# STABILITY AND METABOLIC ANALYSIS OF WALKING ON CROSS-SLOPES WITH VARIOUS VERTICALLY PLACED BACKPACK LOADS AND WITHOUT LOADS

by

Robin James Elliott

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## STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Robin James Elliott**

has been approved by the following supervisory committee members:

**Donald Bloswick** , Chair **18 April 2016**
Date Approved

**Andrew Merryweather** , Member **18 April 2016**
Date Approved

**Kenneth L. DeVries** , Member **18 April 2016**
Date Approved

**Eric Wood** , Member
Date Approved

**John Scarlett** , Member **12 April 2016**
Date Approved

and by **Tim Ameel** , Chair/Dean of

the Department/College/School of **Mechanical Engineering**

and by David B. Kieda, Dean of The Graduate School.

# ABSTRACT

Though many who walk along roadside cambers and hill edges may have an interest in making their travels sure and effective, those most concerned may be soldiers in the infantry. They need to be injury free and have as much energy as possible when they march into battle.

Walking on uneven ground without being injured by falling down (particularly with a heavy backpack) is generally accomplished by maintaining stability. This present study was conducted to determine an individual’s most stable position (using a stability formula which compares dynamic center of mass with center of pressure) when wearing a backpack under differing load positions - low back, middle back or high back – and differing walking angles: level, as well as along a cross-sloped surface.

Furthermore, this study investigated the stability of persons walking along a cross-slope without a load.

Finally, this study attempted to determine which combination of backpack load location and slope tilt best conserved metabolic energy.

To carry out this backpack stability research, a group of 15 participants were asked to walk along an indoor track under the varying conditions mentioned (i.e., low to high backpack load positions and level to 10 degree tilted cross-slopes). The trials of their walks were performed randomly. The participants were recorded in a motion capture system and force plates documented their stepping times and locations.

Again, the same 15 participants walked along the track under the same conditions, but without the loads to determine the effect of different cross-slope angles on their stability.

Lastly, the same participants walked the track under the various conditions wearing portable oxygen sensors to analyze their energy expenditure.

The results of these limited tests indicate no significant stability differences between 0, 5 or 10 degree angles in cross-slope walking loaded or unloaded. Nor was any significant stability differences noted between the various load locations of the backpacks. Nor was there a significant energy difference between the conditions.

Dedicated to my aunt, Donna Mae Blair Reid, and to my inestimable Heavenly Father.

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# 1 INTRODUCTION[1]

Many people use backpacks to transport loads from one location to another. The duties of these individuals range from firefighter to wilderness guide to army foot soldier. While these jobs, and others like them, make physical demands of the wearer, perhaps the most critical among them is the work of the soldier. According to the official United States Army website, army.mil/info/organization, "the Army's mission is to fight and win our Nation's wars by providing prompt, sustained land dominance…" To do so most effectively, each soldier in the field should be at their best. Two areas of interest to a foot soldier are the ability to maintain optimum balance in the field and to conserve energy, especially when carrying a heavy backpack.

## 1.1 Military Walking Challenges

Balance is an important walking attribute not only when done on level ground, onto which a soldier wearing a loaded backpack might fall and be hurt, but when marching on mountainous slopes where a loss of balance may mean falling a great distance causing extreme injury or death [1, p. 115].

The term balance can be defined as "a fundamental physical ability which underlies proficient performance of many gross motor skills, including many necessary for skillful performance of sports and physical activities" [2, p. 135], [3]. As well, this expenditure,

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[1] Elliott R (2016) Determining the Lateral Stability of Persons Walking on Cross-Sloped Surfaces with Backpacks Loaded at Various Levels. J Ergonomics 6:160. doi:10.4172/2165-7556.1000160

on staying stable, is expected to exact more energy when balance is challenged. Consequently, understanding ways in which a soldier wearing a backpack can improve their balance may provide more safety for the soldier and also an increased savings in human energy.

Some stability and metabolic studies have been done on soldiers wearing backpacks in different conditions [1], [4]–[11], but in preparation for this research, no previous studies were identified which specifically addressed wearing a backpack while cross-slope walking. Cross-slope walking is defined as walking on a surface which is laterally slanted. Persons wearing backpacks encounter cross-slopes along the edges of roads, on mountain trails and hill sides. Walking on a cross-sloped surface results in multiple dynamic postural changes compared to normal walking [12, p. 411], [13, p. 187], [14, p. 17]. These changes are the effects of asymmetrical muscle and postural adaptations to maintain the upper body's upright position [12, p. 411], [13, p. 187]. The GRFs in the frontal plane are particularly affected while walking along a cross-slope [14, p. 17]. Cross-slope walking is a balance challenging effort requiring constant exertion against one-sided lateral forces [13, p. 185], [15, p. 1].

