Ergonomics of the Rucksack: Timing, Accessibility, and Mobility Considerations

by

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ABSTRACT

Military equipment is designed to protect and support soldiers in the operational environment, which can be highly stressful, hazardous, and extremely challenging. In addition to the rigorous training that soldier's receive to operate under these conditions, they are also issued specialized equipment, spanning offensive, protective and supportive capabilities. It is critical that military equipment does not compound the stress that military personnel are likely to endure while deployed to a combat theatre. This paper examines the military rucksack as a crucial piece of equipment and the effects of rucksack design on the performance of military personnel. Specifically, we examine ergonomic factors of time, accessibility, and mobility which comparably have not received the same attention as other aspects such as load carriage and weight distribution. We report the results of three experimental studies with a group of participants designed to evaluate the drawbacks of current rucksack design from a human factors standpoint. Our results shed light on the most relevant problematic areas of current designs and the requirements for developing future more effective solutions.

Keywords: military equipment, rucksack design, performance, 3D printing, ergonomics, accessibility, mobility, time,

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CHAPTER 1. INTRODUCTION

Military equipment is designed to maximize protection and support for military personnel in the operational environment. Elevated levels of stress and frustration, caused by poorly designed equipment may hinder personnel capabilities. Combined with the dangers of the combat environment, equipment that impedes soldier performance, may significantly increases the risk for casualties.

In this study, I evaluated a supportive piece of equipment, the rucksack, which I speculate to have as much of an impact on safety and combat effectiveness as standard protective equipment. The rucksack is a fundamental piece of equipment for any combat troop and houses essentials such as ammunition, sleep systems, rations, spare batteries, and other necessary gear. These items may quickly translate into heavy loads for the carrier (Birrell et al, 2007). Military personnel in Iraq and Afghanistan, for example, have experienced rucksacks weighing 60-100 lbs, leading to limited mobility, accessibility, and injury (Birrell, et al., 2007, Murphy, 2011). There exists a significant body of work that addresses the rucksack limitations of load carriage and weight distribution. However, soldier’s continue to endure complications related to their rucksacks.

1.1 Focus of the Study

Despite the significant body of work on loads and weight distribution in military rucksacks, other ergonomic aspects such as the effect that time required to pack and unpack various loads has on the ability to organize, accessibility to essential gear based on precedence, and mobility while worn have not received the same attention. This may be attributed to the fact that in past conflicts military forces have often been able to establish forward operating bases (FOBs) which allow units to return to after a mission. With the ability to establish FOBs timing, accessibility, and mobility factors may not have been as significant to consider in the development of rucksacks. However, as potential threats are reassessed, specialists suggest that future conflicts will likely require combat troops to rely all the more on their equipment: "*learning how to cook their own meals, cover their faces in camouflage paint, dig foxholes and latrines, lay concertina wire and live out of their rucksacks*" (Schmidt, 2016). This constitutes an assessment of the current rucksack design and an evaluation of its ability to perform in future. This research investigates 3 ergonomic factors, time, accessibility, and mobility, that we hypothesize to play a critical role in the way military personnel interact with their rucksack.

1.1.1 Time

Time is a critical component of military strategy. Factors of time in regards to military strategy include government response, asset allocation and troop mobilization (JP 3-35, 2013). Within the many factors of military strategy lies a concept known as deterrence. Deterrence is ability to dissuade military action of an adversary without the overt use of force. A form of this deterrence is the ability to rapidly assemble and deploy combat troops that can arrive anywhere in the world within a 48-hour window. Among the many factors involved in this capability, the element of time is key. The time in which military personnel can mobilize is vital to achieving the mission's desired end-state (JP 3-35, 2013). In order to rapidly deploy these types of units, at the individual level, must be able to timely and efficiently pack their gear, which includes their rucksack. At the team and squad level, a few seconds of time may not seem like much, however, these few seconds begin to add up at the platoon, company, and battalion levels.

Minute tasks such as packing a rucksack before a mission or packing after staying the night in a patrol base come with an associated time cost. These time costs may be relatively subjective depending on the skill level of the packer and the sense of urgency of the situation. However, poor rucksack design may significantly impede the wearer's ability to quickly pack and organize their rucksack. In hurried situations packing often turns into rapid and arbitrary stuffing of the rucksack in order to get out of the area or onto the next objective and meet the time hack. In an operational environment, members of an element can only move as fast as the slowest individual within that group.

To illustrate the importance of time in regards to packing, let us consider the following scenario based on examples from military personnel experience: a Platoon Leader receives a mission and issues a warning order to their subordinates which contains the packing list of items to be taken on the mission. Following pre-combat inspections, the platoon will move on foot to their objective, where they will conduct various actions and await further instructions. Movement on foot can take a considerable amount of time and the actions on the objective, which may or may not involve combat, will add to the level of exhaustion the soldier may be experiencing. The platoon will set up a patrol base for the evening instead of returning to the FOB. A patrol base is often set up in terrain that adversaries would consider of little tactical value, which means it will probably move over rugged terrain (Army, 2004). Once established, several tasks must be conducted, including defining sectors of fire, withdrawal plans in case of an emergency, communications, and security. Sleep is lower on the priorities of work within the patrol base, so when it is time to withdraw, fatigue can make packing all the more tedious and time consuming. Small tasks such as rolling up a sleeping mat, changing into a pair of clean socks, or throwing on the rucksack can become increasingly frustrating as fatigue continues to build.

All these factors are considered part of the job and most military personnel tolerate the minute pains associated with the time it takes to pack and unpack their rucksack. However, these minute pains brought about by design flaws may further diminish a soldier's energy levels when the soldier is highly fatigued, making certain tasks increasingly frustrating. Thus, interfering with concentration and energy management. If these design issues could be decreased or eliminated it would allow military personnel the ability to focus on other essential tasks, leading to better performance in the operational environment.

In the context of this study, we examine time at the individual level, measuring the individual's interaction with their rucksack and the amount of time necessary to pack and unpack various loads, under various conditions. Through design, we aim to minimize time costs, and facilitate an interaction with the rucksack that allows the wearer more time to focus on the mission rather than packing and retrieving items.

1.1.2 Accessibility

Through accessibility analysis, the study aims to minimize the amount of detracting tasks in regards to rucksack related functions that soldiers may encounter and allow them to focus on tasks that are considered missional essential. Accessibility to contents of the rucksack is typically dependent on how frequent an item may be used. Items regularly needed may be packed at the top, while items needed occasionally will be placed based on precedence. However, there are instances when gear initially thought to be nonessential, suddenly becomes important and the soldier must now excavate through their rucksack to retrieve it. Additionally, equipment that is packed within the rucksack is generally not accessible while worn. It is important to realize that when the rucksack is worn, it is difficult to reach into the compartments for equipment. Therefore, this study considers accessibility when worn and accessibility when the rucksack is not worn as two distinct categories which must be incorporated in the overall considerations for accessibility. In this study, we have adapted the criteria from (Grandin, 2011) to define the different categories of accessibility in regards to carrying loads.

The first classification of accessibility is defined as *active interaction*, which considers the ability to access equipment within the rucksack, the manner in which items are packed, and the components that allow contents to be organized (Grandin, 2011). Active interaction is the primary focus of the accessibility portion of this study. The second classification, known as *passive carrying*, encompasses in-transit interactions with the wearer and factors of load-carrying (Grandin, 2011). Although secondary in the context of this study, passive carrying is still a critical factor. While immediate access to highly essential items can be mitigated through the use of the Fighting Load Carrier (FLC) - a tactical vest with MOLLE webbing that allows for an assortment of storage pouch configurations - there is no readily available method for retrieving items within the rucksack while it is worn, and the wearer is moving on foot. For example, a scenario where a soldier wants to access a portion of a their rations that are stored in a sustainment pouch on the sides of the rucksack, he/she may have to enlist the help of a fellow soldier, or stop and take off the rucksack in order to obtain these rations. The problem becomes more severe when access to the main body of the rucksack is needed, as opposed to just reaching into sustainment pouches which are generally more accessible. In this study, experimental testing was conducted to provide a better understanding of accessibility via passive carrying.

Another factor that was considered is the relationship between accessibility and time (as defined in our study). Previous research as well as direct accounts from military personnel suggest that these factors may be correlated. The active interaction classification of accessibility not only considers the ability to access contents, but also the organization of these contents and the components used in organization. The relationship between being able to efficiently utilize the space available and organize the arrangement of contents based on precedence will likely have a significant effect on the time it takes to pack a rucksack.

1.1.3 Mobility

For the purposes of this work, mobility is defined as the soldier's ability to get down into the prone position from an upright posture, stand up from a prone or seated position to an upright posture, to make sudden changes in momentum, and to maneuver terrain while wearing a rucksack.

When troops are in contact, there are a few courses of action that could take place. For example, troops may be instructed to execute bounding, which requires the ability to move quickly from the ground, to an upright position, to a rush to the next covered position, and then back down to the ground. These movements can be taxing, and even dangerous when under fire. The additional complexity of moving with a rucksack that inhibits the wearer's mobility, while simultaneously conducting military combat maneuvers, could results in catastrophic situations.

Movements under fire and closing with threats will require military personnel to traverse terrain. The following excerpt illustrates the impact of mobility. *"In Afghanistan a lieutenant led his patrol in hot pursuit of a Taliban band….When the officer dismounted his troops and sent them after their quarry, they fell even further behind, for each man had to clamber upward encumbered with 60 pounds of body armor, and well as weapon, ammunition, communications and survival pack. The officer aborted the mission."* (US Army Combined Arms Center, n.d.).

CHAPTER 2. LITERATURE REVIEW

2.1. Background

Throughout history, militaries have employed various methods for transporting necessary equipment and supplies. Armies have utilized pack-animals, oxen drawn carts, and their shoulders to move essentials to the front lines. Since the mid-1800s, US soldiers have utilized some form of a backpack as a means to transport food, ammunition, weapons and other materials to the battlefield. During the American Civil War soldiers used haversacks, similar to oat bags, to tote essentials such as bulk weaponry and medical supplies (Coggins, 2004). World War II brought about a series of canvas backpacks featuring straps, pockets, and frames, allowing soldiers to reliably pack more equipment. During the initial years of the Vietnam war, U.S. troops used the M1967 or the MLCE (Modernized Load Carrying Equipment) but in 1974 the U.S. Army began issuing the ALICE pack (All-purpose Lightweight Individual Carrying Equipment). The ALICE pack has an approximate capacity of 2500 cubic inches and featured a large nylon rucksack with an aluminum frame (Babeu, 2014). Today, soldiers carry the MOLLE (Modular Lightweight Load-Carrying Equipment) which replaced the ALICE pack, and was designed based on soldier feedback. The MOLLE rucksack has a capacity of approximately 3000-4000 cubic inches depending on the configuration (see Figure 1).

This rucksack is part of a system for load carrying which includes a Fighting Load Carrier (FLC), a rucksack frame, the rucksack, sustainment pouches, six lashing straps, waist pack, hydration system, and an assortment of pouches, as shown in Figure 2 (US Army Natick Soldier Center, 2010).

Figure 1. Current State of the Art: Modular Lightweight Load-Carrying Equipment

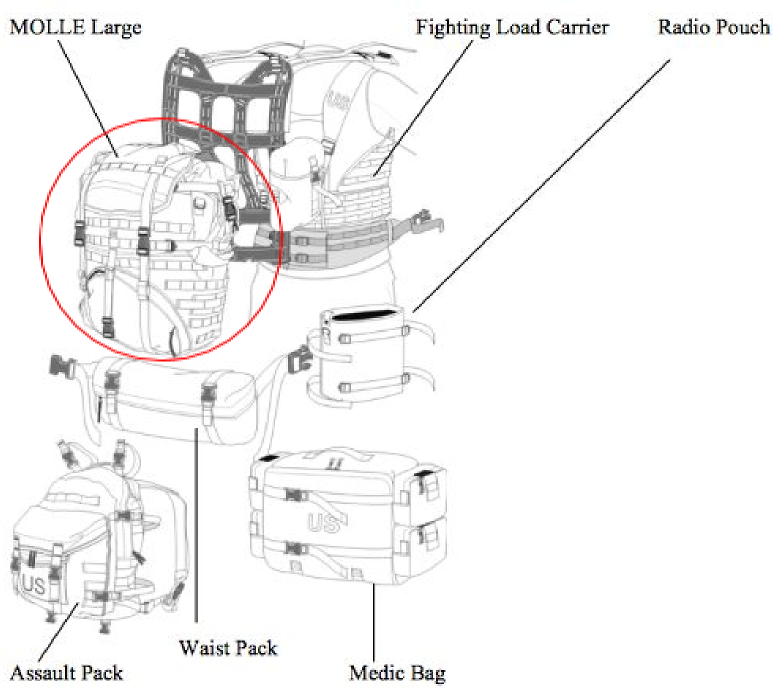


Figure 2. Modular Lightweight Load Carrying Equipment System, adapted from MOLLE II Use and Care Manual (US Army Natick Soldier Center, 2010)

To understand the issues related to rucksack design, it is important to examine the types of loads that military personnel can be expected to carry. A typical 40-100 lbs load on a soldier's back for extended periods of time as well as as an ineffective rucksack design can put a significant physiological strain on the individual. The load is a critical component of planning for military commanders. The weight, configuration, and contents of a load will greatly depend on the mission. A soldier's load will contain equipment necessary to complete the mission and sustain continuous operations. In the same manner that commanders must consider external threats to the mission, so too, must they consider the risk of injury and exhaustion during the mission due to excessive loads (ATP 3-21.18, 2017) .

To prevent carrying everything during the mission, commanders utilize the method of echeloning loads. There are three echelons of loads: combat loads, sustainment loads, and contingency loads. Combat loads are the minimum essential equipment needed to fight and survive during the immediate operation. Sustainment loads are comprised of equipment needed to sustain operations and is usually left with a support element and can be brought up to the front when needed. Contingency loads are for equipment that is not necessarily for ongoing mission, such as extra clothing. For the purposes of this study we will focus on the echelon of combat loads.

There are three types of combat loads: fighting load, approach march load, and emergency approach march load. The *Fighting Load* is comprised of essential items that are needed for the soldier to maneuver and close with threats. The fighting load is worn on the individual. The *Approach March Load* is made up of the fighting load and additional essential equipment. This equipment is packed within the rucksack and weighs approximately 30 lbs (a conservative estimate, as other items may be necessary depending on the needs of the mission). A standard fighting load and approach march load with accompanying weights of each item are shown in Table 1. The total weight is approximately 100 lbs, not including the weight from the contents to be placed in the rucksack.

