Investigation into Biomechanical Response and Health Consequences of Military Rucksack Design for Female Soldiers

Thesis

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Abstract

Rucksack, or backpack, design has been the subject of scientific study for over fifty years, yet improvements are still being implemented in both industry and the military. In particular, the need for female-specific equipment in the US military has become more evident since the combat exclusion rule was lifted allowing women to serve in combat roles. Female soldiers use exactly the same rucksack as the men in training and in the field. Women experience greater injury rates than men in the military; load carriage is a major cause of these injuries. Although load carriage affects patterns in gait, physiological effects, and health outcomes, the differences in male and female response to the current military rucksack under dynamic, field conditions are unknown. This investigation establishes a foundation for future design research to improve the military load carriage system. The objectives of this investigation are to examine past research on the effects of rucksack use and design, concentrating on military applications, and to analyze the current military rucksack suspension system design using finite element modeling in the context of creating a better adapted design in the future for female soldiers.

A review of the literature was completed exploring biomechanical, physiological, and health effects of load carriage, specifically focusing on military applications and effects on female users. In addition, an analysis of military equipment was completed to gain a full
understanding of the system and the interactions between the clothing, personal protective equipment, and load carriage devices. Individual and group interviews of experienced users provided information about equipment use in the field. Furthermore, a targeted analysis using finite element modeling was completed for the purpose of investigating the interaction between frame design and load carriage effects on female anthropometry for the current US military rucksack (MOLLE IV).

The results of the finite element model of the MOLLE IV rucksack frame show a trend that suggests differences in axial force in the shoulder straps may be due in part to back-waist length variations, with an increase in shoulder strap force as the waist-back length decreases. Future research is necessary to design and evaluate improved rucksack frame and suspension system designs in order to provide female soldiers with better adapted equipment.
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Fields of Study

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From military to recreational applications, rucksacks are an integral tool for carrying equipment in remote locations. While recreational packs are typically updated yearly with industry releasing new designs, the rucksacks used by the US military have had many fewer iterations. In 2001, the Modular Lightweight Load-carrying Equipment (MOLLE) system replaced the All Purpose Lightweight Individual Carrying Equipment (ALICE), which had originally been issued during the 1970s (Polcyn et al., 2002). Images of the MOLLE and ALICE rucksack frames are in Figure 1.1. Rucksack, or backpack, design has been the subject of scientific study for over fifty years (Clarke, 1955), yet improvements are still being implemented. Additionally, there are recreational packs on the market specifically designed for male or female body types. Differences in the pack design for women include the slenderness of the rucksack, the angle of the hip belt, and the range of adjustability. Conversely, the military does not offer a gender-specific design for a rucksack to account for differences in anthropometry, which is suggested to correctly design clothing and personal equipment (Gordon et al., 1989). The need for female-specific equipment in the US military has become more evident since the combat exclusion rule was lifted in 1993, allowing women to serve in combat roles (Ling et al., 2004). In 2010, over 200,000 women were serving on active duty, which comprised 14.5% of all active duty personnel (Census.gov). These women use exactly the same rucksack as the men in training and in the field. Although the requirements for load carriage need to remain consistent, the design of the
suspension system, comprised of the frame, shoulder straps, chest strap, and waist belt, could be optimized for the female user. The objectives of this investigation are to examine past research on the effects of rucksack use, concentrating on military applications, and to analyze the current military rucksack suspension system design using finite element modeling in the context of creating a better adapted design for female soldiers. The motivation for this investigation is to establish a foundation for future design research to improve the military load carriage system.

Figure 1.1: This figure shows the MOLLE IV (left) and ALICE (right, with shoulder and waist straps attached) rucksack frames. Both frames are viewed from the posterior. Photo References: MOLLE: NC Tactical; ALICE: Amazon.
1.1 Methods

Various methods were employed throughout the investigation and analysis in this report. First, a review of the literature was completed exploring biomechanical, physiological, and health effects of load carriage. Though the focus was on military rucksack carriage in females, a range of studies was incorporated to create a complete picture of load carriage. Studies included male and female subjects, different styles of rucksack or load carriage system, and diverse data collection techniques. In addition, an analysis of military equipment was completed to gain a full understanding of the system and the interactions between the clothing, personal protective equipment, and load carriage devices. Individual and group interviews of experienced users provided information of equipment use in the field. A discussion with four military females was directed at achieving an understanding of the effects of rucksack carriage on current female military users and identifying areas of improvement to tailor the design for females. Furthermore, a targeted analysis was completed for the purpose of investigating the effects of the current US military rucksack (MOLLE IV) frame design on the female anthropometry. ANSYS 14.5 was utilized to complete a finite element analysis of the MOLLE IV frame, and a detailed model description is located in the design section of this document. These methods outline an initial investigation into the impact of rucksack suspension system design relevant to use by female military personnel.
Chapter 2. Injuries and Health Background

Rucksacks are worn in order to carry equipment for prolonged travel, creating an extended and dynamic interaction between the rucksack and the soldier. Soldiers therefore spend much time training and marching while carrying the rucksack. In an investigation of military injuries, Jones et al. (2000) discussed training injuries as one of the most important causes of morbidity for military personnel. Specifically, combat soldier activities, for example road marching while wearing a rucksack, were the 3rd highest cause of injuries in the Army in 1994 (Jones et al., 2000). After reviewing past literature, Knapik et al. (1996) listed the following injuries that are commonly associated with prolonged load carriage: foot blisters, stress fractures, back strains, metatarsalgia (foot pain), rucksack palsy, and knee pain. Basic training, as well as other training courses such as the Leader Development and Assessment Course, require soldiers to complete multiple long distance marches as preparation. Unfortunately, injuries are a common occurrence at basic training and are typically caused by overuse. Furthermore, many injuries have been shown to occur in the 3rd to 5th weeks of training, happen primarily during long marches, and have an average recovery time of 10 weeks (Bessen et al., 1987). Because the treatment typically involves rest, it can be costly to the military due to lost time and the need to repeat training in the future (Ross, 1993a). The following sections outline specific medical issues that have been associated with rucksack use as well as specific susceptibility that females have for injury.
2.1 Health Issues Associated with Rucksack Use

Pack Palsy. One of the predominant injuries that results from load carriage is pack palsy or rucksack paralysis, with various Army posts reporting as many as 50 cases of rucksack paralysis each year (Bessen et al., 1987). The clinical symptoms include minor pain, paresthesia, numbness, and paralysis of the upper extremities (Knapik, 1989). Corkill et al. (1980) suggested that the mechanism was peripheral nerve injury, though the investigation only looked at 3 cases of pack palsy. The effects of pack palsy stem from compression of the brachial plexus nerve (Bessen et al., 1987). Multiple studies have been conducted to identify causes and suggest methods to avoid this injury.

In a study investigating the ALICE rucksack, 15 of 12,850 soldiers not utilizing the frame\footnote{These soldiers wore the ALICE rucksack with the metal frame removed.} sustained brachial plexus injuries while only 3 of 19,050 soldiers using the ALICE frame experienced nerve palsy (Bessen et al., 1987). Additionally, it has been shown that not wearing a chest strap results in decreased sensory function in the upper limbs when compared to wearing the chest strap (Hollins, 2012). Furthermore, Wilson (1987) detailed 6 cases of brachial plexus injuries at basic training in males who were carrying packs without the metal frame or waist strap. For these 6 cases, the motor function improved in minutes, though numbness lasted hours (Wilson, 1987). The period of recovery is an important figure for pack palsy in the military because reduced motor function, even for a few minutes, reduces the ability to handle and fire a weapon. Weakness that makes carrying a rifle while marching difficult has also been reported as a symptom of pack palsy (Bessen et al., 1987). The shoulder straps of a rucksack encircle the shoulders, touching and compressing the clavicle and brachial plexus. The discomfort felt in the shoulders as a
result of carrying a rucksack is present beginning at the initiation of load carriage as the upper limb is very susceptible to short-term discomfort (Birrell & Hooper, 2007). Finally, after reviewing the literature Knapik et al. (2004) suggested that hip belts be worn because they reduce the pressure on the shoulders and thus increase the comfort.

Pack palsy is a serious and prevalent injury in the US military (Bessen et al., 1987). Although more research is needed into the effects of various design components of the rucksack, wearing the chest strap, waist strap, and utilizing the pack frame are all important factors in reducing the likelihood of developing pack palsy.

**Blisters.** A second extremely common injury due to rucksack marching is foot blisters. Blisters were found to be one of the predominant injuries in addition to back pain and strains due to road marches (Knapik et al., 1992). In another study, blisters occurred in 60% of participants and the foot discomfort began 30-45 minutes into the march (Birrell & Hooper, 2007). While blisters are primarily caused by the friction between the foot and the sock inside the shoe, the creation may be amplified by many other factors including carrying a load. For example, Knapik et al. (1997) showed that carrying heavy weights in a double pack had a lower incidence of blisters compared to carrying the ALICE pack, which may indicate that a more even load distribution reduces blister formation. This may stem from the changes in gait while carrying loads with various distributions about the body (detailed later).

**Stress fractures.** Overuse injuries such as stress fractures have been associated with load carriage and road marching (Knapik et al., 1996). Research into load carriage as a causal path for stress fractures is limited; however, there are a few studies that investigated potential methods of reducing the risk. Giladi et al. (1985) created an alternate training
technique in which one group marched a reduced number of cumulative miles while carrying a load, while the other group marched greater cumulative miles and carried the same load. While it seems logical that reducing the cumulative exposure could reduce the occurrence of stress fractures, the study showed no significant difference between the groups in number of stress fractures (Giladi et al., 1985). It is interesting to note that a cause of the study not finding a significant difference could be attributed to the fact that the rate of increase in miles marched was the same during the primary injury time frame for both groups. Furthermore, Knapik et al. (2012) reviewed the literature and concluded not only that physical training can improve load carriage performance, but also that the regimen could be better tailored at basic training to improve health and performance of the soldiers.

Female Susceptibility to Injury and Health Consequences

Although females do not constitute a majority of users in the recreational or military populations for carrying a backpack, they form a significant subset of the population and need to be investigated. Literature has shown that females are more susceptible to injuries through evidence that female US military basic trainees experienced a higher incidence of injuries than men while completing the same activities (Ross, 1993b, Bell et al., 2000). However, the cause of this susceptibility is not fully understood. While Bell et al. (2000) states that the increased rate of female injuries was due to females being less fit than men upon entering training, Heller et al. (2009) found that the increased postural sway in women’s gait could amplify the probability of falls and injuries. Not only is the rate of injuries higher for load carriage in women, some injuries have only been identified in women. A study of long term load carriage detailed two women with anterior sterno-clavicular dislocation (Shoaib et al. 2002). Additionally, hip fractures are a notable injury in
women at basic training with the cause attributed to rucksack use (Personal Communications, Devon Furey).

*Stress fractures.* Injuries to bone, such as stress fractures, are much more likely in female rather than male US military training populations (Jones et al., 1989). A study of British Army recruits showed that 10.7% of women experience stress fractures while only 2.8% of men exhibit similar injuries. Bone scans were used to further confirm the injury case beyond the onset and complaint of pain (Macleod et al., 1999). The risk of hip fracture mentioned previously has not received much attention in the literature. A study investigating fatigue during marching with the ALICE rucksack concluded that “hip musculature did not excessively fatigue” during marching (Quesada et al., 2000). Unfortunately, this study was only conducted with male soldiers and the ‘prolonged’ march was only a forty minute test. Thus, the effect on women is unknown as well as the effect of repeated loading for days or weeks. Furthermore, because the study used the ALICE rucksack, the effects of the current MOLLE IV system are also unknown. These reasons are the suspected cause of the discrepancy between the data suggesting hip musculature did not fatigue (Quesada et al., 2000) and the reports of multiple hip fractures in women at basic training (Personal Communications, Devon Furey, Brittany Pedreschi).

In his review of prevention strategies for overuse injuries, Ross (1993b) emphasized the extrinsic factors of training techniques and equipment. This emphasis on prevention leads to the notion that better rucksack designs, suited to the anthropometry of the user, may be able to prevent injuries.
Chapter 3. Effects of Rucksacks Design and Loading

Although rucksacks have been a mode of transporting food and equipment for hundreds of years, experimental studies into their design and use did not begin until the 1950s (Clarke, 1955). Studies investigating load carriage typically fall into one of the following categories: biomechanical, physiological, and perceptual responses. The following sections review the current literature regarding load weight and placement of a rucksack, contrast the response of females and males to load carriage, and evaluate numerous designs that have been studied.
3.1 Load Weight

*Biomechanical.* Increasing the weight that is carried on the back intuitively increases the stresses that the body experiences; however, investigation is necessary to identify the biomechanical effects of load weight on the body. One of the most prominent and widely agreed upon biomechanical effects of load carriage is forward lean of the trunk (Kinoshita, 1985, Harman et al., 2000a, Ling et al., 2004, Attwells, 2006, Birrell & Haslam, 2009). These studies conclude that because the backpack weight is posterior to the subjects’ center of mass, the subject leans forward in an effort to maintain better balance. Along the same reasoning, forward lean has been identified to increase with increasing loads carried on the back (Kinoshita, 1985, Harman et al., 2000a, Polcyn et al., 2002, Ling et al., 2004, Attwells, 2006, Birrell & Haslam, 2009). Additionally, gait changes have been studied in response to varying load weights. Using video assessments, Kinoshita (1985) identified that time in double support increased as load increased. Double support refers to the period of the gait cycle during which both feet are in contact with the ground. This trend has been further confirmed both with similar techniques (Harman et al., 2000a) and as methods for collecting data and performing analysis have improved, using motion capture systems (Ling et al., 2004, Birrell & Haslam, 2009). Further significant effects on gait include increase in knee flexion (Kinoshita, 1985), increase in knee range of motion (Harman et al., 2000a), increase in stride frequency (Harman et al., 2000a), and decrease in stride length (Birrell & Haslam, 2009) with increasing load weight. Finally, Polcyn et al. (2002) has shown initial intuition to be correct in that increased weight carried increases magnitude of forces within the joints.
Physiological. The metabolic cost of carrying a load has been examined extensively using various study designs. Physiological measures such as increased oxygen uptake have been shown to increase as a result of carrying weight when compared to no weight (Kirk & Schneider, 1992, Quesada et al., 2000, Polcyn et al., 2002). Furthermore, it has also been shown that the metabolic cost increases as the load weight increases nominally (Quesada et al., 2000, Polcyn et al., 2002), as well as relative to the subject’s body weight (Silder et al., 2013). The physiological cost of carrying a load could not only cause fatigue but could also inhibit performance in tasks that are completed either while carrying the load or shortly after the load is removed.

Performance. The level of performance exhibited by soldiers is impacted by carrying a loaded rucksack. Knapik et al. (1997) demonstrated that soldiers’ march times on the same road course increased as load increased. Load carriage also significantly impairs a soldiers’ marksmanship accuracy following a 20 km march (Knapik et al., 1997). A study by Holewijn & Lotens (1992) further showed that load carriage lowered performance in obstacle and mobility tests. Although load has been shown to negatively affect performance on various tasks, load carriage did not significantly decrease the ability to accurately throw a grenade (Holewijn & Lotens, 1992, Knapik et al., 1997). The difference between marksmanship accuracy and throwing a grenade leads to the thought that load carriage could affect fine motor skills to a greater degree than larger full body tasks. Performance loss is a serious result of load carriage for soldiers because a soldier must be able to accurately and effectively perform tasks at any point during or post load carriage.

It is evident that carrying a load affects the subject’s gait pattern, physiological response, and performance and that the effect is more pronounced as the weight increases. While
carrying no external load may be ideal, soldiers must, of course, carry the appropriate equipment during missions. Understanding this need, guidelines to US military commanders state that weight of the approach load\(^2\) should not exceed 33kg (72 lbs) (Polcyn et al., 2002). However, it is understood that equipment can weigh up to 120 lbs with body armor, gear, and the rucksack, far above the recommendation (Personal Communications, Tim Ruffing). Therefore, studies must not look solely at decreasing the weight but also at the placement and suspension system interacting with the soldier.

**Male versus Female Response to Load**

It is understood that the anthropometry of males and females differs. In general, men are taller with wider shoulders while women are shorter in stature with wider hip breadth (Gordon et al., 1989). Furthermore, a backpack with shoulder straps and a waist belt suspends from the shoulders as well as the hips. The distance that the pack suspension system should cover when fitted properly (the waist-back length, the distance from the cervical landmark to the posterior level of the navel), is longer for males than females by 3.5 centimeters (1.38 inches) for the fiftieth percentile US soldier (Gordon et al., 1989). With the difference in anthropometry, it is not surprising that men and women have altered gait changes in response to loading via a backpack (Martin & Nelson, 1986, Pandorf et al., 2000, Polcyn et al., 2002). Furthermore, it has been suggested that the proportion of weight supported by the lower back compared to the shoulders could be influenced by the structural difference in the pelvis between men and women (Lafiandra & Harman, 2004).