Some articles have been published to describe the ground reaction forces (GRF) and the kinematics of non-load carrying cross-slope walking [13], [14]. Others have touched on conditions similar to cross-slope walking for functional body coordination [14] and energy consumption as compared to level walking [16]. One study was carried out with transfemoral amputees walking on a moderately angled cross-slope. The author of that report indicated that the transfemoral amputees expended more energy than walking up an incline [17, p. 184].

Lastly, some articles have addressed walking on level surfaces and sagitally inclined surfaces carrying loads of different distributions [4], [8], [11], [18]–[27]. However, there were no articles found that recorded studies of cross-slope walking while wearing a backpack loaded at various positions.

### 1.1.1 Stability

Balancing the body when standing in one spot can be described as a physical process in which the body's center of mass (CoM) is kept within the base of support (BoS) [28, p. 1], (Figure 1-1). Note that when standing motionless, the BoS represents the area and perimeter in which the center of pressure (CoP) resides and the CoP is usually close to the vertical projection of the CoM.

Standing balance is often characterized as a generally stable static state in which a body is able to stay upright without changing either foot location [29, p. 124]. From this definition, balance is assumed to have a limit that can be exceeded, but subsequently regained by moving one or both feet. So, for a person to walk, a tradeoff between standing balance and foot movement must be used. During walking, the area of stability, or base of support (BoS), is temporarily abandoned each time a step is taken to make bodily progress. In fact, it is noted by Patla that the word cadence, which is closely associated with walking, comes from the Latin caderer, to fall [30, p. 48]. Normal walking, then, is a continual process of regaining the base of support for the body's center of mass as it "falls" forward (and to the side of the same foot which is trailing) – it is a constant changing of foot placement to anticipate the onward fall of the body. Patla also explains that dynamic stability (contrasted stability of with the more static immobile standing) requires that the body's center of mass (CoM) be maintained by a continual