Table 1. Fighting load and Approach March Load - possible items carried (adapted from (Headquarters, Dept of the Army, 2017))

Fighting Load	**lbs.**		**Approach March Load**	**lbs.**
Uniform complete (ACU, T-shirt, socks, boots, belt, patrol cap)	7.8		Assault pack	3.1
Advanced combat helmet	4.2		T-Shirt	0.2
Field load carrier (FLC)	5.8		Socks (2 pair)	0.4
Knee pads	0.5		Wet weather top and bottom	3.0
M4 (no magazine)	6.4		Poncho	1.0
5.56 unit basic load (UBL; 210 rounds and 7 magazines)	7.0		Poncho liner	1.5
AN/PEQ-15 (ATPIAL)	0.5		Weapons cleaning kit	1.0
M68 (CCO)	0.9		Entrenching tool with carrier	3.5
AN/PAS-13(V)1 (LWTS)	1.9		2-quart canteens (2 each)	10.0
AN/PAS-14(MNVD) includes helmet mount	1.2		MRE (3 each, stripped)	4.2
Soldier Plate Carrier System (SPCS)	5.9		**Subtotal**	**27.9**
SAPI (font and back), SBI (sides)	16.0		Add Fighting load	68.9

<table>
<tr><td>1 quart canteens (2 each, with water)</td><td>4.6</td><td rowspan="7"></td><td>Total</td><td>96.9</td></tr>
<tr><td>MRE (1 each, stripped)</td><td>1.4</td><td colspan="2" rowspan="6">Legend
ATPIAL: advanced target pointer illuminator aiming light
ACU: Army combat uniform
CCO: close combat optic
LWTS: light weapon thermal sight
MRE: meals, ready to eat
MNVD: monocular night vision device
SAPI: small arms protective inserts
SBI: side ballistic insert</td></tr>
<tr><td>M67 fragmentation grenades (2 each)</td><td>2.0</td></tr>
<tr><td>Compass</td><td>0.5</td></tr>
<tr><td>Bayonet w/scabbard</td><td>1.3</td></tr>
<tr><td>Individual first aid kit</td><td>1.0</td></tr>
<tr><td>Subtotal</td><td>68.9</td></tr>
</table>

2.2. Load Carriage And Weight Distribution

Carrying equipment into battle has long been a concern of commanders. Throughout history the weight carried by foot soldiers remained around 40 lbs. This weight increased to approximately 60 lbs in World War I, and again to 80-90 lbs World War II (Lehmann, 2000). Within the last three decades soldiers have continued to see increases in the amount of weight they carry.

There is evidence that shows that overloaded personnel can suffer significant reductions in combat effectiveness. For example, during operation “Urgent Fury,” the 1983 Invasion of Grenada, soldiers were so weighed down that they could hardly move when seizing an airstrip: “...*we were like slow moving turtles. My rucksack weighed 120 pounds. I would get up and rush for 10 yards, throw myself down and couldn’t get up. I’d rest for 10 or 15 minutes, struggle to get up, go 10 more yards, and collapse. After a few rushes, I was physically unable to move and I am in great shape. Finally, after I got to* *the assembly area, I shucked my rucksack and was able to fight, but I was totally drained.”*

In certain instances, weight overloading has resulted in mass casualties (Knapik et. al, 2010). During the D-Day invasion on Omaha beach during World War II, soldiers were loaded into landing craft vehicles approximately 10 to 11 miles off-shore and made their way to the beach head. As the LCVs (landing craft vehicles) approached, they came under heavy fire and many LCVs were forced to lower their ramps prematurely before landing on the beach. Many of the Soldiers disembarked into water above their heads. Weighed down by the equipment they carried, several struggled to stay above water, and many drowned (Lewis, 2003).

In 2003, a study on combat loads conducted during Operation Enduring Freedom concluded that today's soldiers still carry excessive weight on their backs (Assessment, 2003). However, the weight is comprised of essential equipment and gear that the soldier cannot leave behind on missions. Excessive weight combined with the harsh environment and the strains of combat can severely undermine soldier's’ performance (Dean, 2008). The problem of heavy load carriage continues to persist today as personal protective equipment, body armor, and advanced combat technologies add to the weight soldiers must carry.

Considering the weight military personnel must haul depends on many factors that retain considerable levels of variability, a definable “light load” may never be realized (Babeu, 2014). Currently, there are several solutions being developed to alleviate the issues surrounding load carriage and weight distribution such as robotic suites with supportive spines that enable soldiers to carry more weight (Machi, 2017), mechanical exoskeletons that are worn by soldiers and assist with load carriage (Slocombe, 2015, Yu, et al., 2014), and even autonomous robots that follow combat elements and act as a mechanical pack mule, hauling the heavy equipment of military personnel (Stimpert, 2014).

In this research study, we investigate ergonomic factors of rucksack design which have been comparatively overlooked and may affect the ability of the soldier to carry necessary equipment and perform on the battlefield. Limiting factors of rucksack design that are not addressed during the development process may result in adverse conditions during combat operations. Restrictions related to design flaws may also cause physical discomfort which could possibly lead to decreased performance and increase the risk for injury (Opincă, M., Antip, A., Deaconu, A. 2013). In this regard, it is imperative to develop supportive equipment just as much as protective equipment.

CHAPTER 3. RESEARCH METHODOLOGY

A mixed methods approach was used for data collection and analysis. Both qualitative and quantitative data, subjective and objective, were gathered to capitalize on the strengths of each method and broaden the understanding of the problem (Creswell, 2013).

To examine personal interactions with the current military rucksack, survey data was collected from personnel with military experience and familiarity with the standard MOLLE rucksack. The survey consisted of 11 questions, 8 of which were recorded using a 5-point Semantic Differential scale to facilitate quantitative analysis. Three open ended questions were included to allow participants to share their experiences using their own words. This portion of the survey remains qualitative but allows for broad feedback from participants which is critical in developing an understanding the issues with current designs (See Appendix A).

Additional quantitative data was collected via three experiments aimed at measuring different aspects of a soldier's performance and interaction with the rucksack. Studies that evaluate military backpack systems generally use a 2-mile ruck march, an obstacle course, timed specific military maneuvers, and marksmanship as common performance measures (LaFiandra et. al., 2003). However, this research examines ergonomic factors that place a greater emphasis on user interaction, organization, accessibility, and mobility. Therefore, performance measures from similar studies were adapted by emphasizing the specific factors to this work. Research methods also included the use of subject matter experts spanning a wide range of expertise. Experts in rucksack use, combat operations, and military apparel retail were interviewed as a part of the data collection process. These individuals would also be utilized throughout the design process as well as validation.

3.1 Participants Selection

A group of 10 healthy subjects volunteered to participate in the study. To be considered for participation, subjects were required to meet the following criteria: age between 18 to 35, past or current military personnel (including military cadets) who have completed at least a 12-mile ruck march, with at least one week of living in field conditions, and are in good health as indicated by the participant. As a safety measure and as a method to ensure data integrity, individuals without prior experience using a rucksack were excluded from the study. Demographic data of our study are shown in Table 2.

The research protocol was approved by the University of Houston Institutional Review Board. All subjects gave informed consent prior to participation and were informed about the purpose of the study, the testing protocol, the potential risks associated with testing, measures taken to ensure safety, and acknowledged that their participation was completely voluntary and they could withdraw at any time. Participants were allowed to conduct any preparatory physical task they considered necessary to be in a ready physical state for testing. The study was conducted at various locations at the University of Houston, including the Energy Research Park, and the Carl Lewis International Complex. Criteria for site selection included safety, adequate space necessary to conduct the testing, likelihood of minimized interruptions, and control of the environment.

Table 2: Demographic data of the sample used in the study

Participant	Sex	Age	Height (in)	Weight (lbs)
1	M	Early 30s	76	235
2	M	Early 20s	71	190
3	F	Late 20s	66	153
4	M	Mid 20s	64	137
5	M	Late 20s	64	135
6	M	Early 20s	64	168
7	M	Mid 20s	68	179
8	F	Early 30s	64	142
9	F	Early 20s	63	120
10	M	Early 20s	73	200

The experimental portion of the study was divided into three different tests: (1) Pack & Retrieve, (2) Donned Accessibility, and (3) Mobility. To minimize the unwanted effects of the potentially competitive nature of the tasks as well as peer pressure among participants, all experiments were conducted individually, one subject at a time. Participants had no contact with the rest of the group before, during, or after the experiment. The standard MOLLE rucksack was used for all tasks. After each test, a NASA task load index sheet was administered to all participants to collect the subject's rate of perceived workload.

3.2 Experiment 1: Pack & Retrieve

The first experiment was designed to record the amount of time it takes a subject to pack an approach march load in three different scenarios: (1) at the subject's own pace, (2) as quickly as possible, and (3) as quickly as possible while simultaneously executing a fine motor skills task (i.e. solving a puzzle). Additionally, this test asked subjects to locate objects after they have been packed away to gauge the impacts of packing under various conditions on the ability to effectively organize items as they are packed away and locate them when they are needed later.

Subjects began the tasks with the contents of a rucksack laid out in front of them and instructed to start packing on the verbal command of "Go." Once all items had been packed, the subject was instructed to retrieve three of them from the rucksack. This was performed for three iterations following the sequence described below. Each iteration becomes gradually more complex than the previous one.

The items included on the packing list used in the experiment are shown in Figure 3.

3 tan t-shirts
3 pair green socks
3 pair undergarments
2 pairs of ACU blouse and trouser
2 wet weather bags
1 ACH (Advanced Combat Helmet)
1 pair of wet weather top and bottom
1 pair of desert tan combat boots
1 sleeping bag
1 sleeping mat
1 (MRE) Meal Ready to Eat
1 Pair of Elbow Pads
1 Pair of Knee Pads

Figure 3. Items used in experiment 1.

1st Iteration

The subject was asked to pack the items into the rucksack at their own pace. The subject was also free to organize the rucksack however he/she chose. The time it took to perform this task is recorded. This iteration was used primarily to familiarize the subject with the task, and served as a baseline for subsequent tests. After the subject had finished packing at his/her own pace, he/she was asked to retrieve three random items from the rucksack and record the time it took to retrieve them.

2nd Iteration

The subject was asked to pack the items into the rucksack as quickly as possible in their own manner. The time it took to perform this task was recorded. This iteration was used to gauge how quickly and effectively the subject can organize his/her rucksack. After the subject had finished packing he/she was asked to retrieve 3 items from the rucksack and record the time it took to retrieve them.

3rd Iteration

The subject was asked to pack the items as quickly as possible while simultaneously solving a fine motor skill task, i.e., solving a puzzle. The puzzle is meant to complicate the tasks and induce a mild form of stress that reduces the subjects ability to concentrate solely on packing a rucksack. This iteration is an attempt to replicate conditions of impaired concentration that military personnel may experience when quickly packing their rucksack in the operational environment, while simultaneously thinking of the upcoming mission or dealing with a potentially threatening situation. The time it took to perform the packing task was recorded. After the subject had finished packing, he/she was asked to retrieve three items from the rucksack and record the time it took to retrieve them.

3.3 Experiment 2: Accessibility

This test was used to examine how accessible items are from a rucksack while it is being worn and the subjects are walking. Although most pertinent items are generally carried on the fighting load carrier, there may be scenarios in which items packed into the main body of the rucksack would suddenly become relevant and are immediately needed. Therefore, evaluating the accessibility of the rucksack while it is being used may provide insight as to how accessibility can help or hinder in certain situations.

A track outlined with cones was set up in the shape of an oval. Subjects walked around this track while wearing the rucksack and were asked to reach for an item in either one of their sustainment pouches. The purpose is to reach the item as quickly as possible, but-no time limit was established. However, if the subject is unable to reach the item within the sustainment pouch after five minutes (a time we considered reasonable), he/she was given the option to quit this portion of the test. The time it took to reach the item, or the time it took before the subject voluntarily quit this test, was recorded.

3.4 Experiment 3: Mobility

This experiment was used to measure mobility (as defined within the context of this study) and aimed to understand the effects of current rucksack design on the soldier's ability to get up and down, quickly traverse terrain, and make sudden changes in momentum. Three parts were defined for the mobility test:

Part 1: The Get up, Get down Test

Subjects start in the prone position, don the rucksack, and stand. For each participant, the time to complete the task was recorded. Then subjects move from the standing position, remove the rucksack, and get into the prone position. The time to complete this task was then recorded. Additional feedback from the subjects on perceived effort was also recorded.

Part 2: 30m Shuttle Sprint

A single 30 meter lane was marked with a turnaround point at the furthest side of the lane. Subjects conducted a 30m sprint while wearing the rucksack from the designated starting point down to the 30m mark turnaround point and returned to the starting point. Time starts when the subject initiates movement down the lane and ends when the subject has reached the turnaround point and comes back to the starting position. The time to complete this task, as well as feedback from the subjects on perceived effort were recorded. Five minutes were then provided to recover.

Part 3: Mobility Course

The mobility course is in the shape of an "S." The course is as follows: straight ahead 10 meters movement, turn right 5 meters movement, turn right 10 meters movement, turn left 5 meters movement, turn left 10m movement. In the center of the course, there is an obstacle that subject was required to step over while conducting the second right turn 10 meter movement. The main purpose of this test was to observe the effects of significant changes in momentum.

CHAPTER 4. RESULTS AND ANALYSIS

4.1 Survey Results

A total of 45 responses were collected. Descriptive statistics and frequencies of responses are shown in Table 3 and Figures 4 and 5, respectively. Two distinct factors are measured in the survey: Factor 1 (Questions Q1-Q6, and Q9), and Factor 2 (Questions Q7 and Q8), as the Semantic Differential scales used in those questions are not comparable. Cronbach's alphas for the Factors 1 and 2 were .67 and .42, respectively. The major themes that emerged from the free responses (Q10 and Q11) are illustrated in Figures 6 and 7, respectively. Only ten responses were recorded for question Q11, the majority of which suggesting issues already addressed in previous questions.