**Biomechanical.** Men and women both exhibit trends such as forward lean and increased time in double support but the degree to which these measures are affected by weight

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\(^2\) The approach load refers to the equipment carried by the soldier including a water-filled canteen, simulated grenades, simulated M16 ammunition, and a backpack (Polcyn et al., 2002).
differs between genders. While forward trunk lean increased for both males and females as the load weight was increased, males exhibited a higher degree of forward lean (Martin & Nelson, 1986, Pandorf et al., 2000). Additionally, men spend less time in double support than women when carrying the same rucksack (Pandorf et al., 2000, Polcyn et al., 2002). The longer time spent in double support by females may indicate that they are less stable under the same load as males. Females demonstrated a greater sensitivity to load magnitude than men when studying kinematic characteristics of gait such as stride length, stride rate, single leg support time, double support time, swing time, and trunk inclination (Martin & Nelson, 1986). One study found that men and women adopt similar gait adaptations such as duration of stance phase and peak joint angles when carrying a load (Silder et al., 2013). However, this study used a vest that distributed weight evenly about the torso, while the other studies examined only weight in a backpack. Given that biomechanical differences were not observed with the weight in a vest, the response seen in females to backpack load carriage is potentially due to the fit and the uneven distribution between the front and the back of the torso.

**Physiological.** The differences between men and women in terms of physiological effect of load carriage is unclear. Males and females have shown similar energy costs when calculated per unit body plus load mass (Pandorf et al., 2000); however, in a separate study when loads were normalized to body mass, the metabolic cost was greater for men (Silder et al., 2013). The study conditions, such as load distribution are likely the cause of the discrepancy. As was seen in the biomechanical response, the effects were different depending on the load distribution and weight carriage technique.
Perceived response to load carriage not only indicates pain, but responses can also be used to identify shortfalls and areas for improvement in designs. Reported pain, soreness, and discomfort in the back have been noted to a greater extent by women wearing the same pack as men (Harper et al., 1997). Although this could be a result of women being more vocal, women also reported more problems with the fit and stability of the ALICE pack (Harper et al., 1997), which may indicate a failure in the design to accommodate female anthropometry. It is reasonable to believe that the increased discomfort women experience stems from the fit and stability of the rucksack design. A better design is needed to reduce discomfort and increase the stability of female soldiers.
3.2 Load Placement

The weight in a backpack can be organized to concentrate mass in specific regions while placing higher volume, lower mass items elsewhere. It has been repeatedly found that carrying a load high on the back is beneficial (Clarke, 1955, Jacobson et al., 2003, Knapik et al., 2004, Stuempfle et al., 2004, Simpson et al., 2012) through both biomechanical and physiological studies and models.

*Biomechanical.* A seminal study by Clarke (1955) found that placing a load higher on the back caused less muscular fatigue. In a biomechanical analysis, Simpson et al. (2012) demonstrated that while all three load positions studied caused forward trunk flexion, the most superior level on the back resulted in the most upright posture when carrying 30% of the body weight. With the weight placed higher on the back, the trunk would not need to flex as far forward in order to recover a level of balance after the change in center of mass. Though shown to be beneficial, it has been found that a load placed high on the back negatively impacted performance and had greater perceived discomfort compared to a load distributed about the waist only (Holewijn & Lotens, 1992). In reality it is not practical to carry the entire load from the waist as the volume would be too great. However, a waist belt can be used in order to move weight from the shoulders to the waist, which will be detailed later. Perhaps carrying weight high but also allowing weight to be carried through the waist is the solution.

The effects of load placement have also been examined through biomechanical models. A two-dimensional biomechanical model was created in which optimization was used to minimize the objective function of forces on the shoulders and the waist (Pelot et al., 2001). When the center of gravity of the backpack was set as a variable, the optimized solution
placed the center of gravity as high and as close to the back as possible within the constraints of the model (Pelot et al., 2001), which agrees with past research (Clarke, 1955, Jacobson et al., 2003, Knapik et al., 2004, Stuempfle et al., 2004, Simpson et al., 2012). While this model further validates a high center of gravity as beneficial, it is only a two-dimensional model and thus does not account for the full shape of the body or the differences in shape between men and women.

Physiological. Knapik et al. (1996, 2004) noted from the literature that the load center of mass should be carried as high and as close to the body as possible because it results in the lowest energy cost. Furthermore, a study investigating the physiological responses to weight at varying heights in a backpack found that the highest weight placement (at the thoracic vertebrae 1-6) corresponded with the lowest metabolic cost and perceived discomfort (Stuempfle et al., 2004). Perceived discomfort was also lower for a vertical load distribution tested against the regular distribution (Jacobson et al., 2003), likely because the load center of mass was brought closer to and higher on the body.

To assess the validity of their laboratory studies, Hasselquist et al. (2004) explored the differences in center of mass and moment of inertia between soldier-packed rucksacks and laboratory rucksacks from previous studies. The study showed that the laboratory loaded rucksacks did not capture the full range of center of mass or moment of inertia that the soldier experienced when packing their own rucksack. Thus, they recommended that future studies distribute weight to match the way a soldier packs in order to optimize design features (Hasselquist et al., 2004). Although studies can be conducted to assess the effects of load placed in various positions, the reality is that the soldier actually packs the rucksack they carry. While the packing method can be influenced by studies and soldiers are aware
that high placement of weight is more comfortable (Personal Communications, Tim Ruffing, Devon Furey), in the field soldiers may not pack optimally. Therefore, research must not only focus on weight but also the design of the rucksack and how that may be optimized to relieve physical stresses.
3.3 Rucksack Frame and Suspension Design

One method of ameliorating the negative effects of load carriage is to carry the weight high and close to the body. However, other design features can also influence the load distribution, the resulting biomechanical effects, and the perceived discomfort. The following sections investigate various design features that have been studied in efforts to minimize stresses during load carriage including frame use and design, various distributions of the weight about the body, and the effects of changing the suspension system comprised of shoulder, waist and chest straps.

Frame vs No Frame

Rucksacks were originally made and carried without a frame. The US military instituted their first framed pack, the All-Purpose Lightweight Individual Carrying Equipment (ALICE), in the 1970s (Knapik et al., 2010). Since that time, studies have been conducted to assess the usefulness and need for a framed rucksack. Perceptually, packs without a frame have been reported to be the least comfortable when compared to packs that incorporate a frame (Legg & Mahanty, 1985). Though there are many potential causes for this preference, it is likely influenced by the distribution of weight that the frame allows. Holewijn (1990) showed that while standing, a frameless pack caused peak shoulder skin pressure that was 10 times greater than a pack worn with an external frame. Furthermore, it was found that the average pressure while walking was 5 times greater with a frameless pack (Holewijn, 1990). Although the shoulder strap attachment points differed slightly between the framed and frameless rucksacks, they both incorporated a waist strap in the design. Furthermore, the effect of an internal frame system, comprised of two bent stays, has also resulted in the lowest compressive forces on the upper body, while the same pack without stays (no frame)
resulted in the highest loads (Reid et al., 2006). The reduction of pressure on the shoulder would not only increase comfort but could potentially decrease the rate of injuries such as rucksack palsy. In fact, it has been found that the rate of brachial plexus injuries in soldiers not utilizing the frame (0.12%) was higher than the incidence for soldiers using the ALICE pack with frame (0.016%) (Bessen et al., 1987). Overall, carrying a rucksack without a frame during a long road march corresponded to a 7.4 times greater risk of sustaining an injury compared to soldiers wearing the pack with a frame (Bessen et al., 1987). It is clear that a rucksack design should incorporate a rigid frame in order to assist in weight distribution and reduce the rate of injuries.

**Internal vs External Frame**

While modern recreational packs are commonly designed with internal frames, typically bent stays, the US military’s current rucksack design still incorporates an external frame. The discrepancy in the style of frame used may be accounted for by the fact that studies conflict in their assessment of internal and external frames. While energy cost has been found to be most efficient when carrying a pack with an internal frame (Harman et al., 2000b), conflicting evidence from another study showed no significant difference in energy cost between the internal and external frame designs (Kirk & Schneider, 1992). Furthermore, preference for frame style is inconsistent. One study found that women preferred an external frame pack (Bloom & Woodhull-McNeal 1987), while another showed a division where half the women preferred the external frame with the other half preferring the internal frame (Kirk & Schneider, 1992). Furthermore, though women preferred the external frame pack, no objective reason was evident because the study found no significant difference in the center of gravity position for the internal and external frame packs (Bloom & Woodhull-McNeal 1987). Although research has not provided a clear answer, the US
military developed and is continuing to use the MOLLE rucksack system with an external frame and modular design important for allowing soldiers to carry different modules depending on the requirements of a mission. The external frame of the MOLLE allows for greater modularity but external frame packs generally weigh more than packs with an internal frame. Current internal frame recreational packs on the market weigh about 1 pound less than their external frame competition within the same capacity range (Campmor). Furthermore the empty MOLLE rucksack (8 pounds) weighs about twice that of current recreational packs of similar capacity (ranging 3.5-5 pounds) (Campmor; PM Soldier Equipment, 2007). Since the evidence is inconclusive, an internal frame rucksack, with a modular design, may allow for a lighter load without significantly affecting the energy cost or perceived discomfort. Further research is needed to examine not only the physiological effects of frame style but also biomechanical changes due to frame design.

Load Carriage Location

In addition to backpack load carriage, other methods of carrying have been explored through research in efforts to identify techniques that are the least detrimental. One study created an exoskeleton that surrounded the lower extremities in order to reduce the vertical force on the subject. However, the results showed an increase in metabolic cost in terms of oxygen consumption as well as greater trunk flexion during the trials that utilized the exoskeleton (Gregorczyk et al., 2010). Though the subjects were familiarized with the exoskeleton and given ample time to practice, moving the load to the lower extremities did not prove to be beneficial. The findings may be due in part to the idea that the feet have the
highest energy cost for load carriage when compared to other parts of the body (Soule & Goldman 1969). Additionally, using a backpack with a frame and waist strap had lower metabolic cost, oxygen consumption and heart rate, than when carrying the same load divided in separate bags on each shoulder (Legg et al., 1992). On the other hand, an investigation of load placement on energy cost found that carrying a load on the head actually proved to have the lowest cost in terms of oxygen uptake (Soule & Goldman 1969). While it may seem reasonable to find ways to move loads to the head, the findings were based on walking on flat ground and the maximum weight carried on the head was 14 kg (31 lbs) which is below the weight that soldiers typically carry. Furthermore, agility may be compromised if loads are transferred to the head. Although evidence shows that carrying a load on the head may offer benefits in terms on oxygen uptake, the currently used method for the US military of backpack load carriage is likely more reasonable and may be improved with future research.

Double Pack

The double pack, or front-back pack, is a design that incorporates two rucksack compartments where one is worn on the front of the torso and one is worn with or without a frame on the back. While the designs vary slightly, studies have investigated various effects of carrying a double pack including biomechanical (Kinoshita, 1985, Harman et al., 1994, Lloyd & Cooke 2000), physiological (Legg & Mahanty, 1985, Johnson et al., 1995), and perceptual responses (Legg & Mahanty, 1985, Johnson et al., 1995, Knapik et al., 1997). Biomechanical results for the double pack show that wearing a double pack causes less forward lean compared to a regular backpack (Kinoshita, 1985), allowing the subject to

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3 Compared to carrying various loads on the head and hands, load carriage on the feet resulted in the greatest energy (millimeters oxygen per minute) cost per kilogram total (body plus load) weight. Thus moving the load to the lower limbs could have a similar negative effect on energy cost.
adopt a more upright walking position (Harman et al., 1994). While other effects of load carriage were also present while carrying the double pack, such as increased time in double support, the gait parameters of the double pack system were closer to that of normal walking compared to a regular backpack (Kinoshita, 1985). Additionally, the double pack design has lower propulsive forces during the gait cycle which could be an advantage (Lloyd & Cooke 2000). Furthermore, the double pack design has also been perceived to be more comfortable than a traditional framed backpack (Legg & Mahanty, 1985) and has resulted in a lower incidence of blisters on long road marches (Knapik, et al., 1997). Finally, after a general review of the literature, Knapik et al. (1996) concluded that double packs have lower energy costs than regular backpacks.

Although many studies have identified benefits of distributing the load between the front and back of the torso, there are quite a few drawbacks. Fundamentally, the double pack has been reported to be difficult to don and doff (Legg & Mahanty, 1985), which could waste valuable time for soldiers in the field. Once wearing the double pack, subjects have experienced ventilatory impairment (Legg & Mahanty, 1985) and greater heat stress (Johnson et al., 1995) attributed to the weight and covering of the front pack. While the double pack resulted in less low back discomfort at high loads, the pack increased the discomfort experienced in the neck and hips (Knapik, et al., 1997). Moreover, the double pack design has also shown a negative effect on performance. March times were longer with the double pack than with a regular backpack (Johnson et al., 1995, Knapik, et al., 1997). Finally, in the field, the double pack could have negative visual and agility effects. Placing volume on the front of the body may not only reduce the ability to see the ground directly in front, but it could also decrease maneuverability (Knapik et al., 2010). Despite the fact that many studies mention the practical limitations of a double pack, moving load to
the front of the torso appears to be beneficial. Perhaps the solution is a system that allows for high weight, low volume objects to be carried on the front, allowing for more even weight distribution, while placing large volume on the back. Though a new design could reduce visual impairment by reducing volume, ventilatory impairment may persist. Furthermore, female response to greater pressure on the chest and breasts must be evaluated, as this pressure may cause increased pain.

Vest

A vest, designed for load carriage, is worn as an item of clothing that has pockets to hold equipment and does not utilize a frame. Using a vest as a primary load carriage system or as part of an integrated system can allow for weight to be distributed more evenly about the torso than a backpack alone. The distribution of weight about the trunk in a vest style structure has been rated as more comfortable than a standard backpack with or without a frame (Legg & Mahanty, 1985). The US military uses a method that incorporates vests which hold not only bullet resistant plates, but also various tools or ammunition. Knapik et al. (2010), in a review of the literature, discusses how a vest with pockets can provide some of the benefits of wearing a double pack without having the bulkiness that reduces agility. Unfortunately, a vest alone is not likely to be able to carry the full volume and weight needed for a military mission. Therefore, US soldiers carry a rucksack in addition to wearing various vests. Although the effects of wearing various vests with a rucksack are not well known, Reid et al. (2006) layered tactical and bullet resistant vests under a rucksack to examine the effects on skin pressure. Although the study used only a 50th percentile male manikin and all tests were static, the findings show the importance of the vest design. The study shows that the addition of the vest with bullet resistant plates, or body armor, not only increases skin pressure through added weight, but also pushes the mass of the
rucksack posteriorly, requiring a greater moment to maintain position (Reid et al., 2006). Additionally, the peak skin pressures found when wearing the vest with bullet resistant plates were located at the edges of the plates where the load caused the plate to dig into the body. This not only identifies a negative interaction between the plates and the rucksack, but also a potential flaw in the individual designs. Finally, the study discussed how the shoulder straps migrated laterally due to the additional bulk in the shoulder region (Reid et al., 2006). This lateral migration of the shoulder straps has been identified as an issue in female soldiers (Group Interview, November 20, 2013). Even with the negative effects, the vest system does offer necessary safety and utility to the soldier. Thus, more research should be conducted to optimize the design not only of the vest, but also to create a positive integration of the vest with the rucksack.

**Suspension System**

The suspension system of a rucksack consists of the waist belt, shoulder straps, and chest straps and considers the attachment location to the frame or rucksack. Shoulder straps are fundamental characteristics of rucksacks, yet their design has not been fully developed. Specifically, women have recognized issues with the fit of shoulder straps ranging from the attachment location to the straps not holding after adjustments (Harper et al., 1997). While the shoulder straps need individual improvement, it is important to remember that they interact with the entire suspension system as well. Perceived discomfort has also been an issue for women considering the fit of the frame, as the frame has been reported to be too long and too wide (Harper et al., 1997). In an effort to remove stresses, Clarke (1955) created an experimental pack that included a hip belt. The pack design with the waist belt resulted in the least muscular strength loss as well as the least muscular fatigue (Clarke, 1955). Though a waist belt and frame are utilized, the shoulders still support a
considerable portion of the load, notably when using the ALICE frame (Harman et al., 2000a). On the MOLLE rucksack, the use of a waist belt and frame allow the hips to bear 30% of the vertical force while 70% remains on the shoulders (Lafiandra & Harman, 2004). The addition of a waist strap in conjunction with a frame clearly allows for some force to be transferred from the shoulders to the waist. Furthermore, Hollins (2012) found that wearing a chest strap had less negative effects on physiological measures and reduced the perceived discomfort compared to not wearing a chest strap. The style of the chest strap does not appear to be important as long as a chest strap is worn. Therefore, future research should focus on optimizing the design of the shoulder and waist straps, as well as the frame.