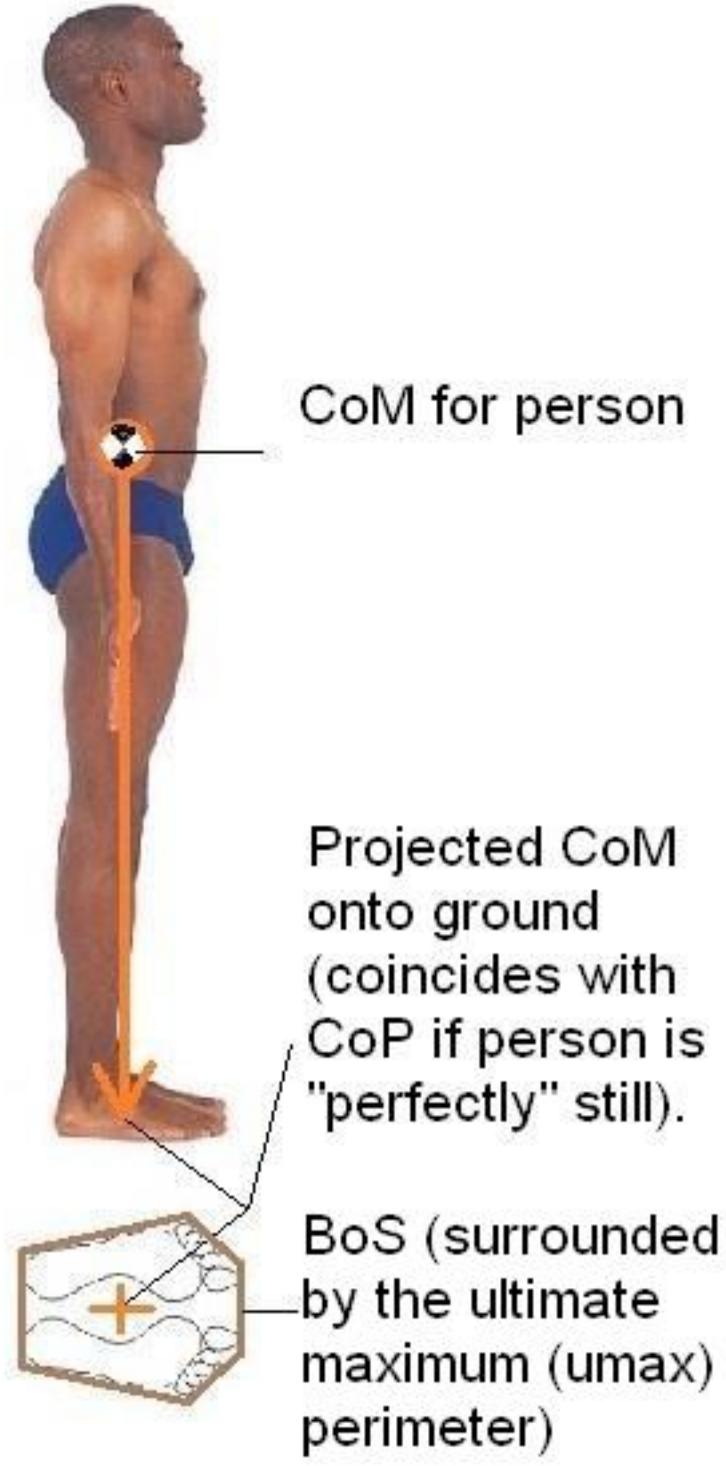

Figure 1-1 Static postural stability

predictive modification of the CoP [30, p. 48]. Thus, stability is maintained in a dynamic sense when the CoM is consistently supported time and again such as when walking or running (Figure 1-2).

As can be seen from the image (Figure 1-2), the CoM is outside of the BoS and therefore beyond the CoP. However, the body will be caught when the right foot (shown in the air) lands, as the person moves forward. The landed right foot will modify the support for the CoM so that the forward moving and side shifting body mass can move onward without falling over. The degree or firmness of stability, when walking or running, depends on the body accurately anticipating and coordinating the location of the dynamic CoM and CoP to provide adequate support for itself as it moves [28, pp. 2–3], [30, p. 48].

Additionally, the body really isn't completely motionless when standing (if so, the CoP would always coincide with the CoM). However, when stable, the vertical projection of the CoM stays within the BoS (which represents the maximum limits of the CoP when standing). There is a certain amount of sway or small movement of the CoM back and forth and side to side.

The effect of these small movements on the standing person's balance affects the horizontal velocity of the CoM. The velocity of the CoM is a factor when walking or running, as well. The velocity imparts inertia to the CoM. This inertia accounts for forces that tend to offset the CoM in the direction of movement and must be coordinated with the CoP to maintain stability. Using all these concepts, the method of mathematically quantifying the degree of stability can developed from the formula by Hof [28, p. 3] using CoP in place of the $U_{max}$ for walking as per Hof's later article [31, p. 251] (Equation 1-1):

Figure 1-2 Man running with CoM outside of BoS (and CoP)

$$\boldsymbol{b} = \left| \boldsymbol{CoP} - \left( \boldsymbol{x} + \frac{\boldsymbol{v}}{\left(\frac{\boldsymbol{g}}{\boldsymbol{l}}\right)^{1/2}} \right) \right| \qquad \textbf{[1-1]}$$

**b** = stability value

**CoP** = Center of Pressure

**x** = instantaneous lateral point of CoM

**v** = velocity in lateral direction

**g** = standard acceleration due to gravity

**l** = vertical distance from CoM to ground

In Equation 1-1, the "$v/(g/l)^{1/2}$" portion represents the equivalent length of the inertia of the center of mass. This formula is based on modeling the body movement as an inverted pendulum, which is why the value "$(g/l)^{1/2}$" is employed (Hof et al. re-identified the value "$(g/l)^{1/2}$" as "ω").

In this study, the lateral component of Equation 1-1 will be used for determining stability (due to being readily independent of the sagittal component [32, p. 2656]). In this case, the factors for the CoM, CoP and a lateral velocity of the CoM are used for the situation specifically when the on-stepping foot is fully supporting the body, just after the off-stepping foot is in toe-off.

In most cases, a telling indicator of stability is how perturbations affect the maintenance or recovery of the erect body, and this is determined by the size of "b" or the difference between the CoP and the XCoM. The greater the value of "b", the better the stability (this is assuming the XCoM is headed toward rather than away from the CoP; if the XCoM is moving away from the CoP, instability has already begun and a new CoP must be established ahead of the XCoM [28, p. 3] to maintain stability).