Table 3. Survey Results (n=45)

QUESTION		Mean	Std. Dev.
Q1	The MOLLE rucksack is (1-Very uncomfortable, 5- Very comfortable)	3.18	0.89
Q2	Assembling the MOLLE Rucksack is (1- Very difficult, 5- Very easy)	2.64	1.09
Q3	Packing the MOLLE rucksack is (1- Very difficult, 5- Very easy)	3.82	0.89
Q4	How quickly do you think you can fully pack the MOLLE rucksack? (1- Very slowly, 5- Very quickly)	3.58	0.84
Q5	Accessing contents within the MOLLE rucksack is (1- Very difficult, 5- Very easy)	2.93	0.96
Q6	Keeping contents within the MOLLE Rucksack organized is (1- Very difficult, 5- Very easy)	2.73	1.05
Q7	The amount of straps in the MOLLE Rucksack is (1- Too many, 5- Insufficient)	2.36	0.98
Q8	The amount of compartments in the MOLLE rucksack is (1- Too many, 5- Insufficient)	3.76	0.77

Q9	Mobility (i.e., walking, turning, bending, crouching, etc.) while wearing the MOLLE rucksack is (1- Very limited, 5- Very enabled)	2.78	1.13

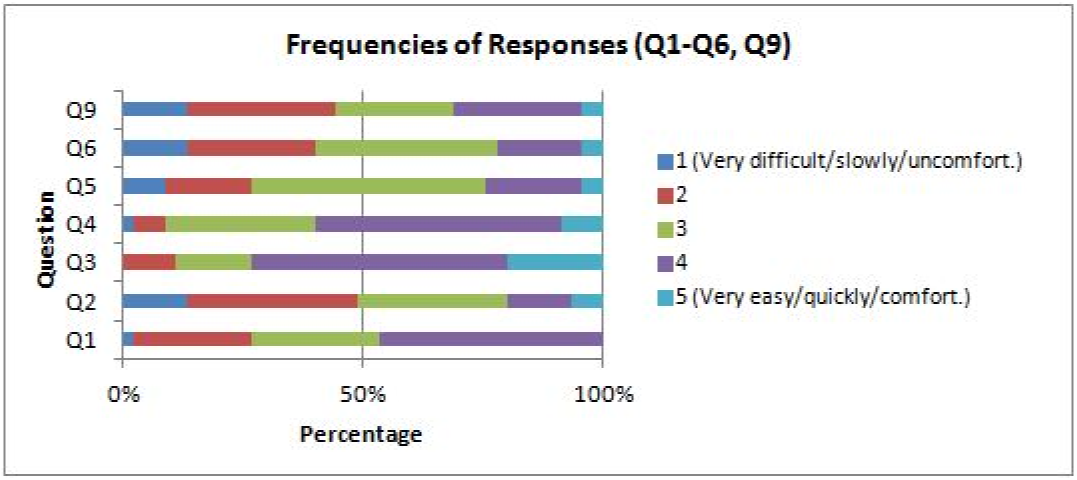


Figure 4. Frequencies (%) of the participants' responses (Questions 1-6, and Question 9)

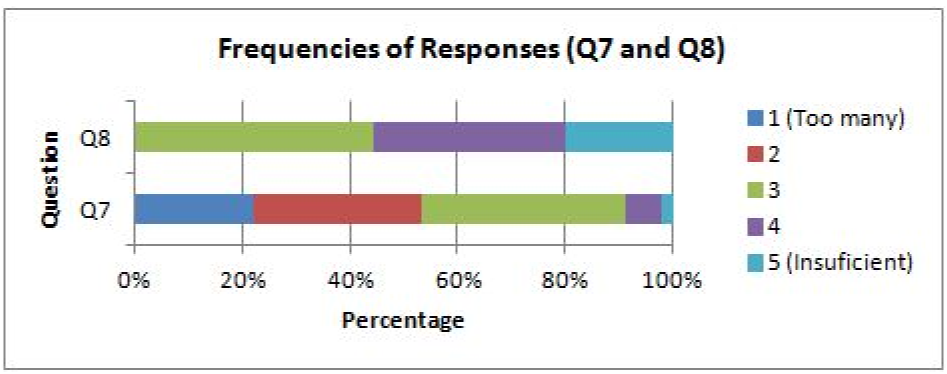


Figure 5. Frequencies (%) of the participants' responses (Questions 7 and 8)

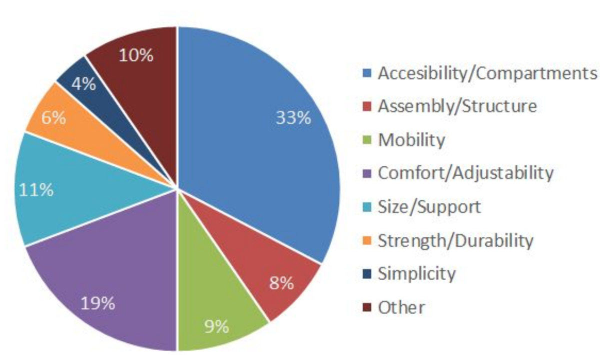


Figure 6. Major themes in response to Q10

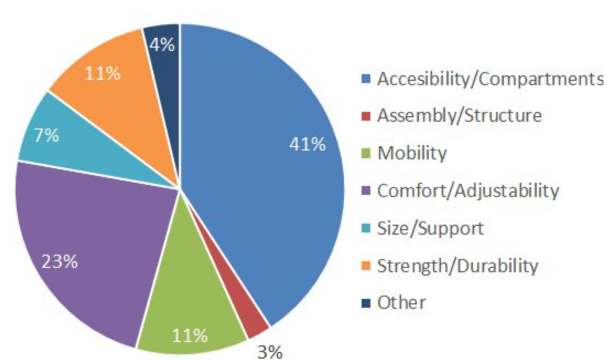


Figure 7. Major themes in response to Q11

Participants were able to respond to open ended questions within the survey. Many of the responses confirmed initial speculations about the shortcomings of the current design, however, there were responses that shed new light on issues that users experience. Below are some of the most significant responses. To determine their significance, replies were compared for novelty, frequency, and relevance.

“The ability to organize gear more easily. Ie more compartments rather than just two large compartments and a couple of sustainment pouches. Mobility while wearing body armor. Comfort, a rigid frame that doesn’t inhibit its ability to conform to the individual.”

“More compartments to allow easy access to gear without unpacking entire ruck”

“Accessibility...comfortability for long distance”

“Better compartments and better back straps”

“Ability to keep weight high and close to the top of your back; ease of access to contents; compact in size”

“Good weight balance, ease of access in stressful situations (i.e. combat), easy to assemble and disassemble”

“Have more zippered compartments in the main pouch of the ruck so you can separate wet/cold weather gear, sleep systems, extra clothes and gear...it’s all about providing the Soldier with the ability to quickly get to the gear/equipment he/she needs without having to dump the whole ruck out then rapidly repack it and lose your entire system of organization.”

“It's just too cumbersome and large. The comfort level for its size is sub par and its maneuverability it's not advantageous to the infantryman”

“Size of frame, smaller frames available for women and small men”

“The plastic hard frame cracks”

4.2 Experimental Results

The results of the three experiments are reported in Table 4. The Perceived Task Load Results from the NASA TLX test are shown in Table 5. The weighting step of the TLX procedure was intentionally discarded based on conventional practices, as comparable validity for workload can be obtained. Instead, we used the Raw TLX (RTLX) method by averaging the TLX ratings from various instances of the same tasks to determine the overall workload (Hart, 2006).

Table 4. Experimental results (n=10). Time in seconds.

Experiment	Task	Mean	Std. Dev.
Exp. 1 *Timing*	**Iteration 1:** *No time constraints*	239.50 (pack) 20.22 (retrieve)	89.63 (pack) 7.17 (retrieve)
	Iteration 2: *Time constraints*	157.80 (pack) 17.30 (retrieve)	61.23 (pack) 6.15 (retrieve)
	Iteration 3: *Time constraints+Fine motor skills*	213 (pack) 16.90 (retrieve)	54.50 (pack) 4.65 (retrieve)
Exp. 2 *Donned accessibility*	*Retrieve MRE (1 participant unable to finish)*	45.44	24.61
Exp. 3 *Mobility*	**Part 1:** *Get up / Get down test*	5.82 (get up) 6.33 (get down)	2.12 (get up) 3.95 (get down)
	Part 2: *30m shuttle sprint*	11.81	1.55
	Part 3: *Mobility course*	9.53	1.55

Table 5. TLX Results (mean and standard deviation). Scale from 1 to 100, with higher scores indicating more strain.

Task	Mental Demand	Physical Demand	Temporal Demand	Performance Demand	Effort	Frustration	Raw TLX Score
	How much calculating, remembering assessing required?	How much physical exertion required?	How much time pressure was felt, satisfaction with rate/pace?	How successful [were you] at accomplishing the task?	How hard did you work to accomplish your performance level?	How insecure, discouraged, stressed vs. secure, gratified and relaxed did you feel during the task?	Averages across categories for overall score per task.
Packing	M:29	21	50.5	25.5	47.5	25.5	33

	(SD:20.1)	(19.9)	(23.6)	(16.7)	(26.4)	(23.3)	(21.6)
Donned Accessib	45.5 (20.2)	48.5 (18.7)	67 (22.7)	55 (25.8)	74 (12.4)	57.5 (29.3)	57.9 (21.5)
Mobility	28.5 (16.6)	52.5 (31.2)	55.5 (28.5)	27.5 (21.3)	55 (28.8)	19.5 (14.4)	39.7 (23.4)

4.3. Discussion

The current rucksack design received average ratings from survey participants. Specifically, assembly, organization, mobility, the number of straps (too many), the number of compartments (insufficient), and accessibility seemed to be the categories where the majority of the participants have experienced issues, as suggested by the responses to questions Q2, Q6, and Q9. The responses from the survey reinforced our premise that organization, accessibility, and mobility are among some of the major issues that users experience with the current rucksack design.

Feedback from the free response section of the survey lays out precisely the challenges that military personnel regularly experience with their rucksacks. Some responses even suggest potential solutions to these issues. One of the most compelling considerations about the open ended questions is the convergence observed among responses. Accessibility to contents once they have been packed away is the most mentioned topic. Several participants specifically mention this as a shortcoming of the current design and call for future developments to incorporate a means to access items within the rucksack more efficiently. Also mentioned various times is the issue of organization within the main component of the rucksack. Although the MOLLE rucksack is equipped with webbing along its exterior where additional pouches can be fixed, there is almost no compartmentalization on the inside of the rucksack. There is a horizontal flap with a zipper that vertically separates the lower-third from the upper two-thirds of the rucksack. However, this is typically used to store the sleep system. Other issues the are mentioned several times include: integration of the hydration system, rucksack quick release mechanisms, location and number of cinching straps, waterproofing, comfortability, frame sizes, waist belt, and health issues related to rucksack wear. In addition, many participants expressed their elation about research being conducted on this matter. One participant from the survey reached out to a member of the research team and wrote the following: *"I'm glad you're tackling this topic... Having the proper storage, organization and the ability to rapidly get to the clothing/gear/equipment you need is imperative during field training exercises, at high-speed/smoke-show schools and, most importantly, in combat scenarios."*

The behaviors, techniques, and interactions observed and documented during the experiments add an element to the development process that substantially complements the quantitative data collected. During the Packing and Retrieving test, one of the initial observations was that participants took the assigned task as almost a competition against themselves. They were pushing themselves to pack quickly and execute the task as well as they could, even though there was no pressure to perform in this manner. We observed that participants moved rapidly and handled the rucksack quite roughly. Often participants would vocalize their frustration with how tedious packing the items was, being able to fit everything into the rucksack, and closing/cinching the rucksack. In the 1st iteration, most rucksacks were packed with a higher degree of organization and the overall shape of the rucksack was generally uniform. These results could provide an explanation to the large number of positive responses to question Q3 where more than 70% of participants claimed packing the current rucksack is easy or very easy (the survey was conducted under normal non-stressful conditions). However, During the 2nd and 3rd iterations which imposed stressors of time and a distracting fine motor skill task, we noticed that participants did less organizing as they packed. Instead, they stuffed them as quickly as possible, not caring where exactly items went. This behavior was to be expected. As the stress is increased through the iterations, the participant’s ability to actively organize their rucksacks began to diminish. Additionally, the uniformity of the rucksack and weight distribution were also affected by these stressors. During the 2nd and 3rd iteration many of the rucksacks were bulky, unevenly proportioned, and not completely cinched down.

After each packing iteration participants were asked to retrieve three items that were packed within the rucksack. Initially, we believed the variable of time would be an important factor, and we speculated that the amount of time it would take to retrieve items from the rucksack was greatly dependent upon the conditions under which the rucksack was packed. We found this not to be the case, and subjects were able to locate items within the rucksack rather quickly, typically under 30 seconds. However, participants were digging ferociously through their rucksack, displacing the contents that they had just packed. We found that subjects could not necessarily recall where exactly items were, only the general location of the item. Participants frantically rummaged through the rucksack, undoing the packing they had just done to retrieve something. Participants were frustrated that they could not rapidly locate equipment that they had just packed away minutes ago.

In the second experiment, Donned Accessibility, participants were tasked with retrieving an MRE from the sustainment pouch, without taking the rucksack off and continuing to walk without stopping. None of the participants could retrieve the MRE in a natural manner. Many of the participants had to contort their posture in order to even reach the clips of the sustainment pouch, which is just the first step. Manipulating the clasps, lifting the flap, and undoing the draw string added to the level of frustration that participants displayed. Once the sustainment pouch was open, participants still had to physically pull the MRE out, which proved to be difficult. Some tried to lightly jostle it out, while others pulled and yanked. Although some participants retrieved the MRE in under a minute, it was not without a high degree of strain. Many participants were observed grimacing their faces and gritting their teeth while conducting this experiment. One participant could not retrieve the MRE after a minute of trying and decided to not continue. It is important to note that many of the issues experienced while trying to retrieve the MRE from the rucksack would more than likely be exasperated if participants wore body armor, an ACH, and carried a weapon. Additionally, the noise generated by the way in which participants moved do not adhere to standards of noise discipline, making some of these methods unsuitable for the operational environment.

The final experiment tested mobility of the participant while wearing the rucksack. During the 30m shuttle sprint, a notable observation was the way that participants braced themselves against the rucksack in order to further secure the load to their bodies. To many of the participants, the orientation of the load, shoulder straps, chest strap, and waist belt did not adequately secure the load to the body for rapid acceleration and momentum changes. In those that did not use a bracing method, the rucksack could be observed countering the momentum of the participant.The S-mobility course revealed that executing multiple direction changes while simultaneously alternating between acceleration and deceleration caused the load to sway on the participant’s back, and also changed their natural stride pattern. In the Get up/Get Down task, the participants used a variety of methods to doff and don the rucksack and move into the prone position/standing positions. We observed the use of the quick release system by some participants. Those who used the quick-release feature of the rucksack were among the quickest to get into the prone position. However, the rucksack would often clip the lower body of the participant as they were getting down. As a result, when it was time to conduct the Get up portion of the test, participants who had used the quick release system getting down, took the longest to reconfigure the rucksack and get into the standing position.

Responses from the TLX indicated that the majority of the participants experienced the most strain during the donned accessibility experiment, followed by mobility and packing. The higher levels of strain experienced during donned accessibility are a direct reflection of limited access to contents within the rucksack while it is worn. Many of the participants verbally and non-verbally communicated their frustration during this portion of the testing. Donned accessibility reported the greatest levels of strain in 5 of 6 categories measured in the TLX, which suggests that this aspect is a critical issue that needs further attention. Mobility while the rucksack is worn accounts for the second greatest amount of strain by participants. The highest level of strain was reported in the Effort category. We hypothesize that much of this strain can be accounted for in the way participants braced themselves against the ruck in addition to conducting mobility tests. Securing the load as close to the body as possible is an important factor of load carriage. There are features within the rucksack that facilitate this action, however, participants were observed compensating for the remaining slack within the rucksack through bracing. Additionally, we speculate that the Get up/Get down test increased the strain of effort. The engagements with the quick release system presented challenges to the participants that furthered complicated the tasks during the mobility tests. We believe the feedback from the mobility portion of the TLX exposed another flaw in the current rucksack design, which is the way the load is secured to the body, and the usability of the quick release system. Packing featured the least strain according to the TLX. However, it was only a 6.7 point difference from mobility. The results from the TLX do not necessarily correlate to the responses from the survey in terms of accessibility.

The results of the TLX seem to indicate that there is a marginal amount of strain while the responses from the survey indicate that packing and retrieving items presents a high level of strain. We believe that conditions under which the packing test took place did not adequately replicate the degree of stress and fatigue that operational or combat environments are composed of. This limitation likely accounts for the minor discrepancy between the TLX and responses from the survey.