In addition to human subject studies, models have been created that generate insights for design of various suspension system components. One study allowed for stiffness and dampening of the backpack’s suspension system (shoulder straps and waist belt) to be inputs while inverse dynamics was utilized to find reaction forces (Ren et al., 2005). The results suggest that a more compliant suspension system would reduce the peak vertical forces on the torso. Ren et al. (2005) also notes that a more compliant pack could affect the balance and agility of the wearer, though that may be mitigated with the proper combination of compliance and dampening. Nevertheless, the human-backpack model was created using only one subject’s measured gait mechanics carrying a 10 kg backpack. Further testing is needed to know if the idea of a more compliant suspension system would be beneficial to various body types, gaits, and increased loads. Another study, using a 50th percentile male torso, tested various vertical and horizontal locations for attachment of the bottom of the shoulder strap (Reid et al., 2001). A strap angle (Figure 3.1) ranging from 24 to 30 degrees was found to be optimal, in terms of shoulder and armpit pressure, for the shoulder strap with an attachment point just posterior to the body midline at the height of
the iliac crest (Reid et al., 2001). Although the study was only static and no human subjects were involved, the torso was given a forward trunk flexion of 4.6 degrees to mimic the patterns of human load carriage.

Design features of a rucksack can influence the load distribution, the resulting biomechanical effects, and the perceived discomfort. This investigation comprises various features which have been previously studied including frame use and design, various distributions of the weight about the body, and the effects of changing the suspension system comprised of shoulder, waist and chest straps. Although large steps have been made in furthering the design of the rucksack, there is still much room for future research to truly optimize the design in order to reduce negative biomechanical and physiological effects as well as increase utility and comfort for both men and women.

Figure 3.1: This figure describes how the strap angle was found for various horizontal and vertical attachment locations (Reid et al., 2001).
Chapter 4. Analysis of MOLLE IV Frame Design

Throughout history militaries have used varying methods of moving equipment beginning with horses and carts and eventually transitioning to individual load carriage using shoulder bags or rucksacks (Knapik et al., 2010). The US military's first framed rucksack was the All Purpose Lightweight Individual Carrying Equipment (ALICE) which consisted of a small external frame. The ALICE was improved through iterations of design and material improvements and is still used by some soldiers 40 years after its initial introduction in the 1970s (Sampson, 2001). In 1990, the Army adopted a new internal frame backpack that mimicked design features adopted from industry. However, this design was rescinded only 3 years later due to basic design flaws including the pack being too warm against the back in warm weather and feeling unstable or uncomfortable under heavy loads (Sampson, 2001). The internal frame allows the pack to rest closer to the back, which studies, mentioned previously, have shown to be beneficial because the center of mass of the pack is closer to the body’s center of mass. In this case, it also proved to cause greater heat stress because there was no space to allow the back to ventilate. In response, the Army began designing the pack that is currently used, the Modular Lightweight Load-carrying Equipment (MOLLE), which was released in 2001 and continues to hold the title of the Army's standard load-carrying equipment (Polcyn et al., 2002). Similar to the ALICE, the MOLLE has undergone design iterations since its release, especially in regard to the external frame. The frame was reinforced with greater material presence in some areas and made
with a more durable polymer. The rucksack and current frame model is the MOLLE IV and is shown in Figure 4.1. Although the MOLLE was released and has been improved, some soldiers still prefer the smaller frame and more slender rucksack shape of the ALICE (Group Interview, November 20, 2013).

A meeting was organized with four female ROTC cadets at Ohio State University with the intent of discovering the benefits and detrimental attributes of the ALICE and the MOLLE rucksack designs specifically from the viewpoint of women. Each of these women had 3-4 years of ROTC experience and had carried both the ALICE and the MOLLE throughout their training. They commonly carry 35-45 pound loads and distances could range from 3-7 miles for a typical training march. The following ideas were discussed during the meeting.

Figure 4.1: These photos show the US Military’s current load carriage frame, the MOLLE IV (left), and an outfitted soldier carrying the MOLLE IV rucksack (right).
with the aim of discovering potential areas of improvement and ways to better tailor rucksack design, specifically suspension system design, to better fit female soldiers. When donning either the MOLLE or ALICE rucksack it was evident that the four women adopted the same technique for tightening the shoulder straps: the straps were made very tight so they wouldn’t slide laterally off the shoulders. The chest strap, which could also help keep the shoulder straps together, was only consistently worn by one of the women. Likely due to the extreme tightening of the shoulder straps, the women reported experiencing pain in the shoulders with the ALICE rucksack specifically, which has narrow straps. Thus, they preferred the wider and more padded shoulder straps of the MOLLE design. On the other hand, the smaller frame of the ALICE was preferred over the MOLLE by three of the four women. The MOLLE rucksack frame spanned the distance from the sacral curve to the height of the occipital protuberance for the shorter women (5 feet, 2-3 inches), which interfered not only with their gait but also with visibility. Visibility was inhibited because the pack blocked the ability to see posteriorly when the head was turned as the pack interfered with the helmet when worn. The tallest female (5 feet, 11 inches) felt that the size of the MOLLE was appropriate. The waist strap was worn by all the women though only three of the four women utilized the waist strap consistently. These three women all preferred the padding of the MOLLE waist strap over the ALICE and felt that the MOLLE better distributed the weight to the waist. Overall, the four women agreed on the desirability of the wider, padded shoulder and waist straps of the MOLLE, with a smaller frame similar in size to the ALICE, while maintaining the weight distribution of the MOLLE. In fact, one participant suggested a smaller version of the current frame would be better suited for shorter people. Further research and design iterations are needed to create a design that is suitable to smaller, female soldiers and potentially smaller, male soldiers.
4.1 Rucksack Integration with MOLLE Equipment System

The MOLLE rucksack is just one component within the entire MOLLE equipment system. Any future design changes must consider the interdependencies among the various parts of the soldier’s clothing, equipment, and protective gear. While the group interview generated a plethora of ideas and starting points for improving the suspension system design, it is crucial to gain a full understanding of the system before moving forward with changes. Figure 4.2 illustrates the standard equipment worn by soldiers in the field, including combat uniform, helmet, gloves, elbow and knee pads, body armor, load carrying vest, and the full MOLLE rucksack. For a mission in which this equipment is worn, the greatest variation comes from the **Fight Load Carrier** vest. The vest is modular and can be equipped with pouches for varying uses depending on the needs of the soldier in combat since the rucksack would be dropped under fire thus everything needed to fight must remain on the soldier. Figure 4.3 shows 5 common configurations for the fighting load carrying vest as well as the attachment technique to show the modularity. The load carrier vest, independent of the configuration of pouches, does not interfere with the waist belt of the rucksack. Similarly, the **Ballistic** vest is also sized such that it does not extend low enough to interfere with the waist belt. Alternatively, both of the vests cross the shoulders and therefore interact with the shoulder straps of the rucksack. Two methods are adopted depending on the breadth of the shoulder: (1) for wider shoulders the shoulder straps rest outside the top of the vest and (2) with narrow shoulders the shoulder straps overlay the vest (Personal Communication, Tim Ruffing and discussion with female cadets). Both of these methods can create localized pressure, pinching, or bruising. Thus, this interface must be considered when reviewing the design of the shoulder straps. The chest strap,
Figure 4.2: This chart shows the standard equipment utilized for field operations.
Figure 4.3: The attachment method for various pouches is shown at the top left. Five common configurations for the Fighting Load Carrier vest are shown with the description of the pouches utilized just above the drawing. (MOLLE Use care)
when worn, must cross not only the chest but also the additional volume created by the ballistic and load carrying vests. As long as the chest strap spans the distance between shoulder straps, the design of the chest strap was found not to matter, as discussed previously (Hollins, 2012).

Finally, the actual plastic polymer frame design, molded with a high strength flexible thermoplastic (Patent #7644847), interacts with both of the vests and is the attachment point for the shoulder straps and waist belt. The thickness of the waist belt pushes the lower portion of the frame off the back and provides cushioning for weight to be distributed through the frame. Additionally, the thickness on the posterior side of the ballistic vest also pushes the frame away and provides a consistent back shape, though the size varies depending on the size of the ballistic plates (small, medium, or large). With an understanding of the suspension system’s interactions with the MOLLE equipment, it is possible to move forward with understanding the anthropometric considerations used or overlooked in this design.

*Adjustability of MOLLE Equipment.* The current MOLLE equipment system has adjustability features incorporated to account for varying sizes of soldiers. This section investigates how this adjustability works as well as the benefits and detriments of the features. All of the straps can be adjusted for length in order to fit around the shoulder, chest, and waist of the soldiers. Additionally, the vertical position of the waist belt and the shoulder strap attachments can be altered to account for shorter torsos. The adjustments are outlined in Figure 4.4. Although these modifications can be made to better fit the shoulder and waist straps to the length of the torso, the length of the frame is not actually changing. Therefore, if the waist belt is raised with respect to the frame, this indicates that the frame is
Figure 4.4: The attachment location for the waist belt (A) and shoulder straps (B) can be adjusted as suggested by the MOLLE Usecare guidelines (MOLLE Usecare).
shifted down with respect to the body. Similarly, if the shoulder strap attachments are lowered on the frame, then the frame is shifted up with respect to the body. Finally, if both of these adjustments are needed to account for very low percentile torso lengths, the length of the frame would have excess extension superior to the shoulders and inferior to the waist belt. These concepts are depicted in Figure 4.5. While the fit of the rucksack suspension system increases by adjusting the attachment locations of the waist belt and shoulder straps, the frame extension could cause negative effects. If the frame extends further below the waist belt, it could interfere with gait as noted during the discussion with female cadets who discussed the disturbance in walking due to the rucksack extending too low. Meanwhile, if the frame extends further above the shoulder straps, it may interfere with the soldier’s helmet and vision. Therefore, further investigation into the design of the suspension system and the anthropometry of soldiers is needed to create a better adapted design for female soldiers and potentially small, male soldiers.
Figure 4.5: Figure (A) shows the MOLLE IV rucksack suspension system prior to adjustment of the waist belt or shoulder strap attachment locations on a female who is 20th percentile in stature. The additional photos demonstrate the adjustability of the waist belt (B), the shoulder straps (C), and both (D). Note: In all of the photos, the rucksack was positioned such that the top of the waist belt was at the level of the navel.
4.2 Anthropometric Considerations for Rucksack Design

Although the tactical vest with ballistic inserts and the fighting load carrier vest worn underneath the rucksack affect the shape of the soldier, there are a few anthropometric features that are not changed by the equipment and vary greatly between men and women: shoulder width, hip breadth (and shape), and torso length. Men are generally taller with wider shoulders while women are generally shorter in stature with wider hip breadth (Gordon et al., 1989). Table 4.1 details some anthropometric measurements that would be useful in the design, or redesign, of a rucksack suspension system. It is evident through just the measurements listed that males and females differ greatly in various body measurements. Figure 4.6 further illustrates this difference in anthropometry between males and females by comparing scaled body outlines with the MOLLE rucksack frame. This

<table>
<thead>
<tr>
<th>Anthropometric Measurement</th>
<th>10th %ile Female</th>
<th>50th %ile Female</th>
<th>50th %ile Male</th>
<th>90th %ile Male</th>
</tr>
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<tr>
<td></td>
<td>cm</td>
<td>in.</td>
<td>cm</td>
<td>in.</td>
</tr>
<tr>
<td>Biacromial Breadth</td>
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<td>13.4</td>
<td>36.30</td>
<td>14.29</td>
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<tr>
<td>Shoulder Length</td>
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<td>5.14</td>
<td>14.47</td>
<td>5.70</td>
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<tr>
<td>Chest Depth</td>
<td>21.43</td>
<td>8.44</td>
<td>23.74</td>
<td>9.35</td>
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<tr>
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<td>32.72</td>
<td>90.09</td>
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<tr>
<td>Hip Breadth</td>
<td>31.47</td>
<td>12.39</td>
<td>34.15</td>
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<tr>
<td>Waist Breadth</td>
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<tr>
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<tr>
<td>Waist-Back Length</td>
<td>39.75</td>
<td>15.65</td>
<td>42.53</td>
<td>16.74</td>
</tr>
</tbody>
</table>

Note: Chest Depth and Chest Circumference include the breast and are measured at the height of the bustpoint on women and at the nipple on men.
section investigates how these measurements should be used to create a design that would better suit the female body.

*Biacromial Breadth and Shoulder Length* The distance between the right and left acromion landmarks defines the biacromial breadth. The shoulder length measures from the trapezius landmark at the base of the side of the neck to the acromion landmark (Gordon et al., 1989). These measurements of shoulder width are useful in the design of the shoulder straps as well as the frame. First, the width of each strap must be wide enough to distribute pressure but narrow enough to avoid interference with the vests worn underneath. Alternatively, the shoulder strap could be designed to overlay the vest straps, a design in
which the interdependence between elements is sought after rather than avoided. Importantly, the strap must fit within the shoulder length of the soldier. Furthermore, the distance between the straps must allow for both straps to rest on the shoulders without extending beyond the acromion landmark. The biacromial breadth varies between men and women (50th percentile male measures 1.3 inches greater than the 50th percentile female), Table 4.1, thus the shoulder straps in combination with the frame should allow for adjustability in the distance between straps or multiple sizes.

*Chest Depth and Chest Circumference* As noted in Table 4.1, the chest depth and chest circumference include the breast and are measured at the height of the bust point on women and the nipple on men (Gordon et al., 1989). These two measures together help define the shape of the chest and it is important to note the difference in the shape between men and women. Although the chest depth measures are roughly the same for the 50th percentile male and female, the chest circumference, measured at the same location, are quite different with males having a greater chest circumference. This indicates a difference in body shape, in that women have a larger depth to circumference ratio. The difference should be considered when designing the shoulder and chest straps. Furthermore, the added thickness and shape of the tactical and bullet resistant vests needs to be considered in conjunction with these anthropometric measures. While the shoulder straps need to allow for the depth of the chest, the width of the straps distributes the pressure differently for various chest shapes, creating a potential need for multiple strap shapes or sizes. Additionally, the connection points on the frame for the shoulder straps need to be considered to create an optimal strap angle as discussed previously (Reid et al., 2001) because the shape of the chest could affect the angle. Finally, the variance in chest
circumference measures in conjunction with the shoulder strap design can influence the adjustability needed in the chest strap.

_Hip Breadth, Waist Breadth, and Waist Circumference_ The waist circumference, measured at the level of the navel, the waist breadth, and the hip breadth provide a few reference geometries for the shape of the waist and hips (Gordon et al., 1989). These measures are important to the design of the shape, size, length, and adjustability in the waist belt. Additionally, the angle that the waist belt adopts should be compatible with the body shape. Comparing hip to waist size, females have a higher ratio of hip to waist measures, indicating a difference in angle in the pelvis region. Thus, it may be beneficial to angle the waist strap for females such that the superior end of the belt rests more medially than the inferior end of the strap. This idea is shown in Figure 4.7. While this technique is used in industry, it has not been adopted for military rucksack design. In all, it is important to consider the shape of the body over which the waist strap will cover in addition to the length and adjustability.

![Figure 4.7: This sketch demonstrates the idea of creating a waist strap that encircles the body at greater angle from the vertical for women (left) when compared to men (right) to account for the difference in body shape. The thick lines at the height of the navel represent the angle for the waist strap. (Body Images: Deposit Photos)](image-url)
**Waist-Back Length**  The waist-back length measures the distance from the cervical landmark (C7 spinous process) on the back of the neck to the posterior level of the navel (Gordon et al., 1989). The data in Table 4.1 shows the variation in this length between men and women (50th percentile male measures 1.4 inches greater than the 50th percentile female). This measure is important when integrating the shoulder straps and waist strap designs into the frame. The distance from the top of the shoulder straps to the top of the waist belt must span this back length measure. However, simply allowing for adjustment along the length of the frame may not be sufficient as discussed in the group discussion, where it was noted that the frame may extend beyond the torso length for shorter soldiers. Therefore, multiple frame sizes may be necessary to provide proper attachment locations without inhibiting gait or vision. Length sizes could benefit not only women but also men who are smaller in torso length.

The anthropometric considerations discussed are fundamental, though not exhaustive, measures needed for appropriate design of a rucksack suspension system. Additional measurements could be utilized in order to better fit the suspension system to the user and design for various shapes and sizes of male and female soldiers.
A finite element model was created using ANSYS 14.5 to investigate the effects of various anthropometric differences on the weight distribution of the MOLLE suspension system. Utilizing software to analyze the effects of a rucksack suspension system requires the use of geometry and a number of simplifications to represent the female body. Additionally, the model of the frame used has been simplified to a two-dimensional (2D) model with only features which are utilized by the suspension system or rucksack attachment. The general geometry of the MOLLE IV frame, designed in English units, was traced from a photograph within SolidWorks then refined with measurements from a physical frame. The height, width, and size and location of attachment points were all measured in inches and applied to the frame. Figure 4.8 shows the simplified MOLLE frame model that was created. A more

\[ \text{Figure 4.8: This figure shows the simplified MOLLE frame used for the finite element analysis to investigate load distribution. Symmetry was utilized in the model, thus the model on the right was imported into ANSYS.} \]
complex three dimensional model is not necessary for the current scope of investigation because it is known that the current frame is durable in the field, while the purpose of the 2D model is to examine the load distribution on various anthropometries. Using the simplified model geometry and anthropometric measures for the female body, the suspension system and rucksack will be represented using a combination of forces for the rucksack and elements that sense axial forces for the shoulder and waist straps.