Another way to view this is to see stability in terms of its definition. Stability is defined by the online Webster Dictionary as “the property of a body that causes it when disturbed from a condition of equilibrium or steady motion to develop forces or moments that restore the original condition” (merriam-webster.com/dictionary/stability). For a person walking, the concept described here is that the walking person is not easily moved off track or easily falls. Disturbances are less likely to cause imbalance in a body with a greater positive “b” value than one with a smaller “b” since the XCoM must be forced by a perturbation further to the edge of imbalance in the first case than the latter [28, p. 3].

Other authors have also used the distance [33], or even angle [34], between the CoM and the CoP as indicators of stability. Writing of the correlation between the BoS and the distance of the CoM, Huang and Ahmed determined that the stability margin was dependent on the range of the CoP within the BoS and with less margin between the two, the less stable the outcome [35, p. 2].

The above method which includes the factor of the CoM velocity (illustrated by Equation 1-1) seems to account for sufficient details of stability that it can detect even small efforts of destabilization or perturbations [32, p. 2663] .

Perturbations come in various forms. Perturbations to normally stable walking patterns may come from abnormal walking conditions such as cross-slopes [14, p. 24]. Other literature references to cross-slope walking and stability indicate that cross-slope walking requires extensive adjustments to maintain dynamic stability [13, p. 183]. In addition to the potential instability caused by walking on a cross-slope, imbalance may further be caused by loading the body in specific weighted configurations [22, p. 860].

Carrying a heavy backpack creates a weighted configuration considered a postural perturbation to normal walking [1, p. 115] and, according to Heller, causes instability.

With the addition of backpack loading [1, p. 116] Heller says instability increases. Other authors state that for a statically standing person wearing a backpack, there is a linear increase in sway (both front to back and side to side) as the backpack loads increase [22, p. 866], [36, p. 607]. This increased postural sway is considered by those researchers an indicator of less stability [9, p. 105], [36, p. 607], [37, p. 23], [38, p. 21].

Rugelj et al. indicates that postural sway (an indication of postural instability) is unaffected by increased load when it is symmetric with the vertical projection of the CoM [22, p. 864]. Conversely, Qu, et al. shows that increased load, even though symmetrical about the CoM, increases postural instability and that the higher its location from the CoM, the more unstable [37, p. 29].

Assuming, then, the foregoing of Qu et al. weight in addition to the backpack – such as body armor, rifle and helmet – also makes stability more difficult for the soldier to maintain depending on the amount of weight and its location. Soldiers not only don backpacks (with relatively heavy contents), but they also wear a vest of body armor (at up to 7+ kg), a helmet (at 1.5 kg) and hand carry a rifle (typically about 4 kg).

However, if symmetrical loads do not add to instability, the vest, which is typically worn around the torso, may be considered an evenly distributed weight and may not add to postural sway according to Rugelj et al. [22, p. 864]. The helmet too might be considered an evenly distributed weight about the vertical line of the CoM. Note, however, the weight of the helmet may affect head orientation and have an indirect influence on standing posture [39, p. 153].

Concerning the effects of rifle carry on postural stability, no specific literature has been identified, yet, body posture typically will react to unexpected arm perturbations (such as a sudden shift in force on a handheld load) [40, p. 295]. Carrying a rifle with its mass and length could conceivably provide sufficient inertia to create such disturbances or may have a positive effect depending on the coordination of the person holding it. In this study, though, participants were asked to keep the rifle in a position fixed with respect to their body, perhaps reducing its balancing effect.

As previously noted (citing Qu et al.), there is evidence that the vertical location of load placement creates an additional perturbation that challenges stability, yet some authors suggest that, generally speaking, loads placed higher on the back are more stable. The research which supports this position is based on static tests rather than dynamic tests. However, this indicates that high load placement results in less sway. The load, therefore, spends less time in zones closer to stability boundaries than the lower load placement and is therefore considered more stable [9, p. 189]. Also, another reason higher placed loads on the back are considered more stable is they can be brought closer to the body's vertical core than when they are low on the back and body shape causes the weight to be further posterior to the spine [41, p. 519].

Still other studies, however, support middle or lower placed loads as providing more stability [37, p. 27], [38, p. 21], [42, p. 9]. As noted above, some of the reasons given for this are that loads placed higher have a more destabilizing effect [4, p. 47], [23, p. 52].