CHAPTER 5. DESIGN APPROACH

After the initial survey, testing, and data analysis, relevant links were established between the newly collected data and the original intent of this study: the factors of time, accessibility, and mobility. This information formed the foundation of the design approach. The ideation phase was broad in terms of which specific components to focus on. The incorporation of user feedback, survey, experimental data and observations were critical in forming a more coherent direction. The focus was directed away from specific components of the rucksack to categories under which these components fall (time related, accessibility, or mobility).

The following issues were identified. The considerations outlined act as guides for the duration of the ideation and prototyping processes.

5.1 Design Considerations

5.1.1 Time

Time is a critical component of military strategy. One of the greatest time consuming task when it comes to a rucksack is assembly. According to the survey responses, the current assembly process can be confusing and time consuming. This research explored methods by which attaching components to the rucksack frame was simpler or would completely remove the need to assemble the rucksack. Another time consuming task is retrieving items once they have been stored. For this issue, possible solutions may include improving features that can reduce the time to takes to locate items once they have been packed away such as including more compartmentalization capabilities or internal pockets made of transparent but durable material, or insertable features that allowed for a dedicated storage sleeve

5.1.2 Accessibility

By far the most mentioned issue by participants. Accessing contents within the rucksack once they have been packed away can be difficult and cumbersome. This Master's Thesis explored methods in which users can keep the contents of their rucksack effectively organized, while being able to efficiently access them even after they have been stowed away. One of the key considerations for accessibility is being able to retrieve items from the rucksack without having to completely undo the rucksack.

5.1.3 Mobility

For this issue, the rucksack frame is the main focus of the study. Frames were mentioned several times by participants as either being too rigid, uncomfortable, and improperly sized. The material, size, and fit of frame can play a significant role in the user's ability to execute maneuvers within the operational environment.

5.2 Design Process

5.2.1 Ideation

Following the identification of specific design issues, ideation and prototyping began. Many of the ideas generated are continually being developed throughout the entire design process. The ideation process aided in further design exploration, and helped to consolidate the issues that were most relevant to this Master's Thesis.

A significant contributor to the design development process was the Department of the Army's Request for Information (RFI) in regards to a Jungle Rucksack. This document states that the U.S. Army's Research and Development Center is looking to test a new rucksack. Within this document are guidelines, and design criteria that the rucksack would be expected to meet. The RFI stood in as a design brief that gave the design process parameters to design within. The document proved to be helpful in defining real-world expectations for the rucksack, however, it imposed significant constraints. The environment in which this rucksack would be used contains extememe elements. Ideas that were overly conceptual and lacked the ability to properly validate were among the first to be discarded. The elimination of these ideas from the design pool were important in developing concepts that align the expectations of the RFI.

There were several ideas produced, but the following concepts emerged as the most prominent at this time in the study (see Figures 8-12). They would be further developed during the prototyping phase.

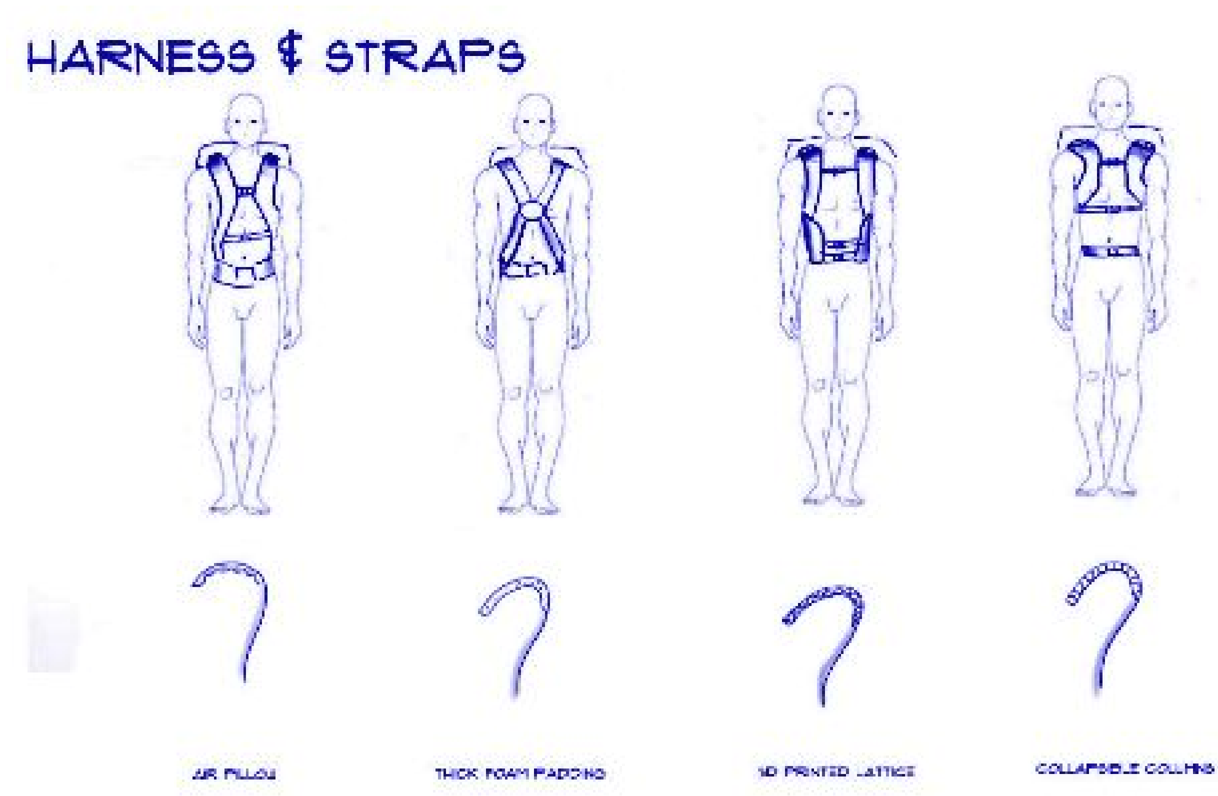


Figure 8. Shoulder straps, harnesses, and waist belts were part of the early ideation process. Shoulder straps affect the way a rucksack sits on the frame, and is also related to mobility.

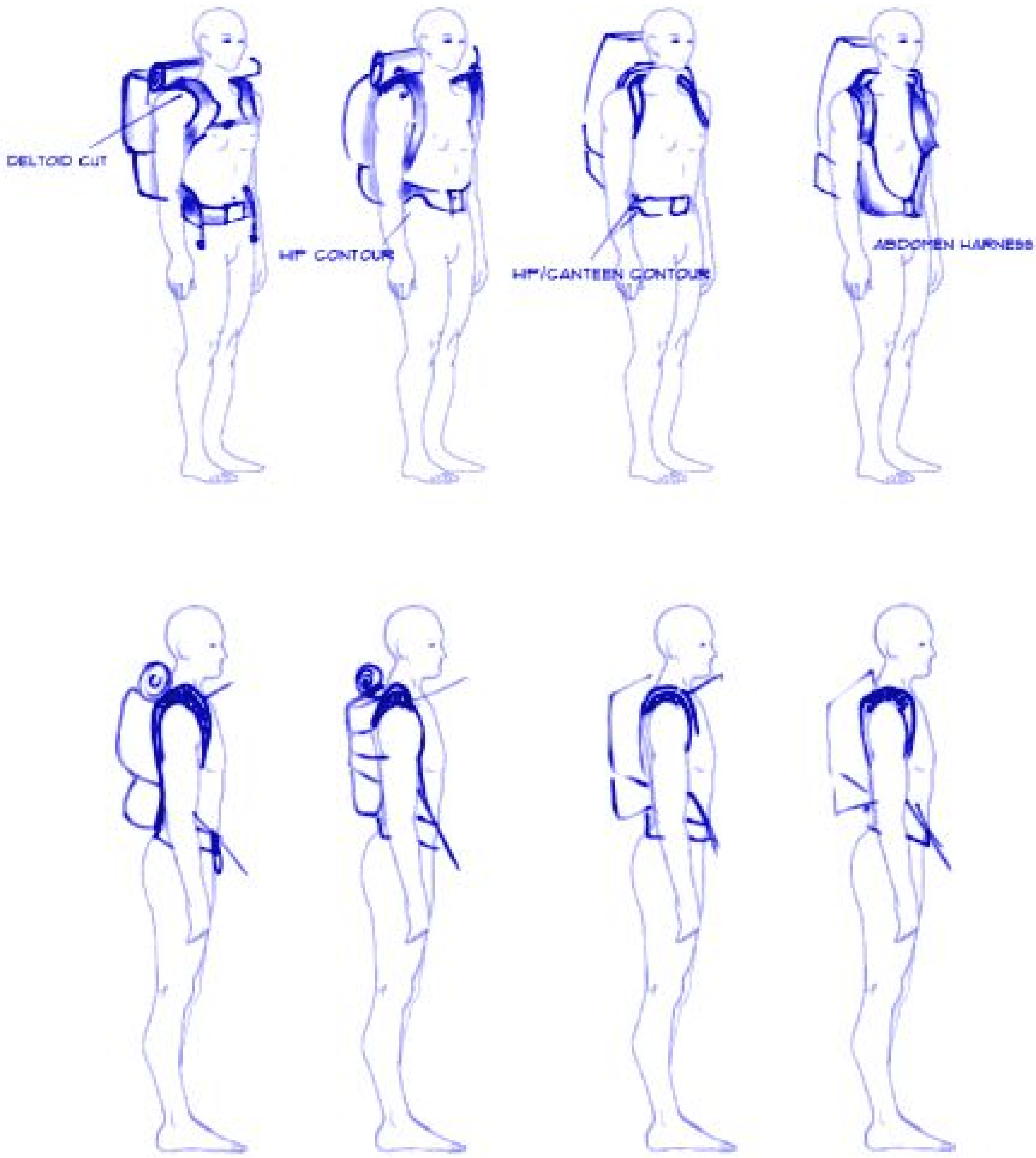


Figure 9. Interference in the shoulder region can create issues for the user when adjusting a load to achieve proper fit. Waist belts play an integral role in the transfer of weight from shoulders to hips.

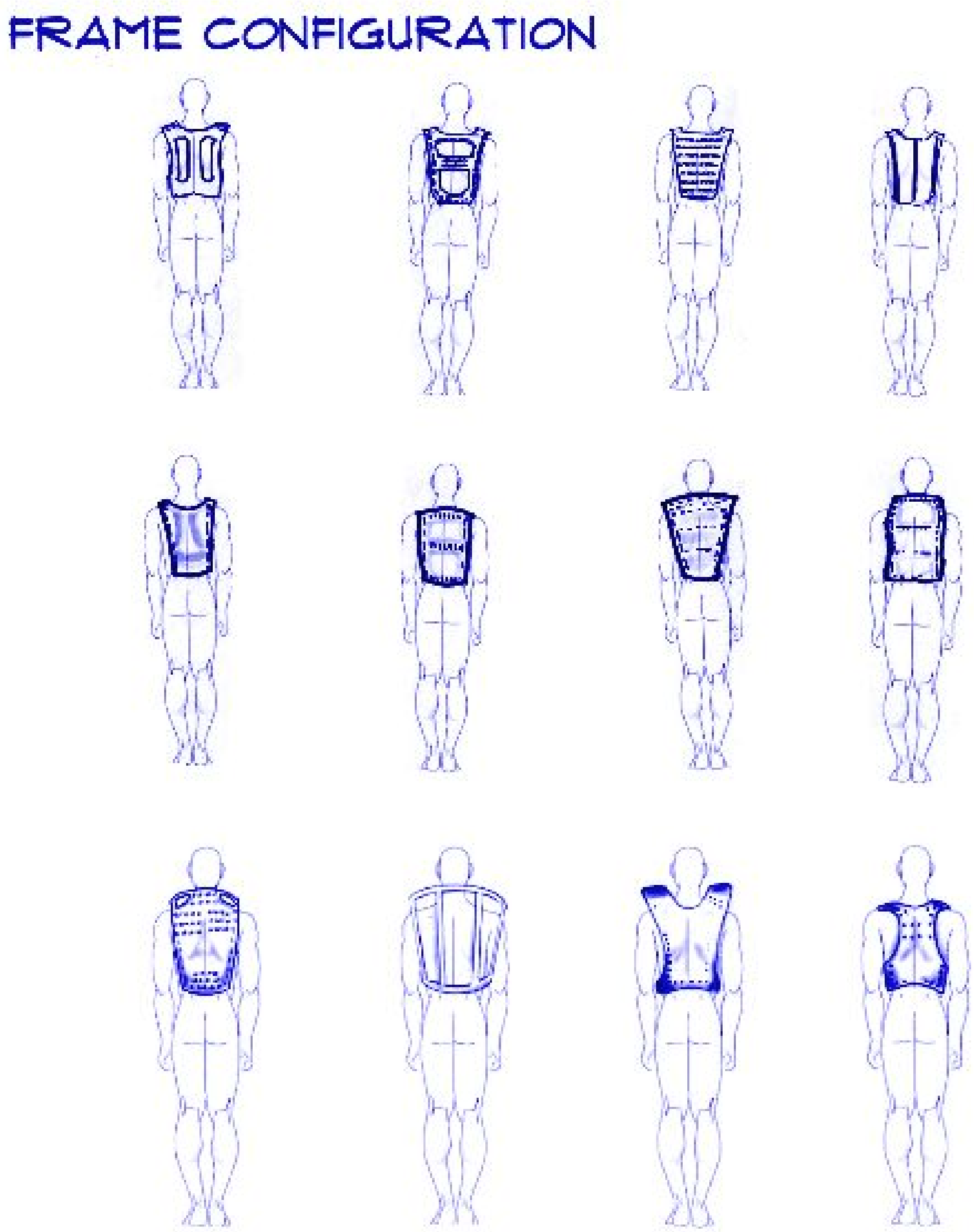


Figure 10. The frame is the foundation of the rucksack. This research study developed several different types of frames ranging from external, internal, combination frames, and 3D printed frames. The goal is to develop a frame that leverages the strength, flexibility, durability, and comfortability.