Shoulder Straps The shoulder straps have been represented using a number of vectors based on anthropometric measures and the geometry of the frame. As seen in Figure 4.9, symmetry has been utilized to simplify the model. The goal of this model is to explore the differences in load distribution caused by various anthropometric sizes. Three anthropometric measures were utilized to calculate the angles of the force vectors which represent the shoulder strap attachment to the frame: shoulder breadth, waist-back length, and chest depth. The 10th and 90th female percentile values for these three measures, see Table 4.2, were crossed to create eight different models (combinations of $\theta_1$, $\theta_2$, $\theta_3$) because no single person fits to the same percentile for all anthropometric measures. Further explanations of the measures used are in Table 4.2. Other models were created to allow basic comparison between male and female anthropometric differences. Using the same anthropometric calculations discussed, models for 50th percentile female, 10th percentile male, 50th percentile male, and 90th percentile male were generated (all measures are listed in Table 4.3). Geometric drawings and calculations can be found in Appendix B and the resulting angles are in Table 4.4 for the eight models comparing female size variations and Table 4.5 for the four other models. Finally, the inferior end of the shoulder strap, connecting to the frame at waist level, was held constant at 30°, Figure 4.9, previously found to be an optimal value (Reid et al, 2001).
Figure 4.9: The figures above show the geometry used to represent the shoulder straps. The simplified frame model overlays the female body images and the angles are shown. The angles in the superior view (left) are on the transverse (XZ) plane and the angles in the side view (right) are on the sagittal plane. Variables are defined in Table 4.2. (Body Images: FindLaw; Shutterstock)
### Table 4.2: Details for the anthropometric measures used are listed for the calculation of the respective angles. Details are from Gordon et al. (1989).

<table>
<thead>
<tr>
<th>Anthropometric Dimension</th>
<th>Model Variable (Figure 4.8)</th>
<th>Description</th>
<th>Used to Find</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Length</td>
<td>s</td>
<td>Biacromial breadth is the distance between the right and left acromion landmarks and shoulder length measures from the trapezius landmark at the base of the side of the neck to the acromion landmark. s is half of the biacromial breadth (symmetry) minus half of the shoulder length (indicates that the center of the shoulder strap rests in the center of the shoulder length).</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>Chest Depth</td>
<td>d</td>
<td>Chest depth includes the breast and is measured at the height of the bust point on women and the nipple on men. d is half of the chest depth measure which gives the location where the shoulder straps and load lifting straps meet on the top of the shoulder.</td>
<td>$\theta_1, \theta_2, \theta_3$</td>
</tr>
<tr>
<td>Waist-Back Length</td>
<td>l</td>
<td>The vertical distance from the cervical landmark to the posterior level of the navel (l). The posterior level of the navel coincides vertically with the height connection point on the frame where the lower shoulder strap and waist belt connect.</td>
<td>$\theta_2, \theta_3$</td>
</tr>
</tbody>
</table>

### Table 4.3: Anthropometric measures used for the calculation of the respective angles for all models are listed. Values extracted from Gordon et al. (1989).

<table>
<thead>
<tr>
<th>Anthropometry</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10th Percentile</td>
<td>50th Percentile</td>
</tr>
<tr>
<td>Shoulder Length, inches</td>
<td>4.13</td>
<td>4.295</td>
</tr>
<tr>
<td>Chest Depth, inches</td>
<td>4.22</td>
<td>4.675</td>
</tr>
<tr>
<td>Waist-Back Length, inches</td>
<td>15.65</td>
<td>16.74</td>
</tr>
</tbody>
</table>
Table 4.4: Angles calculated from the discussed geometry for the eight models of varied combinations of female anthropometric percentiles.

<table>
<thead>
<tr>
<th>Female Anthropometric Measure (Percentile)</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Length</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Chest Depth</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Waist-Back Length</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>90&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Model Angles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ&lt;sub&gt;1&lt;/sub&gt;</td>
<td>19.50&lt;sup&gt;o&lt;/sup&gt;</td>
<td>19.50&lt;sup&gt;o&lt;/sup&gt;</td>
<td>15.80&lt;sup&gt;o&lt;/sup&gt;</td>
<td>15.80&lt;sup&gt;o&lt;/sup&gt;</td>
<td>13.30&lt;sup&gt;o&lt;/sup&gt;</td>
<td>13.30&lt;sup&gt;o&lt;/sup&gt;</td>
<td>10.70&lt;sup&gt;o&lt;/sup&gt;</td>
<td>10.70&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
<tr>
<td>θ&lt;sub&gt;2&lt;/sub&gt;</td>
<td>70.73&lt;sup&gt;o&lt;/sup&gt;</td>
<td>100.4&lt;sup&gt;o&lt;/sup&gt;</td>
<td>74.39&lt;sup&gt;o&lt;/sup&gt;</td>
<td>98.35&lt;sup&gt;o&lt;/sup&gt;</td>
<td>70.73&lt;sup&gt;o&lt;/sup&gt;</td>
<td>100.4&lt;sup&gt;o&lt;/sup&gt;</td>
<td>74.39&lt;sup&gt;o&lt;/sup&gt;</td>
<td>98.35&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
<tr>
<td>θ&lt;sub&gt;3&lt;/sub&gt;</td>
<td>64.36&lt;sup&gt;o&lt;/sup&gt;</td>
<td>44.63&lt;sup&gt;o&lt;/sup&gt;</td>
<td>69.02&lt;sup&gt;o&lt;/sup&gt;</td>
<td>51.00&lt;sup&gt;o&lt;/sup&gt;</td>
<td>64.36&lt;sup&gt;o&lt;/sup&gt;</td>
<td>44.63&lt;sup&gt;o&lt;/sup&gt;</td>
<td>69.02&lt;sup&gt;o&lt;/sup&gt;</td>
<td>51.00&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Table 4.5: Angles calculated from the discussed geometry for the four models that are based on consistent percentiles for each anthropometric measure. The percentile indicated was used for the shoulder length, chest depth, and waist-back length measures for the respective model.

<table>
<thead>
<tr>
<th>Model 9 50&lt;sup&gt;th&lt;/sup&gt; Percentile Female</th>
<th>Model 10 10&lt;sup&gt;th&lt;/sup&gt; Percentile Male</th>
<th>Model 11 50&lt;sup&gt;th&lt;/sup&gt; Percentile Male</th>
<th>Model 12 90&lt;sup&gt;th&lt;/sup&gt; Percentile Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ&lt;sub&gt;1&lt;/sub&gt;</td>
<td>15.88&lt;sup&gt;o&lt;/sup&gt;</td>
<td>9.12&lt;sup&gt;o&lt;/sup&gt;</td>
<td>6.45&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
<tr>
<td>θ&lt;sub&gt;2&lt;/sub&gt;</td>
<td>85.29&lt;sup&gt;o&lt;/sup&gt;</td>
<td>101.80&lt;sup&gt;o&lt;/sup&gt;</td>
<td>112.67&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
<tr>
<td>θ&lt;sub&gt;3&lt;/sub&gt;</td>
<td>56.32&lt;sup&gt;o&lt;/sup&gt;</td>
<td>46.67&lt;sup&gt;o&lt;/sup&gt;</td>
<td>43.01&lt;sup&gt;o&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Waist Belt  Due to the complex interaction between the waist belt size, shape, and fit with the female body, the waist belt connection to the frame was simplified in the model. As seen in Figure 4.10, straps loop through the lateral holes of the frame and pull medially toward the posterior center of the waist belt. This force vector would also create force vertically against the frame as weight is transferred through the belt to the frame. However, the amount of load the waist supports is more complex than can be represented within this model. Thus, an assumption has been used to estimate the direction of force acting on the frame. As Figure 4.10 shows, the waist belt frame connection points are represented
at a 45° angle in the frontal plane. Additionally, shown in Figure 4.10, horizontal elements are included at the same level of attachment to account for the horizontal force that the body imparts through the low back region onto the waist belt. These horizontal elements are in the sagittal plane.

*Rucksack* The weight of the rucksack was set to 40 pounds, a common weight discussed during the group interview (20 pounds is shown in Figure 4.11 due to symmetry). Figure 4.11 shows that the weight is not only distributed between the connection locations to the frame, but is also set away from the frame to account for the moment created by the volume of the rucksack. The load has been applied 0.2 meters (7.87 in.) posteriorly based on a

![Diagram of rucksack and MOLLE frame](Image)

*Figure 4.11:* This figure shows the front and side views of the MOLLE frame with the geometry representing the rucksack load. The distance shown on the side view corrects for the moment caused by the volume of the rucksack. (Body Image: Shutterstock)
study by Hasselquist et al. (2004) which measured the center of mass of soldier-packed rucksacks.

A summary of the elements representing the shoulder straps, waist belt, and rucksack are shown in Figure 4.12 with a photo image of the MOLLE IV rucksack suspension system. The elements are labeled with the variable names used within the finite element model.

![Figure 4.12: This figure illustrates the elements representing the shoulder straps (TS1, TS2, TS3 are the load lifter, superior shoulder strap, and inferior shoulder strap respectively) and the waist belt (TW1, TW2, TW3, TW4 are the inferior and superior frontal plane waist belt and inferior and superior sagittal plane waist belt attachments respectively). The applied rucksack load is shown as four 5 pound forces with 20 total pounds shown due to symmetry (representing a total load of 40 pounds).]
4.4 Model Description

The purpose of this model is to investigate the change in force distribution of the suspension system as the anthropometric measures of females and males vary under the load of a 40 pound MOLLE rucksack. The simplified MOLLE frame (Figure 4.8) was created in SolidWorks 2012 and then imported into ANSYS 14.5 for analysis.

Elements. The analysis was completed using three types of elements. The frame was meshed with 0.18 inch length quadratic triangular shell elements of a single 0.25 inch thick layer. In all, the frame was comprised of about 7800 elements in total. The suspension system was depicted with seven elements representing the shoulder and waist strap interactions with the frame as previously discussed. These were created as truss elements with a 1 inch cross-sectional area. The direction of the two superior elements (top two solid elements in Figure 4.13), were varied as θ₁, θ₂, and θ₃ changed based on the anthropometric measures discussed. Finally, the rucksack load was represented with a removed load from the frame at the four connection locations as discussed. These four loads were removed using separate beam elements of 1 inch cross sections with load applied at the posterior end. The truss and beam elements are outlined in Figure 4.13 and the actual ANSYS model is depicted in Figure 4.14.

Materials. Since the actual composition of the frame is considered proprietary information by the manufacturer, the frame was assumed to be made of high impact polystyrene (HIPS). Material properties for HIPS included a Young’s modulus (elastic modulus) of 2.7*10⁵ psi (1.9 GPa), a Poisson’s ratio of 0.41, and ultimate tensile strength of 4.6*10³ psi (Make It From). Secondly, the truss and beam elements representing the suspension system and rucksack load were created to be essentially rigid when compared to the frame in order to
maintain the geometric vectors. Thus, these elements were assigned the material properties of titanium (Young's modulus of $1.6 \times 10^6$ psi and Poisson's ratio of 0.33).

**Loading and Boundary Conditions.** Because symmetry was utilized to simplify the analysis, additional boundary conditions were applied to the frame, Figure 4.13. Along the line of symmetry (cut in the YZ plane), translation into the plane (UX) and rotation about the line (ROTY) were set to zero. Next, for the truss elements, representing the shoulder and waist strap interactions, the nodes at the end not attached to the frame were constrained such that all degrees of freedom were set to zero. Furthermore, the load of the rucksack was applied to the node at the free end of the beam element such that each of the four attachment locations held 5 lbs of force (total of 20 lbs applied). Finally, to reduce the artificially high stresses caused by the point load of the beams, each of the 5 lb forces was divided between seven different nodes and beam elements surrounding the respective attachment location.
Figure 4.13: This figure illustrates the elements and boundary conditions used for the model. Image (A) shows the labeled truss elements representing the shoulder straps (solid) and the waist belt (dashed). The nodes (rounded) at the end of the elements had all degrees of freedom set to zero. Image (B) details the symmetry boundary conditions and rucksack loads applied (bold). The rucksack load at each attachment point was divided among seven nodes.
4.5 Results of Model

Using the model, the frame was loaded and suspended at angles that simulate how the shoulder and waist straps would adapt to various anthropometric percentile measures of female and male soldiers. All boundary conditions and the applied load for the full ANSYS model are shown in Figure 4.14 where the various elements are shown in different colors (frame=shell=blue, suspension system=truss=purple, and rucksack loads=beam=red). The first eight models listed in Table 4.6 are the full factorial analysis of the 10th and 90th percentile measures of shoulder breadth, chest depth, and waist-back length for females. The final four models use the same percentiles for the three anthropometric measurements which are 50th percentile female, 10th percentile male, 50th percentile male, and 90th percentile male. After the static simulation was complete, the axial force in each of the seven suspension system elements (labeled in Figure 4.13, A) was extracted. Table 4.6 lists the axial forces found for models examined. The load distribution remains fairly consistent between the various models, though the magnitudes change.

The maximum stresses on the frame for all models were concentrated at the point locations of the force (Figure 4.13, B). All models had a peak stress magnitude below 4000 psi. Although these stresses are artificially high due to point loading, they remained below the ultimate tensile strength of 4.6*10^3 psi for the high impact polystyrene (Make It From). Figure 4.15 plots the y-component of stress on the frame for Model 3.

The maximum displacement of the frame occurs in the z-direction (anterior-posterior) with the medial edge (along the line of symmetry of the frame) pushed posterior a maximum distance of 0.18 inches and the lateral edge pulling anterior a maximum of 0.12 inches. Both
of these displacements occur at the superior end of the frame and are plotted, Figure 4.16.

The first three elements listed in Table 4.6 are the load lifter, the superior shoulder strap, and the inferior shoulder strap. The load lifter and the inferior shoulder strap elements hold the greatest tensile forces of all the elements, while the superior shoulder strap is shown to be in compression (indicating slack in the strap which is discussed later). The next two elements are the waist belt lifters inferior and superior attachments. The superior waist belt lifter is close to zero while the inferior waist belt lifter holds a tensile load.

Finally, the inferior and superior waist belt posterior body compressive forces are listed. While there is load attributable to both the inferior and superior attachment locations, the compressive load is higher in magnitude for the inferior element than the superior element.
Figure 4.15: The figure plots the y-component of stress on the frame for Model 3. Units are psi.

Figure 4.16: This figure plots the z-component of displacement of the frame for Model 3. All units are inches.
Table 4.6: Resulting axial forces (lbs) extracted for all of the models examined. The anthropometric percentiles are listed for reference and the first 8 models are female.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
<th>Model 9</th>
<th>Model 10</th>
<th>Model 11</th>
<th>Model 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90th %ile Male</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
<td>50th %ile Female</td>
<td>10th %ile Male</td>
<td>50th %ile Male</td>
<td></td>
</tr>
<tr>
<td>Back Length Percentile</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element Results (model element number)</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
<th>Model 9</th>
<th>Model 10</th>
<th>Model 11</th>
<th>Model 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1 - Load lifter (7814)</td>
<td>12.31</td>
<td>11.86</td>
<td>11.87</td>
<td>11.58</td>
<td>11.96</td>
<td>11.50</td>
<td>11.34</td>
<td>11.50</td>
<td>11.31</td>
<td>11.40</td>
<td>12.01</td>
<td></td>
</tr>
<tr>
<td>TS2 - Superior Shoulder Strap (7815)</td>
<td>-5.21</td>
<td>-6.68</td>
<td>-5.05</td>
<td>-6.06</td>
<td>-5.21</td>
<td>-6.69</td>
<td>-5.05</td>
<td>-6.06</td>
<td>-5.66</td>
<td>-5.93</td>
<td>-6.47</td>
<td>-6.90</td>
</tr>
<tr>
<td>TS3 - Inferior Shoulder Strap (7816)</td>
<td>23.54</td>
<td>20.69</td>
<td>22.57</td>
<td>20.29</td>
<td>23.70</td>
<td>20.84</td>
<td>22.70</td>
<td>20.41</td>
<td>21.87</td>
<td>22.09</td>
<td>20.42</td>
<td>19.03</td>
</tr>
<tr>
<td>TW1 - Waist Belt Lift Inferior Attachment (7817)</td>
<td>7.96</td>
<td>7.00</td>
<td>7.60</td>
<td>6.83</td>
<td>7.92</td>
<td>6.951</td>
<td>7.56</td>
<td>6.79</td>
<td>7.35</td>
<td>7.36</td>
<td>6.76</td>
<td>6.26</td>
</tr>
<tr>
<td>TW2 - Waist Belt Lift Superior Attachment (7818)</td>
<td>0.125</td>
<td>-0.182</td>
<td>-0.0394</td>
<td>-0.285</td>
<td>-0.022</td>
<td>-0.330</td>
<td>-0.157</td>
<td>-0.403</td>
<td>-0.133</td>
<td>-0.206</td>
<td>-0.458</td>
<td>-0.655</td>
</tr>
<tr>
<td>TW4 - Waist Belt Posterior Body Superior (7823)</td>
<td>-6.19</td>
<td>-4.77</td>
<td>-5.69</td>
<td>-4.56</td>
<td>-6.27</td>
<td>-4.85</td>
<td>-5.76</td>
<td>-4.62</td>
<td>-5.35</td>
<td>-5.47</td>
<td>-4.63</td>
<td>-3.93</td>
</tr>
</tbody>
</table>
4.6 Discussion of Results

*Female Variations.* The greatest variations in element forces occur in the inferior shoulder strap (TS3) and the posterior waist belt superior (TW4), with a range of 3.4 and 1.7 pounds, respectively. The least variation was seen in the posterior waist belt inferior (TW3), with a range of only 0.01 pounds. Thus, it appears that the posterior waist belt superior (TW4) accounts for nearly all of the variation in the pressure exerted on the low back through the waist belt attached to the frame (TW3 and TW4). While this may lead to the assumption of an over-designed system, this model is only static and it is likely that the loading patterns would be different when tested dynamically. The inferior shoulder strap (TS3) upon initial investigation appears to hold greater loads when the waist-back length is set to the 10th percentile and lower loads when the waist-back length is in the 90th percentile. This trend can be seen visually in Figure 4.17 and is discussed in further detail below.