There is discussion in the literature that under differing conditions, backpack high load placement is appropriate and at other times, low load placement is more appropriate. These recommendations suggest that high load placement is considered best for level walking, whereas lower level load placement is better for uneven terrain [4, p. 47], [11, p. 758] (Figure 1-3).

Some physiological changes also interact with load location and may ultimately affect

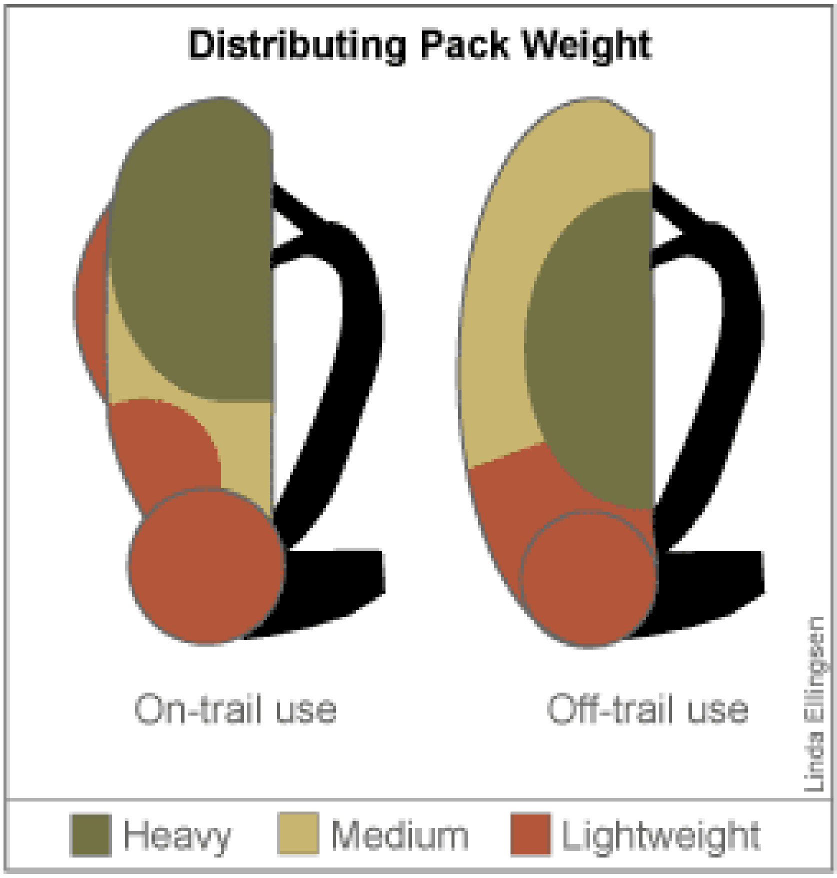

Figure 1-3 Loading [43]

instability. For example, changes in proprioceptive stimulation (placing a load on the back so it stimulates the back muscles differently than unloaded standing) may affect postural control and thus stability [1, p. 116], [44].

### 1.1.2 Metabolism

Stability factors may account for an increase in effort to adjust for posture in order to maintain balance. According to Hollerbach and Checcacci, large and constant responses to lateral perturbations are atypical of our normal walking and make balancing more difficult [15, p. 6]. This may result in an increase in use of metabolic energy. Studies with transfemoral amputees report that they expend more energy walking on a moderately angled cross-slope than up an incline. However, aside from the transfemoral study, the results of which may be primarily influenced by an inability to adequately adjust to a prosthetic leg [17, p. 190], no other specific study was found on metabolic energy use in cross-slope walking.

A soldier's need to ration energy is essential in two ways. In mountainous areas where temperature changes may impact the backpack carrying soldier, it may be especially important. While it is true they must expend energy to stay warm, if they overexert, they may become too warm and, as well, not maintain needed energy reserves.

"The best physiological offset for hypothermia is to maintain heat production by means of exercise, and so fatigue becomes a critical predisposing factor; it is as important to facilitate heat loss, especially during periods of high exertion, as it is to maintain heat production and preserve insulation" [45, p. 620].

When the metabolic energy expenditure is inefficient, less energy is available for mountain or hill climbers to maintain warmth in colder altitudes. The level of activity described by Pugh is 50% to 60% of maximal oxygen consumption at or above which those in cold, wet or windy conditions will not suffer a "drop in core temperature, mental impairment, extreme fatigue and exhaustion" [45, p. 621], [46, p. 335].