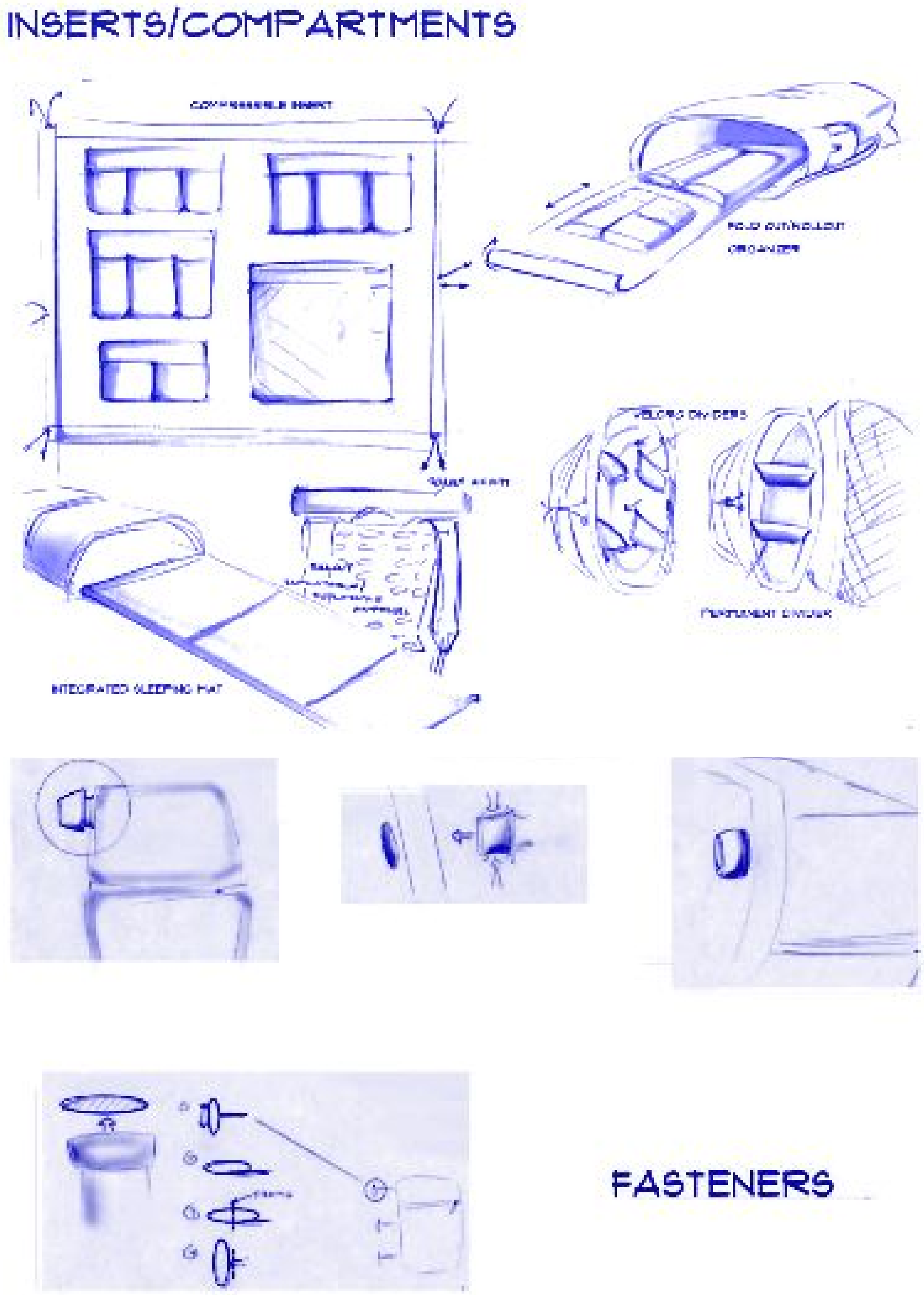


Figure 11. The insertable features compartments, and fasteners were all part of the early initiative to reduce interaction time for users. Inserts would make packing and retrieving items quicker. Compartments allow for greater organization within main body of the rucksack. The fastener system was developed to reduce the time it took to assemble the rucksack. This concept was later eliminated due to use of internal frame.

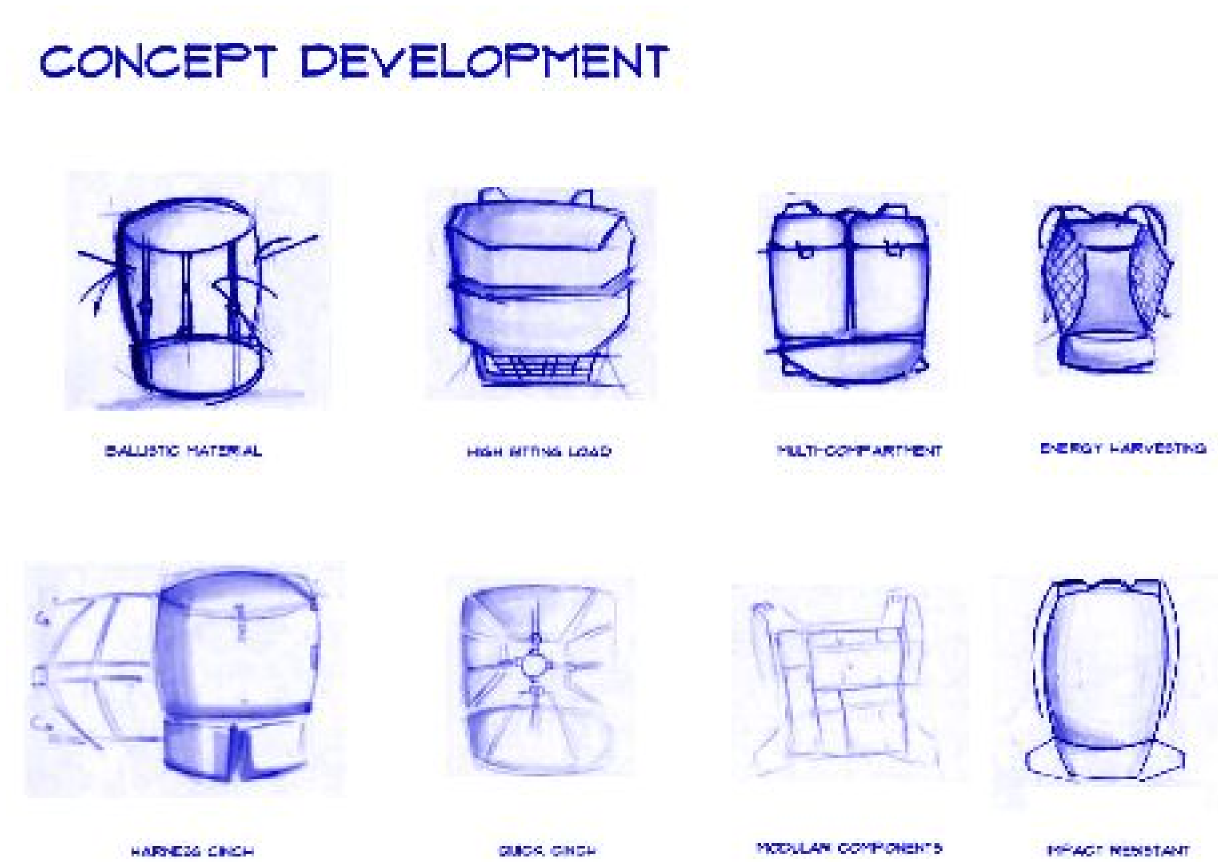


Figure 12. Additional concept ideas such as ballistic material, harnesses, and modularity. Ultimately, the process of divergent and convergent design thinking filtered out these designs to a final concept.

5.2.2 Prototyping

Concept refinement is continuous throughout the design process. In the early stages of prototyping, the focus began with the foundation of the rucksack, the frame. The frame is the primary component that bears the load of the rucksack and aids in transferring weight from the shoulders to the hips. There are two primary styles of rucksack frame: internal and external. Both frames have their own advantages and disadvantages. External frames can usually carry more weight, however, they are rigid and limit mobility. Internal frames boast comfortability and greater flexibility but lack the load bearing capacity and ruggedness of the external frames.

The first frame designed was an exploratory prototype (see Figure 13, left). Anthropometric dimensions were explored and a simple “wire-frame” external frame was built. An inspirational factor in the development of this prototype was the ALICE pack used in the Vietnam War era. Several anecdotal accounts from military personnel praise the ALICE pack for its comfortability, durability, but especially for its frame. The ALICE pack is made of aluminum and is quite simple in construction. Taking cues from the ALICE pack design, this prototype was also designed with aluminum. Aluminum is often used in both external and internal in rucksack frames. It is light, yet strong.

The second frame prototype was similar to the first. An exploration of dimensions with an aim to understand how and if a frame could wrap around the human form. This prototype was created with cardboard and was notched and folded and certain points to allow for contouring to the body (see Figure 13, center).

The third prototype took a different approach to frame development. The concept was developed from the idea of a hybrid frame, that leverages the strengths of both internal and external frames (see Figure 13, right). The goal is to make the frame from a dense rubber, nylon, or plastic that is strong yet flexible. It would be an insertable frame with components that were external to help with load bearing. However, midway through this development, expert feedback remarked that this idea would likely make the frame too heavy, hinder air flow which would suffocate the back of the user, and could develop degradation issues in the operational environment. In order to move the prototyping process along, an internal frame design similar to those used in existing rucksacks was developed. This will be discussed in the concept development section of this Master's Thesis.

Figure 13. Evolution of prototype design

5.2.3 Concept Development

<u>EELBE (Ergonomically Enhanced Load Bearing Equipment). Prototype 1</u>

The initial build of the main body was intended as a proof of concept as well as an experiential design exploration (see Figure 14). Many of the ideas developed during ideation were not fully implemented in this prototype. Due to time constraints only the critical features were incorporated.

Figure 14. First iteration of EELBE

In the front of the main body is sewn a heavy duty YKK # 10 zipper that would allow access to contents with the main body after they have been packed away. Inside the rucksack are sewn in storage compartments that make it easier to organized and recall where equipment has been stowed. Key features of this concept include an internal frame that is strong yet extremely flexible and insertable storage components. The frame was created with two sheets of polystyrene and notched so that shoulder straps can be interfaced and adjusted. This prototype was narrower based on speculation that the wide rucksacks can disrupt linear balance. Also, this first iteration was developed with what is known as “slick sides”, or no MOLLE webbing on the lateral panel of the rucksack. This was done in accordance with the RFI, which outline that future rucksacks should forgo MOLLE webbing on the sides in order to reduce snagging on vegetation in the operational environment. The concept for the shoulder straps were developed to minimize range of motion limitations in the shoulder region.

Upon completion of the first concept, it was fielded to participants and subject matter experts for review. One of the most notable comments from reviewers was in regards to the central zipper that provides access to the main body. The major concern was that the rucksack would not survive airborne operations, so the zipper alone compromised the structural integrity of the rucksack. Their recommendations included the addition of a method of reinforcement that helped to displace forces the zipper could sustain and act as redundant securing should the zipper become compromised. In regards to the insertable/detachable compartments, there were mixed reviews. Some users did not like the attachments and felt as if they impeded their interactions with the rucksack. However, SME review noted that insertable features are consistent with the makeshift inserts created by personnel in the operational environment. SME review recommended that the insertable features could use additionally development to something modular and an improved method for attaching and detaching.

<u>EELBE (Ergonomically Enhanced Load Bearing Equipment). Prototype 2</u>

The EELBE No. 2 attempts to increase accessibility through reduced interaction time, and allow greater mobility over the current state of art standard issue rucksack (see Figure 15). The EELBE is constructed of weather and mold resistant fabric, with heavy duty nylon threading used throughout. All strapping and webbing is polypropylene, however it is important to note, the production model ops for dense nylon. It has an internal frame that consisting of a 1/16th inch polystyrene sheet, formed to enhance mobility, with two reinforcing aluminum stays.

Figure 15. Second iteration of EELBE

The EELBE rucksack has an approximate volume of 4300 cubic inches. Dimensions of the main body are 22” x 18” x 8”, and the dimensions of the sleep system storage compartment is 8” x 18” x 8”. The volume of the EELBE is more than the RFI requests, but it is within the same capacity of the MOLLE rucksack.

The sewing patterns used to assemble the EELBE rucksack are shown in Figures 16-19. Any feature on a panel must be sewn on prior to assembly. Figure 16 depicts the EELBE fully assembled, ready to be closed.