To assess the distribution of load held between the shoulders and the waist, the tensile shoulder elements and the load lifting waist belt elements were summed and the percent of load held by the shoulders\(^4\) versus waist\(^5\) was calculated. Results for each of the models are in Appendix C, Table 9.1. The distribution of load showed that the shoulder consistently held just over 80% of the load while the waist belt held just below 20% of the load for all of the models. Though this is not in full agreement with Lafiandra and Harman (2004) who found that the shoulders held 70% while the waist held 30% of the load, the results are not

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\(^4\) Shoulder elements included in the summation were the load lifter (TS1) and the inferior shoulder strap (TS3). The superior shoulder strap (TS2) was not included because it was shown to be in compression and a secondary model, run without TS2, returned a similar load distribution.

\(^5\) The waist belt lift inferior (TW1) alone was used for the waist belt load. The waist belt lift superior (TW2) was not included because the value was consistently around zero in this static assessment. The waist belt posterior loads (TW3 and TW4) were excluded from the summation because they represent the force on the low back, not force held by the waist.
Figure 4.17: This graph shows the axial force for the respective elements for the full factorial analysis of the 10th and 90th percentile measures of shoulder, chest, and waist-back length for female soldiers.
contradictory. It is possible that a more advanced model may find a more accurate load
distribution that closely matches the previous literature.

Although the range in forces measured for the various models has a small variance, it is
important to note that this is only a static model. A dynamic simulation or a simulation that
contained 3D models of the torso may show greater discrepancies between anthropometric
measures.

**Male versus Female Loading.** Additional models were created to compare various male and
female anthropometries. The 10th, 50th, and 90th percentiles were used for both males and
females. These values allow for inspection over a wide range of sizes and it is interesting to
note the comparisons between male and female percentile measures. For instance, the 90th
percentile female waist-back length measure (17.90 in.) corresponds to about the 40th
percentile male measure (17.88 in.). Additionally, the 50th percentile female waist-back
length (16.74 in.) is actually below the 10th percentile male (16.90 in.). These may be simple
comparisons, but the importance of understanding the differences in sizes must be
understood for the design of the rucksack system.

In Table 4.6, Models 1, 9, and 8 correspond to the 10th, 50th, and 90th percentile female
measures and Models 10, 11, and 12 correspond to the 10th, 50th, and 90th percentile male
measures, respectively. Tables C1 and C2, Appendix C, shows that the distribution of loads
between the shoulder straps and waist belt elements remains consistent through the
models. Similar to the female-only models, about 80% of the load is held by the shoulders
with the remaining 20% held by the waist for all of these models. Although there are no
specific trends identified between the male and female models, the force variations as the
waist-back length increases are more pronounced as the range of waist-back length
increases with the inclusion of male anthropometries. This trend can be seen in Figure 4.18 and is discussed in further detail below.

As discussed, males and females generally differ in size and shape measurements. While these models use various anthropometric measures to customize the model to various percentiles, all of the measures used are straight line size measurements. This model does not account for the actual shape of the soldiers and as such may miss important emergent trends due to the interaction between the shape of the suspension system pieces and the shape of the soldier.

**Waist-Back Length Trends.** As mentioned above, there is a trend in the tensile forces of the inferior shoulder strap attachment to be greater when the waist back length is shorter. Figure 4.18 plots the extracted forces for the respective elements by the associated waist-back length used for each of the models. The clusters of data at 15.65 inches and 17.90 inches are from each of the models created for the factorial analysis of the female 10\textsuperscript{th} and 90\textsuperscript{th} percentile measures, respectively. A trend can be seen in the inferior shoulder strap (TS3), waist belt inferior attachment (TW1), and the waist belt posterior body superior (TW4) that shows a decrease in the magnitude of the force experienced as the waist-back length increases. The angle of the inferior shoulder strap (TS3), which shows the greatest fluctuations as waist-back length varies, was held at a constant angle through all of the models. Therefore, the variations in axial forces in this element (TS3) may stem from the interactions between the other pieces of the suspension system. This trend indicates that for this suspension system, soldiers with longer waist-back lengths may experience lower force magnitudes on the shoulders and waist for the same rucksack load weight. Furthermore, if smaller soldiers are under greater force magnitudes, this may explain part
of the reason why females, who in general are smaller than males, have a greater injury rate. It should be noted that no trends were identified in axial forces compared to chest depth or shoulder breadth.

*Compression in Shoulder Strap.* The superior shoulder strap (TS2) was calculated to be in compression, indicating that the shoulder strap had slack since the actual strap material would not hold compressive forces. Though the negative values for the superior shoulder strap (TS2) are not realistic because the physical straps of the MOLLE system would not
accept compressive force, the results are interesting when compared with user reports.

During the discussion with the female cadets, they explained that female soldiers tighten the shoulder straps (specifically the strap equivalent to the element representing the superior shoulder strap, TS2, in the model) very tight to keep the straps from migrating laterally during movement. While this scenario would create a high tension in the element (TS2), the model actually showed compressive forces while the load lifter (TS1) supported a higher tensile force. This may indicate that soldiers are over-tightening the shoulder straps to maintain ‘fit’ at the expense of high forces on the shoulders. Perhaps a looser fitting shoulder strap with very tight load lifters would be able to remove some of the force from the shoulders of soldiers. This would first require a shoulder strap design that sits on the shoulders without the need for excessive tightening, as well as consistent use of the chest strap as a mechanism to prevent lateral movement of the shoulder straps.
4.7 Sensitivity of the Model

Various aspects of the model have been considered for an analysis of sensitivity. The following sections discuss excessive loading on the frame, variations in the angle of the inferior shoulder strap, and removal of the superior waist belt strap.

**Excessive Loading.** Since the total equipment weight carried in the field can vary greatly from that of training, two additional models were run to assess the load distribution at extremes of loading. This model was run using a load three times greater than previous (total load of 120 lbs) on both the 50th percentile male and female models. Additionally, this model represents the idea of impact loading, for example the loading felt at landing when jumping down from a higher position. Likely due to the static nature of the model, the results showed that the axial forces increased proportionally to the increase in load and the distribution of load remained the same. The results are in Table C3 in Appendix C. Although the distribution of forces was not exactly 30% held by the lower back and 70% held by the shoulders, the results agree with Lafiandra and Harman (2004) in that the load distribution between the low back and the shoulder was independent of load mass, Table C2, Appendix C.

**Angle of the Inferior Shoulder Strap.** The 10th, 50th, and 90th percentile male and female models were further explored by adjusting the angle of the inferior shoulder strap, TS3. This angle, described in Figure 4.9, was set to 30 degrees based on literature. However, this study identified a range of optimal values of 24-30 degrees (Reid et al., 2001). Although the investigation by Reid et al. (2001) used a 50th percentile male manikin to obtain the results, it is thought that the optimal value could vary if the size of the soldier were varied. Thus, additional models were evaluated to examine the effects of changing the inferior shoulder
strap (TS3) to an angle of 24 and 27 degrees to evaluate the range of optimality identified in literature. Because the angle is measured from the vertical, a decrease in the angle causes the inferior shoulder strap to become more vertical. As the torso length increases, it is intuitive that the strap angle may decrease if the chest depth remains similar. The results show that for each model, the axial force in the inferior shoulder strap (TS3) decreases as the angle is decreased. In turn, there is also a decrease in magnitude of force in the waist belt posterior element superior (TW4) which indicates less pressure on the low back. These trends can be seen in Figure 4.19. Furthermore, this trend indicates that it may be

**Axial Forces as Angle of TS3 Varies**

![Graph showing axial forces as angle of TS3 varies](image)

Figure 4.19: This graph shows the axial force in the respective elements as the angle of TS3 varies for the 10th, 50th, and 90th percentile models for male and female measures. The inferior shoulder strap (TS3) and the waist belt posterior element superior (TWs) are the only two elements in the model that change in response to the change in angle of TS3.
beneficial to decrease the angle of the inferior shoulder strap if possible as an effort to decrease the magnitude of force felt on the shoulders.

Removal of Superior Waist Belt Strap. Lastly, the sensitivity of the model was assessed by removing the superior waist belt strap, TW2. In the original models, the TW2 element experienced nearly zero pounds of force, while the inferior waist belt strap (TW1) held all of the waist belt force. This element was removed from the 10th, 50th, and 90th percentile male and female models. The results, after removing the TW2 element, indicate no change in the distribution of load between the waist belt and the shoulder straps. The minor change in force distribution caused by removing the element was seen by a small decrease in the force of the inferior shoulder strap (TS3) and a small increase in magnitude in the force superior on the low back (TW4), Table C4 and C5, Appendix C.
4.8 Model Limitations

Although this model presents useful trends which promote future research on the topic of rucksack suspension system analysis and design, there are a number of limitations that should be addressed. First, the models were created using a simplified model of the MOLLE frame. The model was simplified to be 2D and thus does not fully represent the true geometry of the current military rucksack frame. While this may change the axial forces extracted, the trends seen due to vertical changes (waist-back length) may likely remain because all of the vertical measures were accurate. Next, the vector directions of the truss elements used to represent the suspension system are based on a number of assumptions. These assumptions are discussed in the geometry and model sections. Although the full torso shape was reduced to only a few anthropometric measures, the purpose of the elements was not to match the shape of the torso. Rather, the elements were created based on assumptions, as well as geometric and anthropometric calculations, in order to represent the direction of the force due the suspension system on the frame. Additionally, the geometric calculations were based on the idea that the rucksack was worn in the correct vertical position on the body which is not necessarily true for soldiers in the field or training. Finally, it is important to note that this is a finite element simulation and by definition is an approximation. In all, the limitations of the model do not negate the trends found in the output, but rather provide direction for creating an improved model and future research.
This study has investigated past literature on the effects of rucksack use and has analyzed the current military rucksack design, MOLLE. Although this was an initial exploration on the topic of military rucksack design, many ideas have been produced. Three main categories of future work have emerged from the generated ideas:

1. Design Improvements or Changes to the Rucksack System
2. Training Suggestions and Importance
3. Human Subject Research Strategies and Model Advancement

The following sections gather the ideas proposed throughout this project and provide further detail for the continuation of research in each category.
5.1 Design Improvements or Changes to the Rucksack System

Proposed advancements of the frame, shoulder straps, waist belt, and rucksack are motivated by the review of past literature, discussion with the female cadets, model analysis of the MOLLE IV frame, and search of current recreational backpack features. Table 5.1 lists the proposed future improvements to the MOLLE IV load carriage system. The expected benefits of the proposed features are not limited to improving the load distribution between the shoulders and waist. Additional advantages of these potential designs could include greater comfort by reducing peak pressure points and an increased ability to maneuver in small spaces. While Table 5.1 is not exhaustive, it identifies multiple future directions of design research based on review of the literature, the finite element model, and discussions with current soldiers. Additionally, though these design ideas may be sketched, prototyped, or even built and integrated into the existing system, further research would be needed to assess the biomechanical benefit. Ideas for future research strategies to test the design elements discussed here are outlined below in the discussion of human subject research.

<table>
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<tr>
<th>Proposed Feature</th>
<th>Motivation</th>
<th>Discussion of Expected Benefits</th>
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<tbody>
<tr>
<td><strong>Female-specific waist strap design</strong></td>
<td>Anthropometric differences between male and female waist and hip measures indicate that females have greater hip to waist size ratios than males. Some recreational backpacks have this as an available feature for females.</td>
<td>As sketched in Figure 4.7, a female-specific waist belt would wrap around the waist at a greater angle from the vertical. The thought is that this angled waist strap would allow a greater amount of load to be transferred through the waist belt onto the female hip.</td>
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*Table 5.1: Future design improvements and changes to the MOLLE IV rucksack load carriage system are listed with motivation for the suggestion and discussion of proposed designs benefits.*
<table>
<thead>
<tr>
<th>Proposed Feature</th>
<th>Motivation</th>
<th>Discussion of Expected Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frame and straps designed to account for the interaction with fighting load carrier and/or ballistic vests</strong></td>
<td>Discussion with users identified interference between vests and shoulder straps for smaller shoulders. Literature briefly discusses the negative effect on load distribution due to vests.</td>
<td>By accounting for the interaction between the system elements, the expected benefit is in reduction of peak pressures created at the overlap of shoulder straps and vests and at the edges of the ballistic plates (discussed through a static model in Reid et al., 2006).</td>
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<td><strong>Variable length frame</strong></td>
<td>Model analysis indicates that the waist-back length affected the magnitude of load in the shoulder straps. In turn, changing frame length could reduce load on the shoulder straps.</td>
<td>This feature could be achieved through multiple sizes, telescoping length, modular length attachments, among many other strategies. Regardless of the specific design, having a frame length tailored to the waist-back length of the soldier may not only allow for reduced loads in the shoulder but could also increase visibility and reduce gait interference since these were identified as additional issues for the smaller female soldiers.</td>
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<tr>
<td><strong>Greater flexibility/compliance in shoulder and waist straps</strong></td>
<td>Female cadets agreed on the benefits of the thick padding and width of the current design. Without weakening this advantage, increasing compliance may allow the straps to better conform to the body shape and any additional equipment worn. Compliance in the straps was also suggested from the results of the model by Ren et al. (2005).</td>
<td>As more compliant shoulder and waist straps allow the material to conform to the body shape, the proposed benefit is that greater load could be transferred to the waist. Also, at the shoulders, compliance may reduce negative interactions between the shoulder straps and vests worn.</td>
</tr>
<tr>
<td><strong>More slender shape for frame and rucksack</strong></td>
<td>Discussions with users indicate that width of the current system hinders maneuverability. A taller, more slender shape could also allow for more vertical load distribution as suggested by literature.</td>
<td>This feature was requested for the benefit of increased ability to maneuver in small spaces. Additionally, a more vertical rucksack shape may allow for distributing more load higher on the back which literature shows is most beneficial for reducing forward trunk lean.</td>
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<tr>
<td><strong>Allow the frame to articulate along the current line of symmetry</strong></td>
<td>Without losing the benefits of the external frame, a joint may allow for some of the benefits of the 2-stay, internal frame designs which currently dominate the recreational backpack industry.</td>
<td>An articulating external frame could allow the waist belt to hold a greater proportion of the rucksack load because the frame, in addition to the waist belt itself, could conform to individual differences in body shape.</td>
</tr>
</tbody>
</table>
5.2 Training Suggestions and Importance

Design improvements alone will not be sufficient for creating a better rucksack. Soldiers need training to understand the improvements in comfort and health effects that could be seen by properly adjusting, wearing, and packing a rucksack. Throughout discussions with female cadets and other soldiers, it became clear that in training, as well as in the field, the rucksack was not adjusted or worn properly and that no formal training had been provided (Personal Communications, Tim Ruffing, Group Interview). Specifically, chest straps and waist belts are often not worn. Literature, as discussed previously, has shown the importance of wearing the chest strap and waist belt for reducing biomechanical and physiological effects. In addition to literature findings, wearing the chest strap can accomplish the basic idea of eliminating lateral movement of the shoulder straps. As a result, the shoulder straps would then not need to be tightened as tight as the method identified during the discussion with the female cadets thus likely reducing the pressure on the shoulders.