Generally, carrying a load produces a higher metabolic use – this has been incorporated into a formula, the Pandolf equation (Equation 1-2) [4, p. 49], [47, p. 577]:

$$Mw = 1.5\ W + 2.0\,(W + L)\left(\frac{L}{W}\right)2 + T\,(W + L)(1.5\,V2 + 0.35\,V\,G) \quad [1\text{-}2]$$

Mw = metabolic cost of walking (Watts)

W = body mass (kg),

L = load mass (kg),

T = terrain factor,

V = velocity or walk rate (meters/sec),

G = slope or grade (%)

At heavier loads, the metabolic rate increases steeply (in Equation 1-2, the L term, for load, exponentially increases with higher loads). Not only do metabolic expenditures increase with increased loads, but they may increase as well over time when carrying heavy loads [4, p. 49]. Considering then the magnified effect of heavier loads, the metabolic effect of their placement may exact additional energy usage.

Backpacks for military carry are the heaviest single source of load, but additionally, body armor, rifle carry and helmet all lend to the overall load carriage of the soldier.

The Interceptor Body Armor System (IBA) weighs from 7 kg to 16 kg, depending on its various styles. Results from one study on the metabolic requirements of wearing body armor (at 15.7% body weight) show that wearing body armor increases energy expenditure for slow and moderate walking speeds by 42 kcal/hr and 126 kcal/hr, respectively, and indicators for physical exhaustion rose by 68% when wearing body armor compared to not wearing body armor [48, p. 823].

Using the extra load index [49, p. 1501] for values close to the 4 kg rifle (the weight of an M162A military), the amount of extra energy expenditure is approximately 102% to 108% of a no hand carry metabolism. Rifles are often carried, as shown in Figure 1-4.

Figure 1-4 United States soldiers with loads and rifles (Department of Defense)

## 1.2 Articles

In an effort to understand the stability and metabolic demands associated with various combinations of cross-slope walking with a backpack at different vertical load positions and unloaded cross-slope walking, the following three chapters are here presented.

Each of the cross-slope trials were performed randomly in that for each random selection of track angle, the backpack level was changed randomly after four consecutive “runs”. So, for example, the track may be set at 5 degrees for the first set of trials and the backpack load set at high. In this configuration, the participant walked four separate times before the load location was changed to the next random position (either low or middle). Then four more trials were carried out with the track still at the 5 degree angle and the backpack load location reset for the last position and four more trials run. The track would then be reset to the next random position (0 or 10 degrees) and the process repeated with random load locations and so forth until all nine combinations of backpack load position (three each) and track angles (three each) were tested.

The first study (Chapter 2) measures the stability of a person wearing a backpack loaded at various levels while walking along a cross-slope at 0, 5 and 10 degrees. Using the stability formula illustrated above (Equation 1-1), the stability of the various combinations is determined and a statistical analyses performed to determine if backpack load level and/or cross-slope angle are associated with significant stability differences.

The second study (Chapter 3) is similar to the first, using the same participants, but in an unloaded condition. Only the stability comparison between track angles is measured.

The third study (Chapter 4) measures the metabolic energy usage of the participants wearing the backpacks loaded at the various levels and at the various track angles. The sequence of random testing was the same for the participants as was used for them in the first study (i.e., if the particular participant started out in the backpack stability test at angle 10 and backpack middle, they followed the same course in the metabolic study).

Please note that participants were essentially tested within the range of the least hardy member for carrying the weight and enduring the trials.

## 1.3 Hypotheses

Based on the recommendations of the majority of studies, it is hypothesized that for level walking, a high placement of a backpack load is most stable, while a low placement of the load is recommended for uneven terrain – in this case, the most angled cross-slope. The middle backpack location is estimated to be most appropriate for the intermediate cross-slope angle (5 degrees) as at some point, a transition from high to low location as the optimum is expected.

Generally, for walking without a backpack, a cross-slope is expected to produce more instability than level ground.

Finally, energy expenditure is hypothesized to follow stability, as the more unstable the individual, the more effort would be demanded to maintain balance. It is supposed that if the high load location is most stable on level ground, any other load location will produce higher energy expenditure and so on.

More formally, backpack loading low center of mass is the most stable when the wearer is walking on the most slanted cross-slope of 10 degrees.

Backpack loading mid-center of mass is the most stable when the wearer is walking on the slanted cross-slope of 5 degrees.

Backpack loading high center of mass is the most stable when the wearer is walking on the slanted cross-slope of 0 degrees.