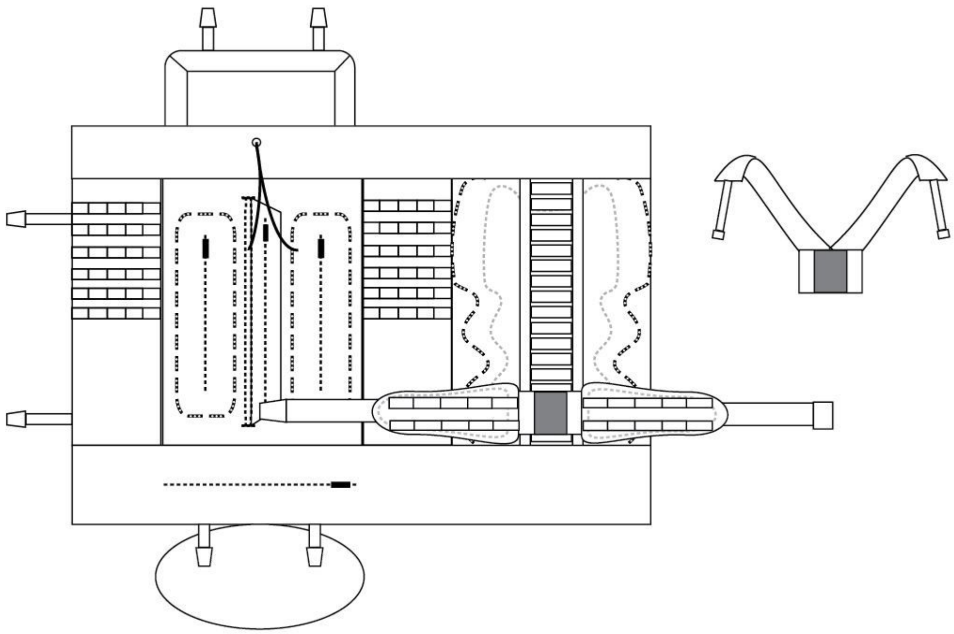


Figure 16. Fully assembled EELBE sewing patterns

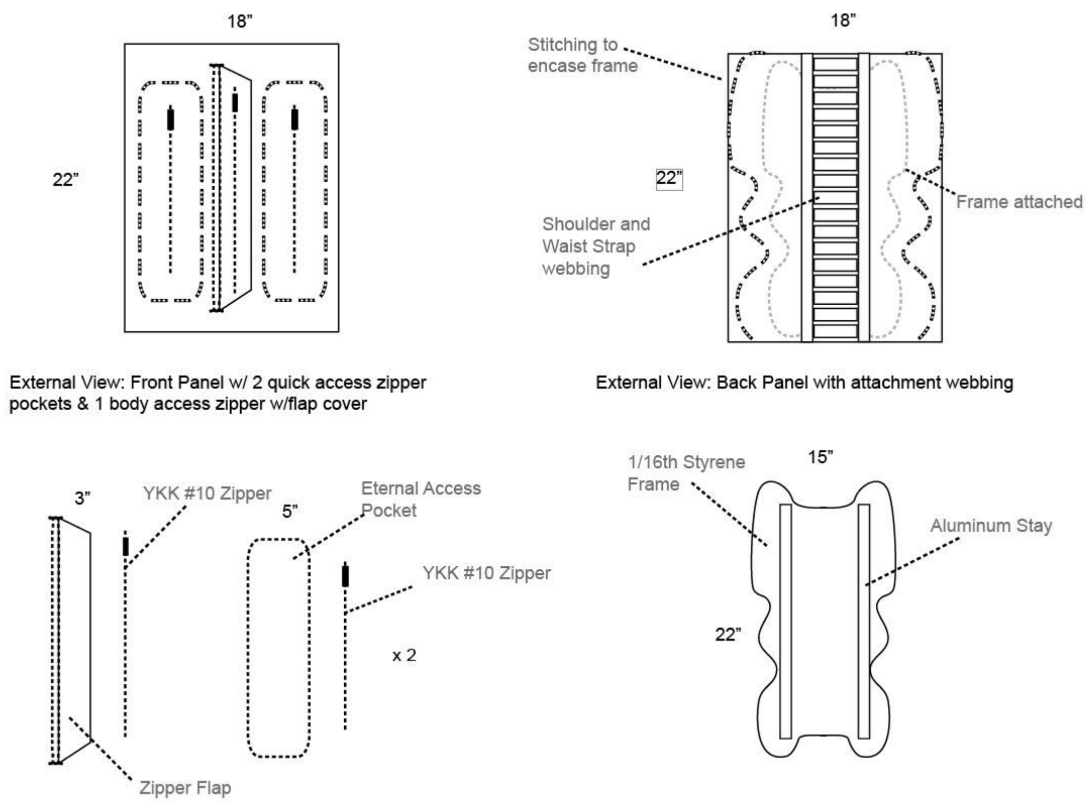


Figure 17. Front and back panels with accompanying components

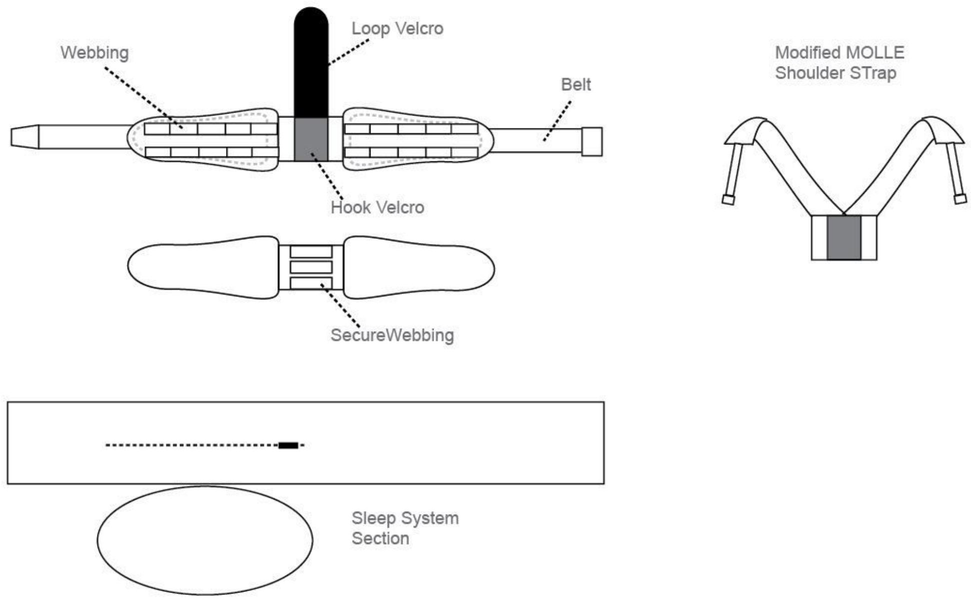


Figure 18. Patterns for waist straps, shoulder strap, and sleep system sections.

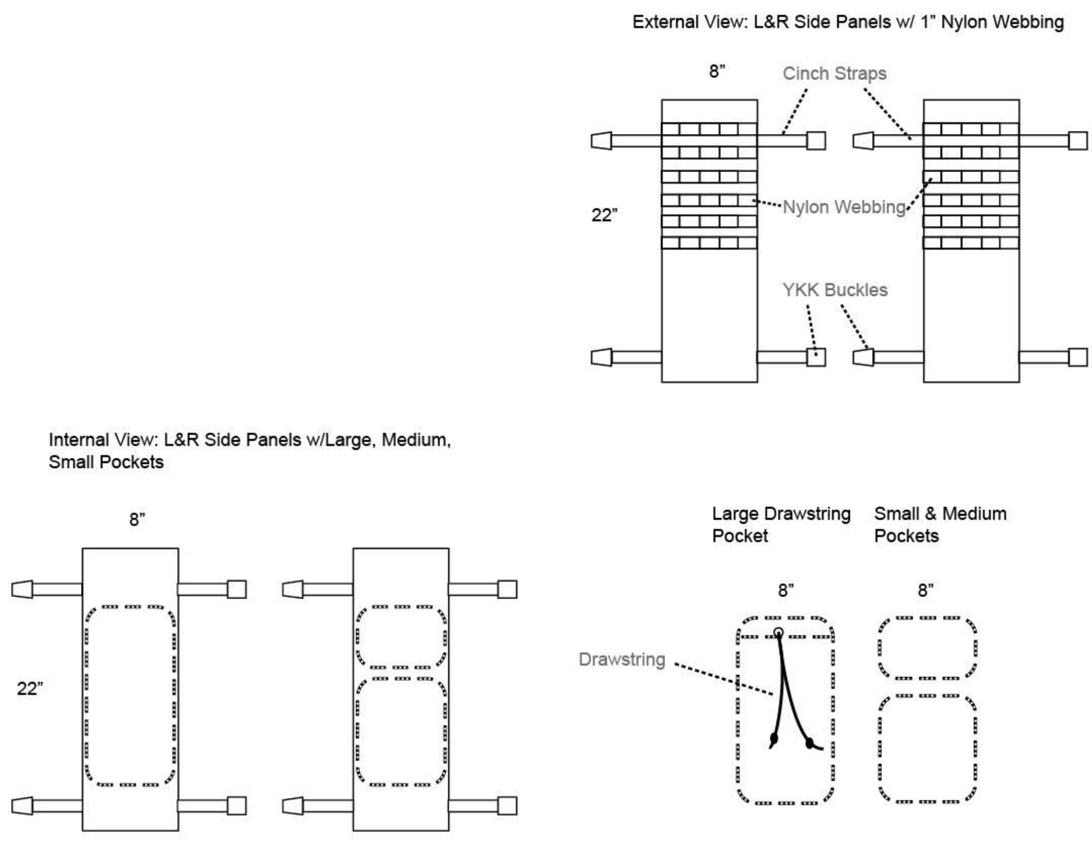


Figure 19. Internal and external view of EELBE side panels.

The primary external feature is the main body access zipper that allows for access to internal compartments (see Figure 20). The concerns surrounding survival of airborne operations were addressed via the addition of two YKK #10 buckles the run perpendicular to the zipper. There are two quick access zipper pouches, on opposite sides of the zipper. These pockets offer more options for organization, and allows users to secure items that they want to quickly access, without having to stow them inside of the main body.

Figure 20. Main body access: front zipper reinforced w/ buckle

The top lid pocket comes with an external quick access pouch that allows users to store items such as MREs, undergarments, socks, maps, etc. and have immediate access to them. This pocket can be operated while the rucksack is worn. This is a significant improvement over the use of the standard sustainment pouch in donned accessibility. Additionally, the lid is water resistant further protecting contents within the main body (see Figure 21).

Figure 21. Top lid w/ pocket

Although the first prototype had “slick-slides” with no webbing in accordance with the RFI, feedback from SMEs recommended the use of webbing. With that recommendation webbing was incorporated on the side panels for this prototype and allows for the attachments of MOLLE style pouches. The shoulder straps are a modified version of the MOLLE shoulder system. Both the shoulder straps and waist straps utilize the CARRY-C system found in civilian hiking packs. It uses the MOLLE webbing concept and significantly reduces the time it takes to install and adjust the straps (see Figure 22). Additionally, a redesign was recommended to the first version of the waist strap. The original was rectangular and needed to be tapered to allow greater mobility on the hip region. Also the second iteration of the waist strap featured webbing along its exterior that allowed for additional attachment based on user feedback back increased accessibility to critical items (see Figure 22).

Figure 22. Webbing and Waist Strap 2

The main body of the rucksack has been compartmentalized with three different pockets small, medium, and large. The large pocket is drawstring, designed with the idea that it could be used to separate soiled clothes. There is also an insertable wet weather bag that uses a zipper to attach, which can further divide the space (see Figure 23).

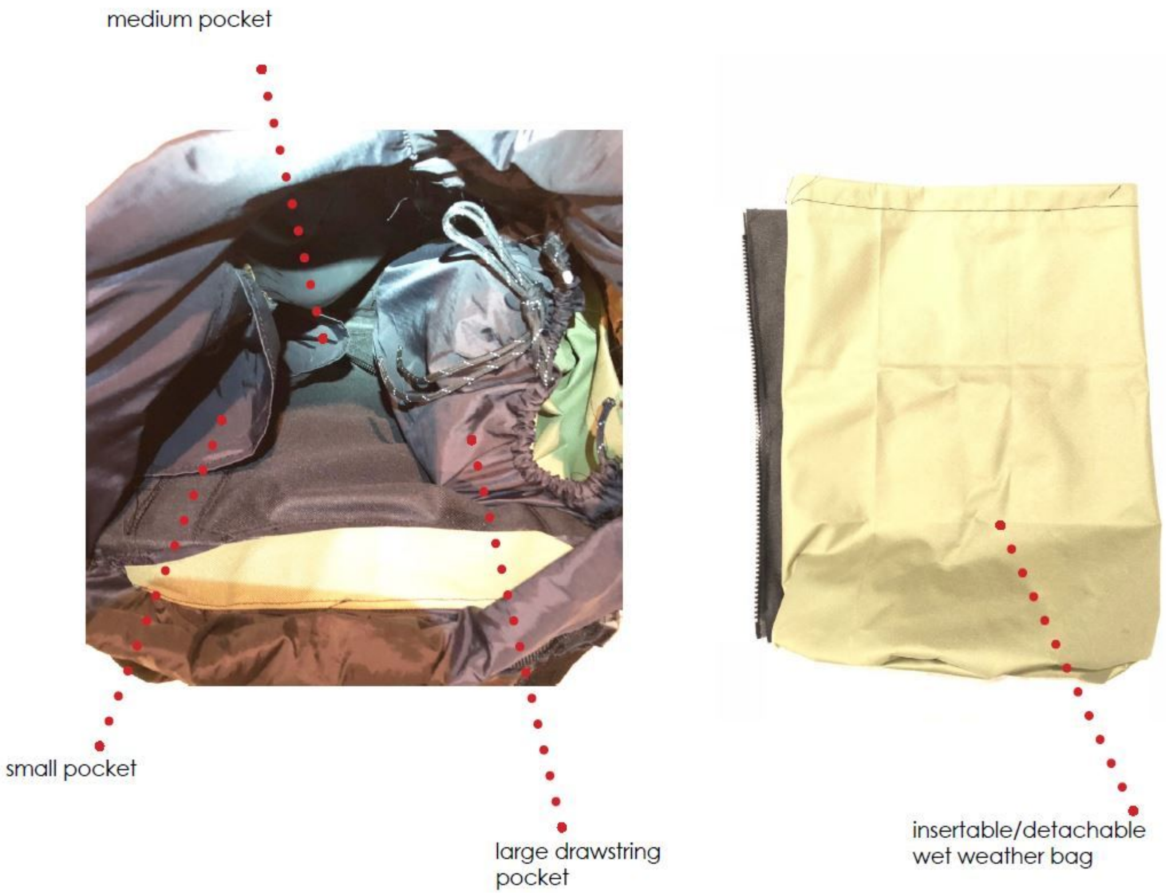


Figure 23. Internal compartmentalization

The frame used in the EELBE was based on standard internal frame design (see Figure 24). However, this frame was modified by removing materials around regions that would limit mobility otherwise. Additionally one-inch thick polyurethane was directly attached to the frame. The frame utilized a very think sheet of styrene that was reinforced by two aluminum stays. The goal was to reach greater flex throughout the frame that would increase mobility, while possessing enough strength to handle to loads.

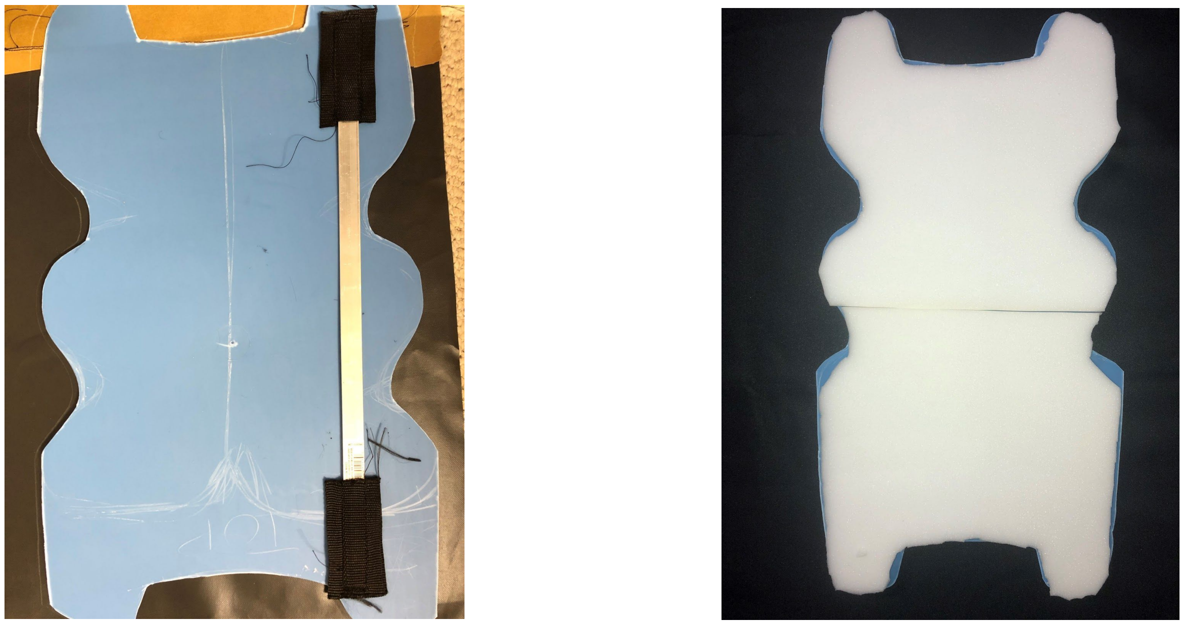


Figure 24. Styrene frame with aluminum stays, covered with polyurethane foam

Based on feedback received during validation, it was determined that the styrene internal frame did not adequately meet the expectations of the users, as durability and ruggedness was sacrificed for mobility and comfort. The demand for a frame that is light, strong, flexible, durable, and comfortable is quite complex. To meet this expectation, additional experimentation and testing is required. In terms of manufacturing, the idea of 3D printing quickly moved to the front. The frame is still under development and will be undergoing testing upon arrival from the manufacturer. Renderings of the conceptual frame are shown in Figure 25.

