would come up with something that it would benefit the female Soldiers."

Impressed with the team and their passion, Landry said, "Their concept was solid. Ultimately, our goal is to figure out a hybridized design the entire population can use more effectively." They were successfully able to create a design for a system they could assemble and demonstrate in a short amount of time. Landry and the students met and began to work on the rucksack last October. They have finalized a prototype and are presenting it as a WPI group senior engineering project for their graduation in May.

ABOUT NATICK SOLDIER RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

NSRDEC is part of the U.S. Army Research, Development and Engineering Command, which has the mission to develop technology and engineering solutions for America's Soldiers.

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