Hypothesis 1**:** the null hypothesis is backpack loading position does not affect stability depending on slope.

Hypothesis 2: the null hypothesis is walkers have the same stability regardless of cross-slope angle (from 0 to 10 degrees).

Hypothesis 3: the null hypothesis is metabolic energy expenditure is unaffected by load position (low back, middle back or high back locations) or cross-slope angle (between 0 and 10 degrees) of a person walking.

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# 2 DETERMINING THE LATERAL STABILITY OF PERSONS WALKING ON CROSS-SLOPED SURFACES WITH BACKPACKS LOADED AT VARIOUS LEVELS[2]

## 2.1 Abstract

Life for a foot soldier frequently involves marching while wearing a uniform, boots, and interceptor body armor vest (IBA) while also carrying a backpack and rifle. Additionally, soldiers may traverse various terrains from smooth to rough, from vegetated to barren, from steep inclines to varying angles of cross slopes. The study presented here is new and unique. It determines the lateral stability of a person walking along a cross slope using a formula which is based on the inverted pendulum. Those who participated in this study walked along cross slopes (0, 5 or 10 degrees) while wearing backpacks loaded at various levels (low, middle or high). The final results of this investigation, however, indicate that neither load position nor cross-slope angle produced significant effects for lateral stability within an alpha of .05 for the participants involved.

## 2.2 Introduction

Working in the military is by nature a hazardous occupation. It requires a soldier to risk life and limb to combat enemies under various conditions. One of the enemies, however, of the United States soldier is not restricted to the battlefield. In the United

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[2] Elliott R (2016) Determining the Lateral Stability of Persons Walking on Cross-Sloped Surfaces with Backpacks Loaded at Various Levels. J Ergonomics 6:160. doi:10.4172/2165-7556.1000160

States' war history, non-combat casualties have resulted in more hospitalizations and lost persons-time than all combat casualties combined [1, p. 713]. Such injury issues have an impact on the mission of the military. As such, these are a cause for further study and effort.

One source of non-combat injuries experienced by ground force personnel is falling down. In some cases, falling down may be attributed to loss of balance from wearing a heavy backpack [2, p. 16], [3, p. 117], [4, p. 128]. Influencing the effect of the backpack on the soldier is its weight. Soldiers in the field may carry backpacks weighing as much as 54 kg [5, p. 10] or more [6, p. 5]. Yet, even packs that weigh under the maximum recommended fighting load of 22 kg (or about one third of the soldier's body weight) [6, p. 31] are said to adversely affect a soldiers stability [3, p. 116].

Besides weight, two other aspects of carrying a backpack may affect stability and therefore increase the risk of falling. These are the load location within the backpack and the terrain traversed while carrying the pack. Load location defined here is where the center of the backpack load mass is vertically located; whether it is near shoulder height, the middle of the back or low down near the lumbar region. The terrain a soldier must traverse, as mentioned above, varies. Walking surfaces such as hard, sandy, canted, inclined, slick and uneven present a few of the types of terrains the soldier encounters [6, p. 33], [7]. The terrain specifically studied here, though, will be a cross-sloped terrain of varying angles – such as that encountered along the side of a road or parallel to a mountain range. These will be treated here as level ground, 5 degree or 10 degree slopes.

Authors of various studies have theorized which location in a backpack is best suited for loading. Some have suggested that setting the load mass at the highest location has an advantage that it takes less forward tilt of the back to bring the center of the backpack load closer to the body’s vertical center of mass (CoM) [8, p. 47], [9, p. 4]. Talbot indicates in her study that the higher location results in less sway which is indirectly related to more stability [2, p. 189]. Some researchers, however, say the lower placed loads make it less likely that balance will be compromised in contrast to more top heavy higher placed loads [10, p. 860].

A particular position of the backpack’s loading center for a specific cross-sloped walking terrain may provide the most stable condition for the typical soldier [8, p. 47] and should be identified to improve the soldier’s welfare.

The purpose of this study is to investigate combinations of backpack load locations and hard surface cross-sloped terrain which may prove the most stable to service member backpackers. It is best to measure these conditions using actual walking trials as these are notably different from static trials [11, p. 203].

To test the effect of backpack loading on level and cross-sloped surfaces (5 and 10 degrees), recruits were sought who were able to wear and walk with a backpack, helmet, simulated IBA and simulated rifle which amounted to a total weight of 36.5 kg.