Major topics which need training on the MOLLE or other rucksack arise from previous discussions with soldiers as well as literature findings. The following issues should be addressed in future training:

- Chest Strap – Wear
- Waist Belt – Wear at the level of the navel
- Load Lifters – Tighten after all other adjustments
- How to Adjust Each Component
- How to Pack for Optimal Load Distribution
5.3 Human Subject Research Strategies and Model Advancement

The final category of future work encompasses future research strategies relating to both human subject research and advanced modeling ideas. While future models may be able to address the effects of design changes, results should be validated through biomechanical analysis of soldiers.

*Human Subject Research* Although load carriage has been studied, no study has been identified that investigates the interactions and changes in biomechanical effects on the soldier when the current MOLLE rucksack is worn with other military equipment. The changes in load distribution between the shoulders and waist and biomechanical responses, due to the addition of both the Fighting Load Carrier vest and the Ballistic vest worn under the MOLLE rucksack, should be fully understood in a dynamic setting. Major design changes, as discussed, should be tested to assure proposed benefits are observed.

Methods for analyzing rucksack effects should be expanded beyond current assessment techniques in order to assess the load distribution. Specifically, pressure sensors under the suspension system and tension meters incorporated into the straps could provide a clear understanding of how the load is distributed. Additionally, ROTC cadets or current soldiers should be utilized for future studies since they have similar background training and are the target user. Finally, as ideas are generated and design changes are made to the rucksack system, soldiers should be interviewed and surveyed. This user analysis during development is vital to creating an improved design which continues to account for all field uses and needs.
Multiple improvements could be made to the current model of assessing load distribution between the shoulders and waist. First, a full 3D model of the MOLLE IV rucksack frame could provide more accurate results on how the load is distributed within the frame. Because the design is proprietary, the 3D model is not available. However, an accurate model could be created by using a 3D scanner which creates a point cloud of data from the surfaces of the frame which can then be used to create a mesh and finally a solid CAD model. Next, the shoulder and waist strap representations could be improved by using more elements that are set up to follow the body shape using more anthropometric measures. A further, more advanced, improvement to the model would be to place the loads via shoulder and waist straps onto scaled 3D torso models. This could provide insight into load distribution of the suspension system as well as pressure concentrations. Furthermore, the geometry of the shoulder and waist straps could be more accurately represented in this potential model. Additionally, material properties of the straps should be addressed in order to hold tension but not allow for compression if the strap has slack. The primary difficulties in making these ideas into real finite element models stem from complex geometries and the compliance of human body tissue, the shoulder straps and waist belt. A final idea for a future model would be to create a dynamic simulation that could provide loading results from simulated gait movements. The model ideas discussed are not simple and would require extensive knowledge to build, if they are possible with current software. To begin, a 3D model of the frame and shoulder and waist strap elements with more accurate shapes could be developed.

The literature shows that load carriage not only affects gait but also has negative health impacts. Furthermore, these health issues occur at a higher rate in female soldiers. It is
clear through the anthropometric data and discussion that males and females have different body shapes and sizes. These anthropometric differences do not appear to be accounted for in the current MOLLE suspension system design, leading to the discomfort and injuries experienced by female soldiers, including those spoken with in the course of this investigation. The model shows a trend that suggests differences in load may be due in part to the differences in back-waist length. Furthermore, the recreational backpack industry has employed a number of techniques that the military design lacks, including more pronounced angle of the waist strap for a female design as discussed. Future research is necessary to design and test new ideas for the military rucksack suspension system. The various parts that need to be evaluated for redesign include the waist belt, shoulder straps, and the frame. Further collaboration with current female soldiers will allow for continued problem identification and idea generation. Additional collaboration with field soldiers and veteran soldiers could give insight to other uses for these components in the field in unexpected or emergency situations. As various designs are created, they should be tested for functionality and in a biomechanical analysis. Gait analysis and measures of skin pressure caused by the rucksack suspension could be analyzed to assess the effectiveness of the design. The goal of this future work would be to create a new suspension system design in which anthropometry, past research, and soldier input were combined to create a design that is functional and biomechanically improved for female soldiers.

Rucksack design is not the stopping point for future investigations. As discussions with current female soldiers advanced, it was apparent that other equipment was in need of gender specific design, including the need for female-specific uniforms to provide more room for female hips and hip motion. Designing equipment for female anthropometry and motion could improve comfort and health for current and future female soldiers.
5.4 Conclusion

While women have been serving on active duty for many years in the U.S. military, the equipment traditionally used has been solely designed for men. Although female body armor has been released, there are still many improvements that could be made to the personal equipment used by female soldiers. Specifically, the rucksack design is of primary importance as soldiers are commonly injured due to load carriage on road marches. The load weight, load placement, and design of the suspension system all impact the biomechanical response, affecting males and females differently. Additionally, the anthropometric variance between genders supports the need for at least two frame sizes, to accommodate female and smaller male soldiers. Thus, after examination of past research and an investigation of the current military rucksack, further research is necessary to create a rucksack to better fit a female soldier and potentially a small male soldier.
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Shutterstock. Vestor Illustration of Women’s Figure, Front, Back, Side Views. Figure 4.9, Figure 4.10, Figure 4.11. http://www.shutterstock.com/pic-137013698/stock-vector-vector-illustration-of-women-s-figure-front-back-side-views-silhouettes.html


Vermont’s Barre. Nomex Gloves. Figure 4.2. http://www.vtarmynavy.com/condor-products.htm
Appendix A: Annotated Bibliography

The following pages briefly summarize the literature references used in this document.