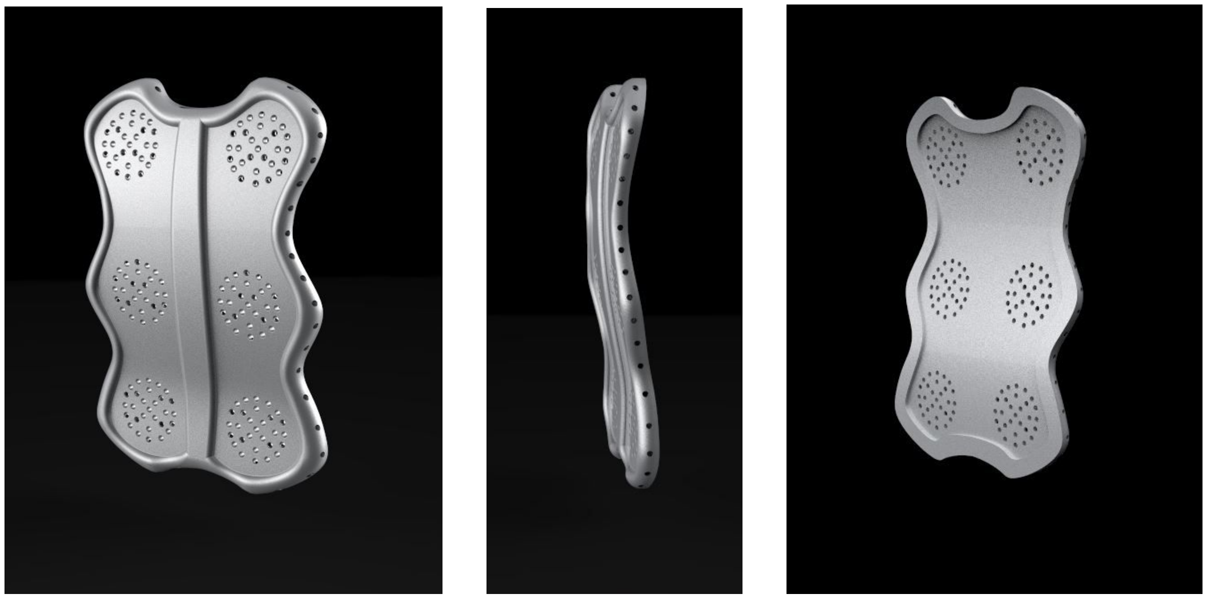


Figure 25. Concept renderings of 3D printed frame

CHAPTER 6. TESTING AND VALIDATION

The same tests and survey were conducted with the EELBE rucksack for validation testing. The data collected from the validation tests and survey are used to compare against the data collected during the testing with the MOLLE rucksack.

6.1 Survey Results

There was one change to the way the survey was administered. The survey was only made available only to those who participated in the experiments. These individuals extensively interacted with the rucksack and through their interactions developed enough familiarity to be qualified to objectively assess the design.

A total of 11 responses were collected from the survey. Descriptive statistics and frequencies of responses are shown in Table 6 and Figures 26 and 27, respectively. Two distinct factors are measured in the survey: Factor 1 (Questions Q1-Q6, and Q9), and Factor 2 (Questions Q7 and Q8), as the Semantic Differential scales used in those questions are not comparable.

Table 6. Survey Results (n=11).

QUESTION		Mean	Std. Dev.
Q1	The EELBE rucksack is (1-Very uncomfortable, 5- Very comfortable)	4.27	0.79
Q2	Assembling the EELBE Rucksack is (1- Very difficult, 5- Very easy)	3.55	1.04
Q3	Packing the EELBE rucksack is (1- Very difficult, 5- Very easy)	4.36	0.81
Q4	How quickly do you think you can fully pack the EELBE rucksack? (1- Very slowly, 5- Very quickly)	4.09	0.54
Q5	Accessing contents within the EELBE rucksack is (1- Very difficult, 5- Very easy)	4.27	0.65
Q6	Keeping contents within the EELBE Rucksack organized is (1- Very difficult, 5- Very easy)	4.18	0.98
Q7	The amount of straps in the EELBE Rucksack is (1- Too many, 5- Insufficient)	2.64	0.67
Q8	The amount of compartments in the EELBE rucksack is (1- Too many, 5- Insufficient)	2.73	0.79
Q9	Mobility (i.e., walking, turning, bending, crouching, etc.) while wearing the EELBE rucksack is (1- Very limited, 5- Very enabled)	4.09	1.04

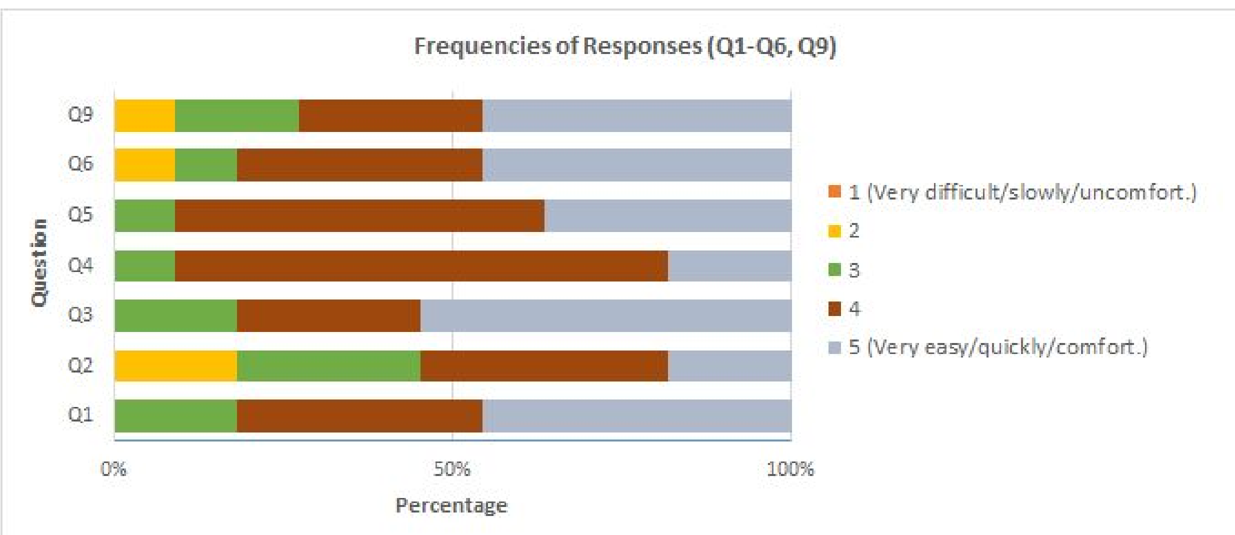


Figure 26. Frequencies (%) of the participants' responses (Questions 1-6, and Question 9)

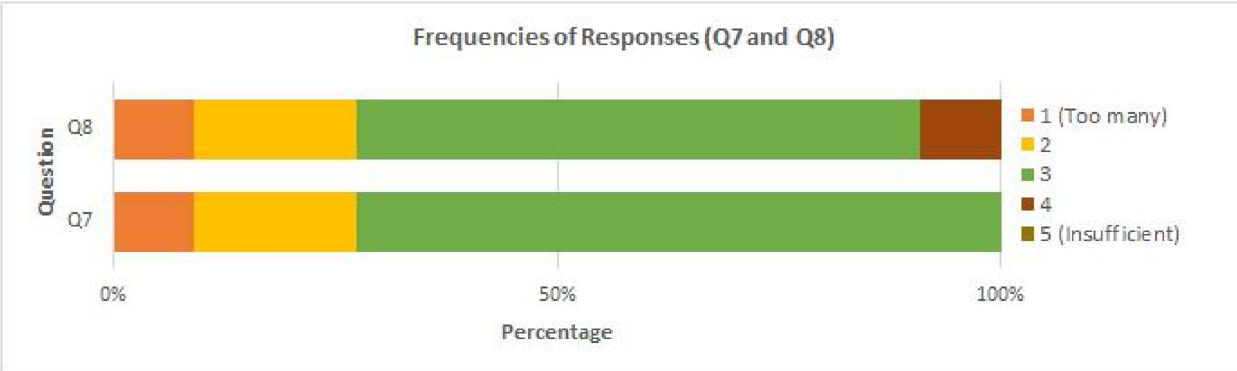


Figure 27. Frequencies (%) of the participants' responses (Questions 7 and 8)

The free response section of the survey allowed participants to express their views on the EELBE rucksack. The data collected from this portion of the survey is critical to the refinement process in future development.

"Better back support system or frame on the back to counterbalance the large amount of weight that can come along with filling the EELBE to its full capacity"

"Compared to the rucksacks that the army currently uses, the EELBE ruck is much lighter and seems to center the weight more appropriately on your back. This allowed it to remain in place (hands free) while I was running and bending, in a real life situation this would allow for better weapon handling."

"The pockets on the outer portion would be better if they were a bit deeper, they hug very tightly to the main pouch to fit a lot of usable space. The webbing on the sides is a great feature though."

"The length of the sack is a bit long, but with enough cinching, it would be fine, especially for a larger person."

"The waist band seemed much more comfortable than existing rucksacks and the ability to move the shoulder straps up and down quickly was far superior to any of the packs I have used, most harnesses are stationary so this was a nice feature".

"The waterproof compartment inside is a nice feature, but needs to be close-able to actually create a water free zone."

"The middle zipper is not integral in the "packing" portion of using the EELBE, but when accessing specific items in the field, this would make a significant difference and save a lot of time and effort searching through the main entry."

"I also like the adjustable height of the chest strap. This creates the ability to adjust it while moving and provides maximum comfort for every sized user.
I like the slimness of the EELBE rucksack. It is a tad too long for those who are height challenged...other than that, it's great!"

"My back was being compressed in the center by the frame strap adjustment. Some adjustment to the

frame can help ease this compression. Also the wet weather back may suit better purpose with the attachment being on the outside versus inside since it can get in the way of packing. Maybe incorporate some form of quick release to get to get to more. Center zipper could extend all the way to the opening to allow even more accessibility. Hope this helps.”

“After performing the tasks, I experienced soreness in both my shoulder blades later on in the day. I never experienced that before with the ruck sack that is issued to us. Usually I would feel something on my traps or shoulders.”

“
The idea of being able to put on and take off the canteen pouches on the belt straps is very useful for small people. We have to take our canteens out of our FLC'S completely just to properly clip in the hip strap. The stiffness of that sustain mentioned pouch makes it very easy to pull items out since it's not limp and catching onto items. The shoulder straps could be made to where they could be more adjusted. It is pretty big. If it could be more compact it would work. It's excellent for both small people and large people. The regular rucksack kind of neglects the idea that small people have issues with the rucksack sometimes.”

“Very comfortable, just needs better framing.”

“Overall, very nice pack. The outer pockets could be slightly larger in volume capacity. Also, the waist belt could have an added plastic strip so that it stays flexed out when donning the pack. The middle zipper is a huge improvement over the current Army pack. The ability to divide the inside into compartments is very nice for planned operations. However, the dividers do not assist in packing time reduction. Lastly, the waist belt padding could be extended around the waist another 2-3" to reduce chafing to the body by the belt.”

“More compartments accessible from the back”

“Shorten the ruck sack. Maybe lift the sleeping back compartment.”

6.2 Experimental Results

The results of the three experiments are reported in Table 7. The Perceived Task Load Results from the NASA TLX test are shown in Table 8. The weighting step of the TLX procedure was intentionally discarded based on conventional practices, as comparable validity for workload can be obtained. Instead, we used the Raw TLX (RTLX) method by averaging the TLX ratings from various instances of the same tasks to determine the overall workload (Hart, 2006).

Table 7. Experimental results (n=10). Time in seconds.

Experiment	Task	Mean	Std. Dev.

Exp. 1 *Timing*	**Iteration 1:** *No time constraints*	155 (pack) 20.21 (retrieve)	55.12 (pack) 8.53 (retrieve)
	Iteration 2: *Time constraints*	83.30 (pack) 18.54 (retrieve)	26.03 (pack) 10.75 (retrieve)
	Iteration 3: *Time constraints+Fine motor skills*	134.90 (pack) 22.27 (retrieve)	82.35 (pack) 12.63 (retrieve)
Exp. 2 *Donned accessibility*	*Retrieve MRE* *(3 participants unable to finish)*	19.31	13.10
Exp. 3 *Mobility*	**Part 1:** *Get up / Get down test*	6.69 (get up) 2.62 (get down)	7.50 (get up) 1.36 (get down)
	Part 2: *30m shuttle sprint*	15.97	12.45
	Part 3: *Mobility course*	9.05	2.50

Table 8. TLX Results (mean and standard deviation). Scale from 1 to 100, with higher scores indicating more strain.

Task	**Mental Demand**	**Physical Demand**	**Temporal Demand**	**Performance Demand**	**Effort**	**Frustration**	**Raw TLX Score**
	How much calculating, remembering assessing required?	How much physical exertion required?	How much time pressure was felt, satisfaction with rate/pace?	How successful [were you] at accomplishing the task?	How hard did you work to accomplish your performance level?	How insecure, discouraged, stressed vs. secure, gratified and relaxed did you feel during the task?	Averages across categories for overall score per task.
Packing	M: 26 (SD: 19.41)	20.50 (12.79)	44.50 (23.03)	32 (23.12)	43 (26.58)	25 (20.95)	31.83 (20.98)
Donned Accessib	45 (30.73)	40 (30.37)	38 (29.65)	54.50 (34.84)	63 (28.89)	47 (29.65)	47.92 (30.69)
Mobility	15.56 (14.88)	28.33 (20.92)	38.33 (20.46)	23.33 (24.49)	40 (22.78)	19.44 (18.28)	27.50 (20.30)

6.3. Subject Matter Expert (SME) Review

As a part of the research methodology, this Master's Thesis included the use of Subject Matter Experts (SMEs) in fields highly relevant to rucksack design and use. The mix of

SMEs consist of a prior service infantry soldier who now works as a military apparel retailer. He has both learned and experiential knowledge of past and present rucksacks. The second SME is Airborne Ranger Infantryman with over twenty years of experience, combat deployments, and access to rucksacks developed for special operators. The last SME has close ties to research and development groups that design equipment for military applications. They acknowledge the improvements in accessibility via the internal compartmentalization and addition of main body access zipper. Additionally, they praised the frame for greater mobility and comfortability.

The summary of their reviews in regards to the final EELBE concept is that it is headed in the right direction. However, there are aspects of the design that they believe would benefit from further development. The critical feedback they delivered was the length of the rucksack. In SMEs opinion, it is too long and the dimensions need to be re-evaluated. Additionally, there should be a pouch to incorporate a hydration bladder, and there was also mention of exploring means by which to improve buoyancy for waterborne operations.

6.4 Discussion

The data collected during the EELBE validation testing was compared to the data collected during the initial MOLLE testing. The values of the survey suggest that the EELBE rucksack outperformed the MOLLE rucksack in several of the evaluated domains. The values from the surveys are shown in Table 9.

The most critical values to this Master's Thesis are accessibility, speed of packing, organization, and mobility. The findings validate that the design of the EELBE is an improvement over the MOLLE rucksack. Although certain areas the MOLLE rucksack proved to be the preferred design, further development of the EELBE may be able to improve those domains as well.