<table>
<thead>
<tr>
<th>Citation (APA)</th>
<th>Type of Research</th>
<th>Objective</th>
<th>Basic Findings</th>
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</thead>
<tbody>
<tr>
<td>Attwells, R., Birrell, S., Hooper, R., &amp; Mansfield, N. Influence of carrying heavy loads on soldiers’ posture, movements and gait. Ergonomics, 49, 14, 1527-1537.</td>
<td>Biomechanical Lab Investigation</td>
<td>To measure the changes in posture and gait caused by carrying a variety of military loads and to study the extent and nature of changes</td>
<td>Knee and femur ranges of motion increased with load; trunk flexed further forward; craniovertebral angle decreased (more forward position of head with load)</td>
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<tr>
<td>Bell, N., Thomas W.M., Hemenway, D., Amoroso, P., &amp; Jones, B. High injury rates among female Army trainees: A function of gender? American Journal of Preventive Medicine, 18, 1, 141-146.</td>
<td>Observational Study</td>
<td>Investigate association between gender and risk of exercise-related injury in Army basic trainees, controlling for physical fitness</td>
<td>Females had more injuries and more serious time-loss injuries than men. Women entered less fit. Suggests fitness as a key factor, especially for cardiovascular or run time (Note: when adjusted for fitness level, men and women had no diff in injuries). Suggests remedial training for less fit soldiers to reduce risk of injury.</td>
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<td>Bessen, R. J., Belcher, V. W., &amp; Franklin, R. J. Rucksack paralysis with and without rucksack frames. Military Medicine, 152, 7, 372-5.</td>
<td>Observational Study, Laboratory Follow-up</td>
<td>To document brachial plexus (or similar) injuries, determine the causes and methods of prevention, and to minimize the cost to the government through lost training time, medical care cost, and disability payments.</td>
<td>15 basic trainees (of 12850) sustained &quot;diffuse, disabling brachial plexus injuries&quot; from carrying a rucksack without a frame on road marches. 3 (of 19050) were injured (&quot;more benign, isolated long thoracic nerve palsy&quot;) carrying a rucksack with a frame. Rate of injury was 7.4 times higher when pack frames were not used. With pack frames, the injury was a more benign, isolated long thoracic nerve palsy. Injuries occurred in 3rd to 5th weeks of training and 72% occurred during long marches (10-15 miles) Some Army posts that were contacted reported as many as 50 or more cases of rucksack paralysis each year.</td>
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<td>Biomechanical Lab Investigation</td>
<td>To evaluate the kinematic and spatiotemporal effects of heavy military load carriage on human gait</td>
<td>Decrease in stride length and increase in time in double support with increasing load. Decrease knee flexion and extension and pelvis rotation with increasing load. Increase in pelvic tilt demonstrates forward lean in the trunk.</td>
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<td>Birrell, S. A., &amp; Hooper, R. H. (2007). Initial subjective load carriage injury data collected with interviews and questionnaires. Military Medicine, 172, 3, 306-11.</td>
<td>Subjective Response, Lab Investigation</td>
<td>To assess the incidence and prevalence of load carriage related injuries from early onset injury or discomfort identified through subjective means.</td>
<td>Upper limb is very susceptible to short-term discomfort. The lower limb is not as susceptible. Shoulders were rated significantly more uncomfortable than any other region and discomfort increased with time starting when load was donned. Blisters occurred in 60% of participants. Foot discomfort increased with time, starting at the first notice of pain, ~30-45 minutes into march.</td>
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<td>Bloom, David, &amp; Woodhull-McNeal, Ann P. (October 1987). Postural adjustments while standing with two types of loaded backpack. Ergonomics, 30, 10, 1425-1430.</td>
<td>Biomechanical Lab Investigation</td>
<td>To examine the changes in body posture caused by the two different packs: internal frame and external frame</td>
<td>Both pack types cause subjects to lean forward: mean position of knees, hips, shoulders, and ears were all further forward with a pack on than in the control stance. Men and women did not significantly differ in position or center of gravity for either pack (however, men preferred internal and women preferred external). Torque calculations showed 52% (internal) and 74% (external) of the torque due to the load was compensated for by the change in posture.</td>
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<td>Biomechanical Lab Investigation</td>
<td>To investigate the effect of marching with military packs to (1) evaluate whether muscles under physical stress may weaken when carrying loads and (2) to study this in field conditions with the actual load and load distribution on the body of the rifleman</td>
<td>The muscle groups showing the greatest strength losses were: trunk extensors, hip extensors, knee flexors, and neck extensors. The experimental pack (with hip belt) resulted in the least overall strength loss of the muscle groups tested - least muscular fatigue Combat pack carried high on back was superior to rucksack - higher load placement caused less muscular fatigue</td>
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<td>Case Study, Medical Follow-up</td>
<td>Investigate 3 cases of civilian backpackers who experienced weakness of shoulder muscles during backpacking</td>
<td>Peripheral nerve injury appears to be the mechanism causing pack palsy in all 3 cases. Treatment consists of removing the source of trauma by avoiding further backpacking during recovery</td>
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<td>Physiological Lab Investigation</td>
<td>To examine metabolic effects of soldier performance on a simulated road march, comparing two functionally equivalent military ensembles with changing gradation of marching, and to create prediction equations addressing workload with different loads and treadmill grades.</td>
<td>No significant differences found between the 2 ensembles. Increase in percent grade, increased the metabolic cost.</td>
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<td>To test the hypothesis that the incidence of stress fractures is proportional to the amount of cumulative physical training stresses.</td>
<td>Distribution of stress fracture sites: 72% tibia, 25% femur, and 2% metatarsus. Highest occurrence of stress fractures occurred in 5th through 8th week of training. It is interesting to note that a cause of not seeing a significant difference could be attributed to the rate of increase in miles marched was the same during the primary injury time frame.</td>
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<td>Biomechanical and Physiological Lab Investigation</td>
<td>To study effects of a lower extremity exoskeleton on metabolic cost and gait biodynamics while walking</td>
<td>Oxygen consumption (metabolic cost) was higher for exoskeleton than control VO2 increased significantly with load More flexed posture and higher braking GRF at heel strike with exoskeleton Range of motion decreased with increases in load - possibly due to restriction imposed by the structure of the EXO</td>
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<td>Biomechanical Lab Investigation</td>
<td>To examine the effects of various backpack loads on gait kinematics, ground forces, and muscle activity</td>
<td>Double support time increased with increasing load. Increase in stride frequency, decrease in stride time, increase in knee range of motion, and trunk forward inclination increased with very heavy load</td>
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<td>Belt raised energy cost with external frame but belt use lowered energy cost with internal frame. Internal frame pack used with the belt gave the most efficient load carriage (in terms of oxygen consumption)</td>
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<td>Biomechanical, Physiological, and Subjective Response, Lab Investigation</td>
<td>Assess the MOLLE system against the 'currently' (1994) used ALICE on women</td>
<td>ALICE had lower pressure under the shoulder straps than MOLLE MOLLE had better upright walking posture and fewer shoulder/total-body complaints Time to remove pack and get prone was significantly shorter with MOLLE (quick release mechanism) Zigzag obstacle course: ALICE was significantly faster (move in small spaces) Trunk inclined forward about 3 degrees more with ALICE than MOLLE (attributed to MOLLE center of mass being higher) For approach load only, the MOLLE had higher shoulder strap pressure than ALICE</td>
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<tr>
<td>Harper, W.H., Knapik, J., de Pontbriand, R. (March 1997). Female Load-Carrying Performance. Army Research Laboratory.</td>
<td>Physiological and Subjective Response, Lab Investigation</td>
<td>Examine how females perform tasks such as carrying heavy loads because Army is expanding and more women are assigned to units/specialties requiring heavy load carriage requirements</td>
<td>Women reported more problems with the shoulder straps (fit, location, and maintaining adjustment), fit of the frame (length and width), fit of pistol belts, and fit and stability of the rucksack. Women also reported greater pain, soreness, and discomfort in the back regions than men for heaviest load.</td>
</tr>
<tr>
<td>Hasselquist, Leif, Bensel, Carolyn K., Norton, Karen, Piscitelle, Louis, &amp; Schiffman, Jeffrey M., ARMY NATICK SOLDIER CENTER MA(2004). Characterizing Center of Mass and Moment of Inertia of Soldiers’ Loads Packed for Combat.</td>
<td>Observational Study</td>
<td>To gather data in the field on the COM and MOI of backpack loads packed by soldiers preparing for deployment (i.e. soldier packed loads) and to determine whether the inertial properties of the backpack load fabricated for laboratory study were similar to soldier packed backpacks.</td>
<td>Laboratory backpack did not capture the full range of COM and MOI values seen in the soldier packed backpacks. Some of the laboratory COM and MOIs may be unrealistic/unachievable because of the size and shapes of the equipment needed. Inertial values for the fabricated backpack about all axes are lower than the values for the soldiers’ packs.</td>
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<tr>
<td>Heller, M. F., Challis, J. H., &amp; Sharkey, N. A. (July 2009). Changes in postural sway as a consequence of wearing a military backpack. Gait &amp; Posture, 30, 1, 115-117.</td>
<td>Biomechanical Lab Investigation</td>
<td>To determine how a backpack (military) affected postural sway in females</td>
<td>Center of pressure path length increased 64%, medial-lateral excursion increased 131%, anterior-posterior excursion increased 54% and COP area increased 229% with backpack. Increase in postural sway may increase likelihood of falls and injury.</td>
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Waist carrying mode had less perceived discomfort than shoulder carry mode  
Model created to relate weight and volume to performance loss - recommendations for packing for balanced mass distribution |
| Holewijn, M. (1990). Physiological strain due to load carrying. European Journal of Applied Physiology and Occupational Physiology, 61, 3-4. | Biomechanical and Physiological Lab Investigation     | To investigate effects of various physiological strain parameters that could limit the endurance time of walking with a backpack - to find the limiting factor | The peak skin pressure with frameless was significantly high than with a frame -- frameless pack had average pressure 5x greater than pack with frame.  
Load transfer to waist reduced the shoulder skin pressure to below the threshold value (previously was 3x greater than threshold)  
Increasing weight increased oxygen uptake, heart rate, trapezius muscle force |
Specifically, the influence of two types of chest straps on upper body and whole body measures were compared with the use of no chest strap. | Chest straps reduced the perceived discomfort ratings compared to no chest strap.  
No chest strap showed decreased sensory function compared to chest strap.  
Results suggested that not using a chest strap can lead to blood pooling in the forearm, a decrease in sensory function, an increase in discomfort, and a decrease in motor function of the hand and arm. |
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<tr>
<td>Jacobson, B.H., Cook, D.H., Altena, T.S., Gemmell, H.A., &amp; Hayes, B.M.</td>
<td>Subjective Response, Lab Investigation</td>
<td>To compare the perceived discomfort differences between a standard backpack and one with vertical load distribution (slanted 'shelves')</td>
<td>Vertical load placement may redistribute the load in a manner that reduces symptoms of selected anatomical discomfort: the reported pain was significantly lower for shoulder, neck, low back, and overall comfort</td>
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<td>Johnson, R. F., Knapik, J. J., &amp; Merullo, D. J.</td>
<td>Subjective Response, Lab Investigation</td>
<td>To assess symptoms reported by soldiers carrying various weights in the ALICE pack and the prototype Double Pack</td>
<td>No significant main effect of pack type on any symptom factor Pack*mass interaction showed subjective heat-index was highest for the heaviest weight with the double pack Soldiers took more time to march with double pack Increased mass related to greater fatigue</td>
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<td>Jones, G. R., &amp; Hooper, R. H. (2005). The effect of single- or multiple-layered garments on interface pressure measured at the backpack-shoulder interface. Applied Ergonomics, 36, 1, 79-83.</td>
<td>Biomechanical Lab Investigation</td>
<td>To determine whether interface pressure measurements are a true reflection of skin contact pressure when made over different layers of clothing.</td>
<td>No significant differences in pressure between varying clothing layers. Pressure can be adequately assessed using a sensor placed above the clothing layers rather than at skin surface - opens possibility of instrumenting a pack for in the field interface pressure measurements.</td>
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<tr>
<td>Jones, B. H., Harris, J. M., Vinh, T. N., &amp; Rubin, C. (1989). Exercise-induced stress fractures and stress reactions of bone: epidemiology, etiology, and classification. Exercise and Sport Sciences Reviews, 17, 379-422.</td>
<td>Literature Review</td>
<td>To gain a better understanding of the broad spectrum of osseous reactions to 'stress' currently referred to as stress fractures by discussing the epidemiology, etiology, and evolution of the injuries</td>
<td>Primary risk of exposure to stress fractures is repetitive vigorous physical activity or a change in activity level. Risk of stress fracture for females is greater than for males. “Women are at greater risk of suffering stress injuries of bone than men in US military training populations” Other risk factors include age, race, physical fitness history, and foot wear.</td>
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<td>Jones, B., Perrotta, D., Canham-Chervak, M., Nee, M., Brundage, J. (2000). Injuries in the military A review and commentary focused on prevention. American Journal of Preventive Medicine, 18, 1, 71-84.</td>
<td>Literature Review</td>
<td>To review types and categories of morbidity and mortality data examined by the AFEB and D.o.D. work groups and make suggestions on how such data contribute to each step of the public health process of injury prevention and control</td>
<td>Combat soldiering activities (training activities such as road marching - specifically mentioned) were the 3rd highest cause of injuries in the Army in 1994. Musculoskeletal problems were the leading cause of hospitalization for active duty military personnel in 1994.</td>
</tr>
<tr>
<td>Kinoshita, H. (1985). Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait. Ergonomics, 28, 1347-1362.</td>
<td>Biomechanical Lab Investigation</td>
<td>To describe the effects of 2 different systems on selected biomechanical parameters (kinematic and kinetic parameters describing the support phase) of walking gait, while carrying loads of varying magnitude.</td>
<td>Double support time, knee flexion, and forward lean increased with increase in load. Double-pack reduced the forward lean in comparison with the backpack. Both light and heavy loads modified the normal walking gait pattern.</td>
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<td>Kirk, J., &amp; Schneider, D. (April 1992). Physiological and perceptual responses to load–carrying in female subjects using internal and external frame backpacks. Ergonomics, 35, 4, 445-455.</td>
<td>Physiological and Subjective Response, Lab Investigation</td>
<td>To determine if differences exist between the metabolic, cardio respiratory, or perceptual responses of female subjects carrying internal and external frame backpacks</td>
<td>No significant differences in the energy cost or perception of carrying a moderately heavy load on the back created by pack type. Values changed significantly with changes in slope of treadmill. Regardless of pack type, the shoulders had greater perceived pain over time. 6 subjects preferred external, 5 preferred internal frame pack</td>
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<tr>
<td>Knapik, J., Reynolds, K., Staab, J., Vogel, J. A., &amp; Jones, B. (1992). Injuries associated with strenuous road marching. Military Medicine, 157, 2, 64-7.</td>
<td>Observational Study, Laboratory Follow-up</td>
<td>To describe the injuries that occurred in all soldiers participating in the same march as a previous Knapik paper</td>
<td>79 soldiers had injuries; 12 requested medical attention more than once Most common were blisters (10%) and back (6%) injuries 12 soldiers had back strains and did not complete march 13 soldiers had injuries that resulted in limited duty days Many injuries were not reported (rather, found in active surveillance) suggesting that more injuries may have occurred than were reported</td>
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<tr>
<td>Knapik, Joseph, Everett, Ha, Reynolds, K. (June 1996). Load Carriage using Packs: A Review of Physiological, Biomechanical and Medical Aspects. Applied Ergonomics, 27, 3, 207-216.</td>
<td>Literature Review</td>
<td>Literature review to examine the effects of load carriage from physiology, biomechanics, and medicine and to give suggestions for facilitating load carriage</td>
<td>Locating load mass as close as possible to the body center of gravity results in lowest energy cost Double pack has lower energy cost than backpack Common injuries: foot blisters, stress fractures, back strains, metatarsalgia (foot pain), rucksack palsy (shoulder traction injury), and knee pain. Framed pack with hip-belt can reduce incidence of rucksack palsy.</td>
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<td>Knapik, J. J., Reynolds, K. L., &amp; Harman, E. (2004). Soldier Load Carriage: Historical, Physiological, Biomechanical and Medical Aspects. Military Medicine, 169, 1.</td>
<td>Literature Review</td>
<td>Literature review to examine historical, physiological, biomechanical, and medical aspects of load carriage effects.</td>
<td>Load center of mass should be located as close as possible to the body. Hip belts on rucksacks should be used as they reduce pressure on the shoulders and increase comfort. The energy cost of walking with backpack loads increases progressively with increases in weight carried. On questionnaires, women commented more often than the men that the pack straps were uncomfortable, hip belts ill fitting, and rucksacks unstable.</td>
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<td>Knapik, J. J., Harman, E. A., Steelman, R. A., &amp; Graham, B. S. (February 01, 2012). A Systematic Review of the Effects of Physical Training on Load Carriage Performance. Journal of Strength and Conditioning Research, 26, 2, 585-597.</td>
<td>Literature Review</td>
<td>Literature review to examine the effect of physical training on load carriage performance.</td>
<td>Physical training can improve load carriage performance. Large training effects were apparent when progressive resistance training was combined with aerobic training and when that training was conducted at least 3 times per week, over at least 4 weeks. Progressive load carriage exercise resulted in larger training effects.</td>
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<tr>
<td>Knapik, J. (June 1989). Loads Carried by Soldiers: Historical, Physiological, Biomechanical and Medical Aspects. Army Research Institute of Environmental Medicine Natick, Massachusetts.</td>
<td>Literature Review</td>
<td>To review literature on historical, physiological, biomechanical and medical aspects of load carriage.</td>
<td>Backpack has an energy cost equal to or lower than most other load carriage methods (head, hands, back, low back, thighs, waist, one shoulder) Lists clinical symptoms of rucksack paralysis. Stress fractures more common in females. Note - Paresthesia is a sensation of tingling, tickling, prickling, pricking, or burning</td>
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<tr>
<td>Lafiandra, M., &amp; Harman, E. (2004). The distribution of forces between the upper and lower back during load carriage. Medicine and Science in Sports and Exercise, 36, 3, 460-7.</td>
<td>Biomechanical Lab Investigation</td>
<td>To determine the effects of backpack mass on the forces exerted by the backpack on the carrier and on the distribution of these forces between the upper back (including shoulders) and lower back (sacrum and iliac crest).</td>
<td>Regardless of mass, ~30% of vertical force was held by the lower back, the upper back and shoulders supported the remaining 70% (i.e. 30% of the weight can be transferred from the shoulders/upper back to the hips by use of hip belt regardless of pack mass) Pack also exerts a consistent anterior force on the low back</td>
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<td>Legg, S.J., and Mahanty, A. (1985). Comparison of five modes of carrying a load close to the trunk. Ergonomics 28:1653-1660.</td>
<td>Physiological and Subjective Response, Lab Investigation</td>
<td>To investigate the cardio respiratory, metabolic, and subjective responses to carrying a load close to the body in 5 different ways.</td>
<td>No sig diff in cardio respiratory or metabolic costs in the 5 carriage methods. Back/Front (4) and trunk jacket (5) were rated as more comfortable than backpack with frame (1) and no frame (2) based on subjective responses. Pack with no frame (2) was perceived as lest comfortable. Back/front pack (4) was reported most difficult to don/doff and had restrictive ventilatory impairment. The backpack with frame was easiest to don/doff.</td>
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<tr>
<td>Legg, S. J., Ramsey, T., &amp; Knowles, D. J. (1992). The metabolic cost of backpack and shoulder load carriage. Ergonomics, 35, 9, 1063-8.</td>
<td>Physiological Lab Investigation</td>
<td>To compare the shoulder and backpack load carriage techniques by studying heart rate and oxygen uptake</td>
<td>Heart rate and oxygen uptake lower for backpack than shoulder carry. Metabolic cost of backpacking lower than for shoulder carriage for this speed/gradients</td>
</tr>
<tr>
<td>Legg, S. J., Perko, L., &amp; Campbell, P. (August 1997). Subjective perceptual methods for comparing backpacks. Ergonomics, 40, 8, 809-817.</td>
<td>Subjective Response, Lab Investigation</td>
<td>To compare two different perceptual methods: category ratio scale (CRS) ratings of perceived discomfort and written questionnaires.</td>
<td>No significant perceived regional discomfort differences between packs. Post walk questionnaire pack A had sig less discomfort for muscular strain in shoulders and back and less discomfort for balance and ease of gait. 7 subjects preferred A, 3 preferred B. No sig diff in heart rate between the 2 packs.</td>
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<td>Ling, W., Houston, V., Tsai, Y. S., Chui, K., &amp; Kirk, J. (2004). Women's load carriage performance using modular lightweight load-carrying equipment. Military Medicine, 169, 11, 914-9.</td>
<td>Biomechanical and Physiological Lab Investigation</td>
<td>To evaluate how MOLLE fits women while walking on level surfaces with different loads, to examine women's load carriage performance before and after a simulated march using 5 load levels, and to examine the relationship between shoulder and leg muscle strength and load carriage performance of women while carrying loads using MOLLE.</td>
<td>Increased double support time, increased trunk forward inclination, decreased knee excursion, decreased medial-lateral excursion of COG, and increased vertical excursion of COG, increased discomfort with increasing loads. Some women required modification of the padded hip belt to ensure weight distributed evenly around the pelvis, yet: &quot;Based on the data regarding self-reported discomfort level and load carriage performance, MOLLE fits our female subjects relatively well&quot;...but... &quot;for those women with small waists and wide pelvises, hip belt adjustments may be needed&quot;</td>
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<tr>
<td>Lloyd, R., &amp; Cooke, C. (September 2000). Kinetic changes associated with load carriage using two rucksack designs. Ergonomics, 43, 9, 1331-1341.</td>
<td>Biomechanical Lab Investigation</td>
<td>To evaluate the changes in kinetics associated with load carriage using both traditional rucksack and new load carriage system (which incorporates front balance pockets allowing load to be distributed between the back and the front of the trunk)</td>
<td>New design produced significantly lower propulsive force than the traditional rucksack - findings indicate that there may be some advantage in terms of propulsive force production for the front/back system</td>
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<td>Macleod, M. A., Houston, A. S., Sanders, L., &amp; Anagnostopoulos, C. (1999).</td>
<td>Observational Study, Medical</td>
<td>To track the incidence of trauma related stress fractures in army recruits.</td>
<td>Referred men and women showed 71% and 76% (respectively) scans that were abnormal - suggesting no significant sex bias for referral. 92 (of 855, 10.7%) women experienced stress fractures while 94 (of 3367, 2.8%) men did.</td>
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<td>Incidence of trauma related stress fractures and shin splints in male and</td>
<td>Follow-up</td>
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<td>female army recruits: Retrospective case study. British Medical Journal (</td>
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<td>International Edition), 318, 7175.)</td>
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<td>Martin, P. E., &amp; Nelson, R. C. (1986). The effect of carried loads on the</td>
<td>Biomechanical Lab Investigation</td>
<td>To determine the effects of carried loads on selected kinematic characteristics of walking gait for men and women</td>
<td>Males and females displayed significantly different gait patterns under all loading conditions. The female subjects were affected to a much greater extent than the males, demonstrating greater sensitivity to load magnitude. Male and female trunk angles were similar for the two conditions with the external frame rucksack.</td>
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<td>Pandorf, C. E., Harman, E. A., Frykman, P. N., Obusek, J. P., &amp; Smith, T. J.</td>
<td>Biomechanical and Physiological Lab Investigation</td>
<td>To compare male and female load carriage biomechanics</td>
<td>Despite differences in gait mechanics, males and females showed very similar energy cost per unit body-plus-load mass. Females move knees through smaller range of motion than males; females keep knees bent more throughout gait cycle. Males leaned further forward and spent less time (%) in double support.</td>
</tr>
<tr>
<td>Pelot, R. P., Rigby, A., Stevenson, J. M., Bryant, J. T., &amp; Dalhousie University, Halifax (Nova Scotia) Department of Industrial Engineering. (2001). A Static Biomechanical Load Carriage Model. Ft. Belvoir: Defense Technical Information Center.</td>
<td>Biomechanical Optimization Model</td>
<td>To develop a computer-based static biomechanical model of a backpack to represent the interaction between the pack and the bearer at the principal contact points - and use optimization to find the best location for attaching the suspension system components</td>
<td>2 dimensional biomechanical model of a backpack that allows for input of pack mass and volume; outputs resulting contact forces on the wearer. With objective function to minimize the forces on the shoulders and waist, results said to attach the shoulder straps as high as possible on the pack with the waist-belt is as low as possible. When center of gravity (CoG) is free, results indicate that CoG should be as close to the back and as high as possible.</td>
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<td>Quesada, P., Mengelkoch, L., Hale, R., &amp; Simon, S. (2000). Biomechanical and metabolic effects of varying backpack loading on simulated marching. Ergonomics, 43, 3, 293-309.</td>
<td>Biomechanical, Physiological, and Subjective Response, Lab Investigation</td>
<td>To quantify the physiological and biomechanical responses to prolonged load carriage conditions commonly encountered by soldiers during military marching.</td>
<td>Perceived exertion was significantly higher for 30%BW trial. Energy cost (% VO2 max and heart rate), peaks in hip extension, knee extension, and ankle plantar flexion moments increased with increasing load. Peak knee extension moments declined from pre to post test. Hip musculature did not appear to fatigue excessively during marching.</td>
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<td>Raine, S., &amp; Twomey, L. T. (1997). Head and shoulder posture variations in 160 asymptomatic women and men. Archives of Physical Medicine and Rehabilitation, 78, 11, 1215-23.</td>
<td>Anthropometric Study</td>
<td>To quantitatively describe the postural alignment of the head and shoulders and the surface curvature of the thoracic spine in comfortable erect standing and to examine the effect of age and gender on head and shoulder alignment</td>
<td>Describe poor head and shoulder posture on basis of measurement. Women and men found to have similar posture of the head and shoulders in both the coronal and sagittal planes.</td>
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<tr>
<td>Reid, S. A., Bryant, J. T., Stevenson, J. M., Doan, J. B., &amp; Queen’s University, Kingston (Ontario) School of Physical and Health Education. (2001). Biomechanical Assessment of Rucksack Shoulder Strap Attachment Location: Effect on Load Distribution to the Torso. Ft. Belvoir: Defense Technical Information Center.</td>
<td>Biomechanical Lab Investigation</td>
<td>To determine the lumbar shear and load share borne by the shoulders and hips for various attachment locations for the shoulder strap.</td>
<td>Upper and lower bounds of an optimal range for shoulder straps is 24 to 30 degrees with respect to the vertical axis of the body. Optimal location suggested for shoulder strap lower attachment point is just posterior to the body midline at the height of the iliac crest, this achieves the 24-30 degree angle (for 50th %ile male).</td>
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<td>Reid, S. A., Stevenson, J. M., Kudryk, I., &amp; Queen's University, Kingston (Ontario). (2006). Assessment of the effect of No Stay, Bent Stay or Straight Stay when the Clothe the Soldier Rucksack is Worn with the Fragmentation Vest. Ft. Belvoir: Defense Technical Information Center.</td>
<td>Biomechanical Lab Investigation</td>
<td>To examine the effects of various stays in the rucksack (straight stays, bent stays, and no stay) on pressure effects and load distribution to the body.</td>
<td>Results showed that wearing the fragmentation protection vest under the rucksack and the tactical vest increases the compressive load on the upper body by 50 to 100% compared with just the tactical vest and rucksack. Peak pressures under the FPV were due to the edges of the ballistic plates digging into the body. The addition of the FPV not only adds weight but also pushes the mass of the rucksack out requiring a greater moment to maintain position.</td>
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<tr>
<td>Ren, L., Jones, R. K., &amp; Howard, D. (April 2005). Dynamic analysis of load carriage biomechanics during level walking. Journal of Biomechanics, 38, 4, 853-863.</td>
<td>Biomechanical Lab Investigation, Biomechanical Model</td>
<td>To investigate the biomechanical effects of different backpack suspension characteristics during level walking, in terms of joint loadings, net muscle moments, and mechanical energy expenditure.</td>
<td>Effects of backpack suspension characteristics were assessed by varying the stiffness and damping coefficient in the model: decreasing suspension stiffness significantly reduces the peak values of vertical pack force on the torso. Suggests from the results of the model that a &quot;soft pack suspension could reduce the risk of tissue and nerve damage (rucksack palsy), under shoulder straps and hip belts, and also of back and lower limb injuries.&quot;</td>
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<td>Ross, J. (1993). A review of lower limb overuse injuries during basic military training. Part 1: Types of overuse injuries. Military Medicine, 158, 6, 410-5.</td>
<td>Literature Review</td>
<td>To review various lower limb overuse injuries that occur at basic training.</td>
<td>Plantar Fasciitis, Achilles Tendinitis, Shin Splints, Stress Fractures, anterior compartment syndrome, chondromalacia patellae. It is clear that overuse injuries are a large problem during recruit training. Treatment typically involves rest and can be costly to the military due to loss of manpower and need to repeat training in the future.</td>
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<tr>
<td>Ross, J. (1993). A review of lower limb overuse injuries during basic military training. Part 2: Prevention of overuse injuries. Military Medicine, 158, 6, 415-20.</td>
<td>Literature Review</td>
<td>To examine preventative strategies and look at past attempts to reduce injuries</td>
<td>“The emphasis on dealing with overuse injuries of the lower limb in military basic training must be on prevention” Intrinsic factors and Extrinsic factor discussion Women have higher incidence of overuse injuries than men</td>
</tr>
<tr>
<td>Citation (APA)</td>
<td>Type of Research</td>
<td>Objective</td>
<td>Basic Findings</td>
</tr>
<tr>
<td>------------------------------------------------------------------------------</td>
<td>------------------------</td>
<td>---------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Sampson, James B. (2001). Human Factors Evaluation of the Modular Lightweight Load-Carrying Equipment (MOLLE) System. Army Research Institute, Natick, Massachusetts.</td>
<td>Design Analysis and Improvement</td>
<td>To summarize the front end analysis (FEA) survey and the results from a series of human factors evaluation tests conducted early during MOLLE development.</td>
<td>When ALICE itself was first introduced into the Army it came with many new design and material flaws that were resolved through improvements. In 1988 US Army adopted a new internal frame load-carrying systems (IIFS). Distribution began in 1990 - by 1993 the new pack was unacceptable to a large number of combat personnel. Basic design flaws: too hot against the back in warm climate and unstable/uncomfortable when heavily loaded. In 1994, the design began on the Modular Lightweight Load-carrying Equipment (MOLLE) Users asked for more padding on the shoulder straps - because soldiers tended not to use their hip belts; Users liked capacity to hold bulky cold weather gear.</td>
</tr>
<tr>
<td>Shoaib, A., Mehraj, Q., &amp; Jepson, F. (2002). Injuries of the sterno-clavicular joint in backpackers. Journal of the Royal Army Medical Corps, 148, 3, 267-9.</td>
<td>Case Study, Medical Follow-up</td>
<td>To describe anterior dislocation or fracture dislocation as a result of carrying a large backpack.</td>
<td>Injuries here are unusual because of the nature of the mechanism or injury: may be because of persistent posterior force of the lateral third of the clavicle from shoulder straps (from repeated carrying of backpack for 6 months). &quot;The use of 'one size fits all' backpacks in the military environment may also increase the risk of this injury&quot;</td>
</tr>
<tr>
<td>Citation (APA)</td>
<td>Type of Research</td>
<td>Objective</td>
<td>Basic Findings</td>
</tr>
<tr>
<td>---------------</td>
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</tr>
<tr>
<td>Simpson, K. M., Munro, B. J., &amp; Steele, J. R. (May 2012). Does load position affect gait and subjective responses of females during load carriage? Applied Ergonomics, 43, 3, 479-485.</td>
<td>Biomechanical and Subjective Response, Lab Investigation</td>
<td>To determine the effect of vertical load position on gait and subjective responses of female recreational hikers.</td>
<td>All loads cause forward trunk flexion. High load position was most preferred by participants (although discomfort responses did not show any significant differences); high load position had most upright posture, lowest gastrocnemius muscle activation, and higher first peak deceleration vertical GRF.</td>
</tr>
<tr>
<td>Soule, R. G., &amp; Goldman, R. F. (1969). Energy cost of loads carried on the head, hands, or feet. Journal of Applied Physiology, 27, 5, 687-90.</td>
<td>Physiological Lab Investigation</td>
<td>To investigate the maximum loads that can be placed on different areas (head, hands, and feet relative to equivalent weight on the back) and the relative energy costs incurred by doing so.</td>
<td>Cost per kilogram of weight carried: on the head = 1.2 times expected cost of no load condition at all speeds; on the hands = 1.4-1.9 times (depending on weight and speed); on the feet = 4.2-6.3 times (depending on weight and speed)</td>
</tr>
<tr>
<td>Citation (APA)</td>
<td>Type of Research</td>
<td>Objective</td>
<td>Basic Findings</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
<td>-----------</td>
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</tr>
<tr>
<td>Stevenson, J. M., Bossi, L. L., Bryant, J. T., Reid, S. A., Pelot, R. P., &amp; Morin, E. L. (2004). A suite of objective biomechanical measurement tools for personal load carriage system assessment. Ergonomics, 47, 11, 1160-1179.</td>
<td>Biomechanical Evaluation Techniques for Design</td>
<td>To apply objective standardized assessment tools to the evaluation of load carriage system designs - for Canadian military. To establish physical models and tests to evaluate packs efficiently for an iterative design process</td>
<td>Dynamic Load carriage simulator&lt;br&gt;Range of motion compliance tester&lt;br&gt;Static load distribution mannequin&lt;br&gt;Static biomechanical model and analysis tool&lt;br&gt;Mobility circuit - user trials</td>
</tr>
<tr>
<td>Stuempfle, K., Drury, D., &amp; Wilson, A. (June 2004). Effect of load position on physiological and perceptual responses during load carriage with an internal frame backpack. Ergonomics, 47, 7, 784-789.</td>
<td>Physiological and Subjective Response, Lab Investigation</td>
<td>To compare physiological and perceptual responses to a load carried in a high, central, or low position in a internal frame backpack</td>
<td>VO2, VE, and RPE were significantly lower in the high position compared to the low position&lt;br&gt;HR, R, and RR did not change significantly from high to low position</td>
</tr>
<tr>
<td>Citation (APA)</td>
<td>Type of Research</td>
<td>Objective</td>
<td>Basic Findings</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Wilson, W. J. (1987). Brachial plexus palsy in basic trainees. Military Medicine, 152, 10, 519-22.</td>
<td>Case Study, Laboratory Follow-up</td>
<td>To describe 6 soldiers who, during their basic training, sustained unilateral brachial plexus injuries</td>
<td>The shoulder straps of the rucksacks or duffel bags produced a mild traction injury to the C5 and C6 nerve roots. Each patient demonstrated profound motor weakness and electromyographic abnormalities. 30-50 lb rucksack over several mile march (30 minutes to 2 hours) -- Rucksacks were worn without the metal frame or waist-belt Motor function improved in minutes (but this would still impair ability to aim and fire a gun); Numbness lasts for hours before gradually subsiding</td>
</tr>
</tbody>
</table>
Appendix B: Geometry Calculations