Table 9. EELBE & MOLLE survey data comparison (Scale 1-5).

	EELBE	MOLLE
Comfortability	M:4.27 (SD: 0.79)	3.18 (0.89)
Assembly	3.55 (1.04)	2.64 (1.09)
Ease of Packing	4.36 (0.81)	3.86 (0.89)
Speed of Packing	4.09 (0.54)	3.58 (0.84)
Accessibility	4.27 (0.65)	2.93 (0.96)
Organization	4.18 (0.98)	2.73 (1.05)
Number of Straps	2.64 (0.67)	2.36 (0.98)
Number of Compartments	2.73 (0.79)	3.76 (0.77)
Mobility	4.09 (1.04)	2.78 (1.13)

It is important to mention that while the quantitative data is critical to the validation of this EELBE design, the qualitative feedback from the participants is just as relevant. The free response section of the survey provided additional validation to the EELBE rucksack.

Several comments reinforced the findings from the survey and experiments. Others pointed out drawbacks of the EELBE design, notably its length. The latest version of the EELBE is too long to properly fit a population spanning a fifth percentile female to a ninety-fifth percentile male. Although larger individuals found this rucksack very comfortable, smaller persons did not. Better implementation of anthropometric data is critical to improve this element of the rucksack.

Another issue several respondents mentioned was the frame. To these individuals, the frame needed further development as they felt that it was not strong enough and lacked rigidity. These responses evoked deeper analysis, as the frame is the foundation of the rucksack. When the frame was being designed, feedback from the MOLLE testing and survey was extensively used. The feedback indicated that the MOLLE rucksack frame was too rigid and uncomfortable, which limited mobility. With the EELBE, the frame was perceived as too flexible and although it was comfortable it compromised the load bearing capacity of the rucksack.

Participant observation during the testing of EELBE also provided valuable insights. The external zipper that provided access to the main body was a point of interest. Although there was brief period to allow participants to become acclimated with the rucksack, many initially used the EELBE as they did the MOLLE. If the participant did not use the zipper after a few iterations, they would be reminded that it was available for use. Other participants used the zipper from the first iteration. This may indicate that there are cues that need to be integrated into the EELBE, alerting the user that it is available for use. Once participants began to use the large zipper they could quickly retrieve items that had been stowed away without undoing the entire rucksack. Although the large external zipper was intended to be used for retrieval, some participants also used it during the packing process. This was an interesting unintended benefit of this feature, and it offered more options for the user to organize their rucksack.

The internal compartments were noted by the participants as helping them to remember where they had placed certain items. The designated small, medium, and large pockets can only hold certain items whose dimensions fit within these pockets. In this way, the pocket sizes dictate the types of equipment that can be stored and help the user organize their equipment. When asked how they were able to retrieve items in the manner they did, many participant replied that they knew exactly where things were because of the compartments available to them. Additionally, in this round of testing there were less instances of participants frantically rummaging through the rucksack or dumping the entire rucksack out to retrieve equipment. The external pockets and pouch also made for easier access to critical items. These features allow the user to store items that did not need to be on their person, but also did not need to be tucked away within the rucksack.

The attachable wet weather bag was not as effective as originally intended. In fact, it seemed to impede many users. Participants liked the novelty of the idea but it quickly became clear that the implementation needs more development. Nevertheless, insertable features are features that the users would like to see more of.

The shoulder and waist straps were designed to be simpler to attach and adjust. The shoulder straps are a modified version of the MOLLE shoulder straps. The EELBE shoulder straps feature the same quick release and cinching mechanisms, however, it utilizes a a system similar to webbing for attachment. Users found this to be advantageous over the MOLLE method of attachment. It saves time and is simpler to understand. One drawback to the EELBE shoulder straps due to the attachment method is that they would sit very wide on the users shoulders. If the person was of smaller stature then it made wearing the EELBE slightly more difficult. This problem could be mitigated by using the chest buckle, but it placed pressure on the chest and abdomen.

The waist straps went through two iterations of development. The first version of the waist belt was large and rectangular in shape, but SME feedback suggested tapering the waist straps so that they do not pinch the skin nor interfere with mobility in the hips. Additionally, it was recommended that webbing be added to the belt to allow pouches to be attached if the users felt the need to do so. During testing, a female participant remarked that she appreciated the webbing on the waist strap. With the MOLLE she would have to remove her canteens from her FLC because they would get in the way of the waist strap, which would leave her to rely on one water source, her camel back. With the addition of webbing to the waist straps, she can attach the canteens and not have any interference with her FLC.

CHAPTER 7. CONCLUSIONS

7.1 Critical Takeaways

Load carriage systems have played a role in armed conflict for centuries and issues of load carriage and weight distribution have plagued the rucksack since its inception. A significant number of studies have drawn attention to these issues, as well as the negative outcomes associated with them. Additionally, significant progress has been made in the areas of load carriage and weight distribution. Although many of these developments show promise, viable solutions that can be readily implemented appear to be years in the making.

This study focused on the rucksack as an essential piece of military equipment that plays a significant role in the performance, safety, and effectiveness of military personnel who use it.The standard MOLLE rucksack, which currently serves the sustainment requirements of many military personnel, is an innovation that reshaped the way soldiers carried and interacted with their loads. However, its shortcomings have incrementally been realized throughout the last two decades.

The experimental results, TLX data, and observations suggest that many categories of the current rucksack design need to be addressed and/or re-examined in terms of design, particularly from a user's perspective, to overcome their deficiencies. More importantly, a systems approach should be taken to avoid piecemealed solutions that do not work well together. Eliminating inefficiencies and ill-cooperating equipment has the potential to save time, mitigate stress, and ease the mental burden on military personnel.

The results of this research can help inform future design alternatives and/or modifications, which must naturally complement considerations of weight and comfort, as much of the equipment and gear must always be carried on the rucksack and cannot be left behind. The results presented in this study also raise questions about current ergonomic interventions, particularly regarding the success of adoption and implementation.

This Master's Thesis makes significant contributions to military rucksack design criteria by investigating the influence of factors of time, accessibility, and mobility, and by providing guidelines for future rucksack design and development. In this regard, accessibility is key. Users must be able to get the things they need, as efficiently as possible. To accomplish accessibility, the rucksack must provide internal and external organization capabilities that should allow for the stowage of contents based on user preference. Digging through the rucksack to locate items is archaic. This practice must be done away with. In terms of mobility, the rucksack design should minimize the interference when the wearers is conducting maneuvers. The rucksack frame is the foundation of the design and it should allow the wearer freedom of movement when getting into prone, standing up, changing directions, accelerating, and stopping. Finally, comfortability is important to the user but more extensive testing is recommended to evaluate the long term comfortability.

Another major contribution of this study is that it gives voice to the users who have experienced issues with the MOLLE rucksack design.Their feedback directly shaped the design process and is reflected in the final prototype. Many users have had to accept the shortcomings of the MOLLE rucksack as the norm. This study does not aim to change the domain of rucksack design, but rather to improve the users interaction by shifting the status quo of acceptable design in this field.

It is important to acknowledge that there are several limitations and constraints associated with this study. One of them is the sample size used in the experimental task, which may lead to a possibility for concentrated data that may not represent the experiences of military personnel as a whole. However, other studies within this field have been reported with similar sample sizes of 6-10 subjects (Babeu 2014, LaFiandra, et. al, 2003). The nature of these experiments and the analysis of collected data usually involves a limited sample size, which is compensated by the richness of the output. Additionally, more iterations of the tests need to be performed while the subjects carry their weapon, which would add an extra level of accuracy to the simulated scenarios. We speculate the results will be even more significant, as the weight of the weapon will put an extra burden on the the subjects while performing the tasks.

7.2 Future Work

As future work, it would be interesting to explore and validate new ergonomic solutions that can be applied to military rucksack design, particularly accessibility, as this was the most relevant aspect identified in this study. Additionally, the feedback on the frame design was concerning. The participants and SMEs were split on the effectiveness of the frame. Therefore, a new frame will developed to address the shortcomings of the EELBE frame. The goal is to develop a solution that can meet the overwhelming majority of users expectations.

Moving forward there must also be stress and load bearing test done on this design to ensure that it can stand up to the demands of the operational environment. Drop tests, drag tests, and durability analysis of this design are needed. Usability testing provided intermediate stress to the construction of EELBE but further stress testing is needed to validate the overall design.

Lastly, donned accessibility deserves its own study. The ability to retrieve items from the rucksack as it is worn and the user is moving is complex. This aspect or the rucksack design calls for more research and testing to understand the problem in its entirety.

7.3 Final Remarks

In addition to the impact that ergonomic factors plays in rucksack design development, it is also critical to examine the influence that technology has and will have on the development of the rucksack.

Future Combat Technology

Over the last decade there have been advances in combat robotics technology, and unmanned aerial and ground vehicles being developed for use in the operational environment. Some of the major functions for these technologies will be to assist soldier's on the ground with several combat and support tasks. One concept calls for autonomous robots that can act as a "mechanical pack-mule" that would essentially follow combat units around to transport heavy weaponry, gear, and rucksacks, needing little to no supervision and can maneuver with units.

3D Printing Initiative

Other technologies expected to change the face of the battlefield and thus the equipment soldiers will carry, are the advances in 3D printing and its combat applications. Military researchers are currently testing the feasibility of deploying 3D printers to the front lines to aid combat personnel in nutrition, repairing equipment, and even reconnaissance in the form of small drones. 3D printers would certainly alter the types of equipment carried into the operational environment. One discussions has been the idea of 3D printing a soldier's personalized meals. If food is to be printed based on individualized nutritional needs, then soldiers may not need to carry MREs on their person. More than likely, however, 3D printing equipment is the greatest likely course of action in bringing this technology to the front lines. A potential benefit of 3D printing in the operational environment could be that units may not need to be re-supplied as often. This initiative is one of the leading reasons the EELBE has been designed with a 3D printed frame.

Relevance of Rucksacks

"Super-suits" with robotic spines, exoskeletons, and other supportive gear are also being developed. These technologies are to be worn by military personnel and seek to enhance the capabilities of the human body. Many of these designs would assist soldiers in carrying and lifting heavy loads. Additionally Some argue that this could replace the need for carrying sustainment packs and However, a large drawback to many of these designs are their inability to function without large power supply.

These technologies present a completely new perspective on what gear is necessary in the future and whether or not the rucksacks will still be a relevant piece of equipment in future conflicts. Foresight analyst have predicted by 2025 there will be more combat robots than human soldiers and further into the future soldiers may assume more of a role as an operator. These developments raise critical question, such as: Will rucksacks still hold the place of importance as they do now? What will become of the sustainment packs that have been researched and developed over the years? According to a Senior

Military Instructor who was an Airborne Ranger Infantryman with over 20 years of active duty time and multiple combat deployments, the rucksack will always be an integral part of soldier’s gear for years to come (Interviewer 1, 2017). The rucksack, no matter how technologically advanced militaries become, will in some shape or form exist.

ACKNOWLEDGEMENTS

In addition to being graduate student at the University of Houston I am also a part of the Reserve Officer Training Corps. I have been a cadet for the last three years and will be Commissioning in May 2018 as a 2LT. Over the last three years I have had a myriad of experiences with Army personnel, tasks, and equipment that have given me a unique perspective as an industrial designer.

I have been quite fascinated by the Army’s ability to organize, equip, and mobilize their personnel. There are several pieces of equipment that soldiers use in order to do their jobs. One of them, the Army rucksack, is critical to the soldier’s capabilities and utilized universally across the various occupational specialties. The Army rucksack is comprised of a large pouch which sits on a plastic frame with two sustainment pouches on each side. There are six lashing straps used to tighten down the load, and waist belt to seat the weight on the hips. This is what is soldiers stuff their equipment into.

I have used this rucksack myself many times throughout training and evaluations, where I quickly began experiencing many issues with it. Initially, I thought it was just user error or the fact that I am still very young in my military career. Over time I noticed my peers having similar issues, often complaining while in the field or on ruck march about this or that feature. My instructors and even seasoned soldiers would frequently talk about their experiences, issues and annoyances with the current rucksack.

During the Summer of 2017 I attended my advanced training in Ft. Knox, Kentucky.

During a break between training, I struck up a conversation with an Infantry Captain from the 10th mountain division, who was my instructor. This gentleman has been deployed, has extensive experience with rucksacks, and has participated in a related research study. He about talked his concerns with the current design, he also discussed how many of his peers have experienced similar issues. At the end of our conversation, I asked him if he believed the current rucksack design, with all of its bells and whistles, had any room for improvement. He looked at me and said “There’s Definitely room for improvement, and our soldiers deserve it.” From that moment on, I knew this is what I would dedicate my thesis towards.

APPENDIX A: Survey

In your opinion, the EELBE rucksack is *

	1	2	3	4	5	
Very uncomfortable	○	○	○	○	○	Very comfortable

In your opinion, assembling the EELBE Rucksack is *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

In your experience, packing the EELBE rucksack is *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

How quickly do you think you can fully pack the EELBE rucksack? *

	1	2	3	4	5	
Very slowly	○	○	○	○	○	Very quickly

In your opinion, accessing contents within the EELBE rucksack is *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

In your opinion, keeping contents within the EELBE Rucksack organized is *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

In your opinion, the amount of straps in the EELBE Rucksack is *

	1	2	3	4	5	
Too many	○	○	○	○	○	Not enough

In your opinion, the amount of compartments in the EELBE rucksack is *

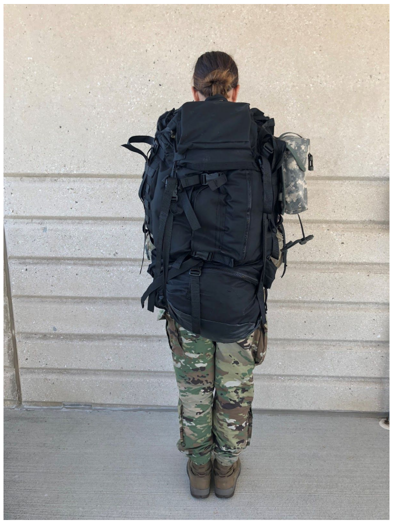
	1	2	3	4	5	
Too many	○	○	○	○	○	Not enough

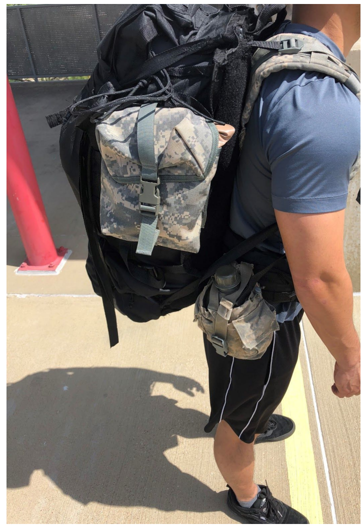
In your opinion, mobility (i.e., walking, turning, bending, crouching, etc.) while wearing the EELBE rucksack is

	1	2	3	4	5	
Very limited	○	○	○	○	○	Very enabled

Please share any suggestions, recommendations, or critiques for the EELBE rucksack. *

APPENDIX B: Additional Photos From Validation and Testing





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