The following drawings and equations supplement the geometric justifications for the finite element model. Figure 4.8 has been copied here (as Figure B1) for ease of understanding.

Variable reference: s=Shoulder Length; d=Chest Depth; l=Waist-Back Length

Figure B1: The figures above show the geometry used to represent the shoulder straps. The simplified frame model overlays the female body images and the angles are shown. The angles in the superior view (left) are on the transverse plane and the angles in the side view (right) are on the sagittal plane. Variables are defined in Table 4.2. (Body Images: FindLaw; Shutterstock)
\( \theta_1 \) Calculation (transverse plane):

\[
\theta_1 = \tan^{-1}\left( \frac{5.625 - s}{d} \right)
\]

\( \theta_2 \) Calculation (sagittal plane):

\[
\theta_2 = \tan^{-1}\left( \frac{d}{17.125 - l} \right)
\]

\( \theta_3 \) Calculation (sagittal plane):

\[
\theta_3 = \tan^{-1}\left( \frac{d}{l - 13.625} \right)
\]
Appendix C: Results Analysis

The following tables provide the full details for analysis of the results in the discussion section.

Table C1: This table shows the shoulder and waist load carriage sums and related percentages for each of the models. All models use female measurements and all loads are in pounds.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
<td>10</td>
<td>10</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Back Length Percentile</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Sum of Shoulder Element Forces (TS1, TS3)</td>
<td>35.85</td>
<td>32.55</td>
<td>34.44</td>
<td>31.86</td>
<td>35.66</td>
<td>32.35</td>
<td>34.33</td>
<td>31.75</td>
</tr>
<tr>
<td>Sum of Waist Belt Element Forces (TW1)</td>
<td>7.96</td>
<td>7.00</td>
<td>7.60</td>
<td>6.83</td>
<td>7.92</td>
<td>6.95</td>
<td>7.56</td>
<td>6.79</td>
</tr>
<tr>
<td>% Load Held by Shoulder</td>
<td>81.8%</td>
<td>82.3%</td>
<td>81.9%</td>
<td>82.4%</td>
<td>81.8%</td>
<td>82.3%</td>
<td>82.0%</td>
<td>82.4%</td>
</tr>
<tr>
<td>% Load Held by Waist</td>
<td>18.2%</td>
<td>17.7%</td>
<td>18.1%</td>
<td>17.6%</td>
<td>18.2%</td>
<td>17.7%</td>
<td>18.0%</td>
<td>17.6%</td>
</tr>
</tbody>
</table>
Table C2: This table shows the shoulder and waist load carriage sums and related percentages for each of the models. All loads are in pounds.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 9</th>
<th>Model 10</th>
<th>Model 11</th>
<th>Model 12</th>
<th>Model 9: 3x Load</th>
<th>Model 11: 3x Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50th %ile Female</td>
<td>33.37</td>
<td>31.82</td>
<td>33.41</td>
<td>31.04</td>
<td>100.10</td>
<td>95.45</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50th %ile Male</td>
<td>7.35</td>
<td>6.76</td>
<td>7.36</td>
<td>6.26</td>
<td>22.05</td>
<td>20.27</td>
</tr>
<tr>
<td>Back Length Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Load Held by Shoulder</td>
<td>81.9%</td>
<td>82.5%</td>
<td>81.9%</td>
<td>83.2%</td>
<td>81.9%</td>
<td>82.5%</td>
</tr>
<tr>
<td>% Load Held by Waist</td>
<td>18.1%</td>
<td>17.5%</td>
<td>18.1%</td>
<td>16.8%</td>
<td>18.1%</td>
<td>17.5%</td>
</tr>
</tbody>
</table>

Table C3: This table lists the axial forces from the original, 50th percentile male and female models as well as the 50th percentile models with 3 times greater load applied.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 9</th>
<th>Model 11</th>
<th>Model 9: 3x Load</th>
<th>Model 11: 3x Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50th %ile Female</td>
<td>11.50</td>
<td>11.40</td>
<td>34.49</td>
<td>34.20</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50th %ile Male</td>
<td>-5.66</td>
<td>-6.47</td>
<td>-16.96</td>
<td>-19.40</td>
</tr>
<tr>
<td>Back Length Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Element Results (model element number)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS1 - Load lifter (7814)</td>
<td>21.87</td>
<td>20.42</td>
<td>65.61</td>
<td>61.25</td>
</tr>
<tr>
<td>TS2 - Superior Shoulder Strap (7815)</td>
<td>7.35</td>
<td>6.76</td>
<td>22.05</td>
<td>20.27</td>
</tr>
<tr>
<td>TS3 - Shoulder Strap Lower Attachment (7816)</td>
<td>-0.133</td>
<td>-0.458</td>
<td>-0.398</td>
<td>-1.374</td>
</tr>
<tr>
<td>TW1 - Waist Belt Lift Inferior Attachment (7817)</td>
<td>-11.90</td>
<td>-11.9</td>
<td>-35.71</td>
<td>-35.70</td>
</tr>
<tr>
<td>TW2 - Waist Belt Lift Superior Attachment (7818)</td>
<td>-5.35</td>
<td>-4.63</td>
<td>-16.05</td>
<td>-13.88</td>
</tr>
<tr>
<td>TW3 - Waist Belt Posterior Body Inferior (7822)</td>
<td>-11.90</td>
<td>-11.9</td>
<td>-35.71</td>
<td>-35.70</td>
</tr>
<tr>
<td>TW4 - Waist Belt Posterior Body Superior (7823)</td>
<td>-11.90</td>
<td>-11.9</td>
<td>-35.71</td>
<td>-35.70</td>
</tr>
</tbody>
</table>
Table C4: This table lists the axial forces from the original 10\textsuperscript{th}, 50\textsuperscript{th} and 90\textsuperscript{th} percentile female models and the models with TW2 removed.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td>10th %ile Female</td>
<td>10th %ile Female</td>
<td>50th %ile Female</td>
<td>50th %ile Female</td>
<td>90th %ile Female</td>
<td>90th %ile Female</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td>10th %ile Female</td>
<td>10th %ile Female</td>
<td>50th %ile Female</td>
<td>50th %ile Female</td>
<td>90th %ile Female</td>
<td>90th %ile Female</td>
</tr>
<tr>
<td>Back Length Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Element Results

<table>
<thead>
<tr>
<th>Element Results</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1 - Load lifter</td>
<td>12.31</td>
<td>12.31</td>
<td>11.50</td>
<td>11.50</td>
<td>11.34</td>
<td>11.34</td>
</tr>
<tr>
<td>TS2 - Superior Shoulder Strap</td>
<td>-5.21</td>
<td>-5.21</td>
<td>-5.66</td>
<td>-5.66</td>
<td>-6.06</td>
<td>-6.06</td>
</tr>
<tr>
<td>TS3 - Shoulder Strap Lower</td>
<td>23.54</td>
<td>23.63</td>
<td>21.87</td>
<td>21.78</td>
<td>20.41</td>
<td>20.13</td>
</tr>
<tr>
<td>Attachment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW1 - Waist Belt Lift Inferior</td>
<td>7.96</td>
<td>7.98</td>
<td>7.35</td>
<td>7.33</td>
<td>6.79</td>
<td>6.74</td>
</tr>
<tr>
<td>Attachment</td>
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<tr>
<td>Attachment</td>
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<td>-6.23</td>
<td>-5.35</td>
<td>-5.30</td>
<td>-4.62</td>
<td>-4.48</td>
</tr>
<tr>
<td>TW3 - Waist Belt Posterior Body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior Attachment</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>TW4 - Waist Belt Posterior Body</td>
<td></td>
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</tr>
<tr>
<td>Superior Attachment</td>
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</tr>
</tbody>
</table>

Table C5: This table lists the axial forces from the original 10\textsuperscript{th}, 50\textsuperscript{th} and 90\textsuperscript{th} percentile male models and the models with TW2 removed.

<table>
<thead>
<tr>
<th>Anthropometric Measure</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Percentile</td>
<td>10th %ile Male</td>
<td>10th %ile Male</td>
<td>50th %ile Male</td>
<td>50th %ile Male</td>
<td>90th %ile Male</td>
<td>90th %ile Male</td>
</tr>
<tr>
<td>Chest Percentile</td>
<td>10th %ile Male</td>
<td>10th %ile Male</td>
<td>50th %ile Male</td>
<td>50th %ile Male</td>
<td>90th %ile Male</td>
<td>90th %ile Male</td>
</tr>
<tr>
<td>Back Length Percentile</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Element Results

<table>
<thead>
<tr>
<th>Element Results</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1 - Load lifter</td>
<td>11.31</td>
<td>11.31</td>
<td>11.40</td>
<td>11.40</td>
<td>12.01</td>
<td>12.01</td>
</tr>
<tr>
<td>TS2 - Superior Shoulder Strap</td>
<td>-5.93</td>
<td>-5.93</td>
<td>-6.47</td>
<td>-6.47</td>
<td>-6.90</td>
<td>-6.90</td>
</tr>
<tr>
<td>TS3 - Shoulder Strap Lower</td>
<td>22.09</td>
<td>21.95</td>
<td>20.42</td>
<td>20.09</td>
<td>19.03</td>
<td>18.56</td>
</tr>
<tr>
<td>Attachment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW1 - Waist Belt Lift Inferior</td>
<td>7.37</td>
<td>7.34</td>
<td>6.76</td>
<td>6.70</td>
<td>6.26</td>
<td>6.18</td>
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<td>-4.63</td>
<td>-4.46</td>
<td>-3.93</td>
<td>-3.70</td>
</tr>
<tr>
<td>TW3 - Waist Belt Posterior Body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior Attachment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW4 - Waist Belt Posterior Body</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Superior Attachment</td>
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</tbody>
</table>