Though the announcement was displayed at the University of Utah campus and available to everyone who met the qualifications, all volunteers came from the military Reserve Officers' Training Corps (ROTC) groups (Army and Air Force) on campus or from the Army Reserves. A total of 15 participants were able to attend the testing before equipment requirements expired. These participants walked with the defined loads under the various conditions described in order to have their stability evaluated. They were also given surveys to assess their responses to walking with different backpack load placements on various cross-sloped angles.

### 2.2.1 Hypotheses

The concept for initiating the trials performed in this study suggested backpack loading position would affect the stability of the wearer per the cross-slope traveled.

Hypothesis 1: the null hypothesis for this study is there is no significant difference in the stability of a person, who is wearing a backpack, regardless of the interaction between the backpack load location (whether at a location low, middle or high on the back) and the angle of-slope (whether a level surface or tilted at 5 or at 10 degrees) being traversed by the person.

Hypothesis 2: the null hypothesis for this study indicates there is no significant difference in the stability of a person, who is wearing a backpack, regardless of the main effect of cross-slope degree (whether on a level surface at 5 degrees or at 10 degrees).

Hypothesis 3: the null hypothesis for this study indicates there is no significant difference in the stability of a person, who is wearing a backpack, regardless of the main effect of backpack load position (whether at a location low, middle or high on the back).

## 2.3 Materials and Methods

In order to quantify the stability of an individual carrying a heavy backpack along a level or cross-sloped surface, an adjustable track was set up at the University of Utah Ergonomics and Safety Laboratory in the Joseph Merrill Engineering building.

### 2.3.1 Participants and Materials

Participants were requested by announcements on the University of Utah campus. Eligible people were to be between the ages of 18 - 50, the heights of 153 - 193 cm, and weights of 48 - 91 kg. Fifteen people (11 males and 4 females) participated (Table 2-1). These individuals were either currently members or officers of the Army ROTC or Air

Table 2-1 Gender, heights, weights and Body Mass Indices (BMI) of volunteers

| Gender | Height in cm | Weight in kg | BMI |
|---|---|---|---|
| M | 183 | 78.5 | 23.4 |
| M | 175 | 75.2 | 24.6 |
| M | 173 | 63.9 | 21.4 |
| F | 161 | 57.6 | 22.2 |
| M | 182.5 | 76.7 | 23.0 |
| M | 192 | 74 | 20.1 |
| F | 164 | 57 | 21.2 |
| M | 173 | 76.5 | 25.6 |
| M | 184 | 71.5 | 21.1 |
| M | 186 | 74.5 | 21.5 |
| M | 168 | 70 | 24.8 |
| F | 174 | 54.5 | 18.0 |
| F | 167.5 | 60.5 | 21.6 |
| M | 174 | 83.5 | 27.6 |
| M | 179 | 84.5 | 26.4 |

Force ROTC programs on campus or involved in another military program (in the Army Reserves) and had experience carrying backpacks of the weights used in the study. Each participant signed a consent document verifying their voluntary participation in this study. They were reminded that at any time, they could choose to stop testing. Participants were compensated for their time.

The result, for a statistical power of 0.95, was to test here with a sample size of at least 7 (determined from a study as close in nature to this as available). More than twice that number were desired, but due to lack of volunteers, only 15 eventually agreed to participate. For this study, however, the final statistical power was not the 0.95 expected.

### 2.3.2 Personnel Equipment

#### 2.3.2.1 Personnel markering

Each participant had small reflective marker balls attached to them at specific locations on their bodies. These locations were the same for each participant and represented the landmarks of shoulders, elbows, wrists and so on until all appropriate landmarks were identified along with the backpack, helmet and simulated rifle. By using the reflective markers, each body segment was defined to the computer system and provided information for determining the overall center of mass for the participant and additional weights.

#### 2.3.2.2 Personnel apparel

Participants were asked to wear tight fitting biker shorts, a tank top shirt, and military style boots. The smallest boots available were too large for one participant so alternative foot wear was used. Since no significant outliers for this participant were determined by final statistical analysis, the change in footwear was not appreciable and the data used.

#### 2.3.2.3 Additional weights on personnel

To mimic the marching foot soldier, participants were asked to wear and carry additional items to those noted above, which added 36.5 kg of additional weight on their person.

Participants donned a weighted vest (at 11.6 kg – used to simulate Interceptor Body Armor (IBA)), an Army helmet (1.8 Kg) and carried a simulated rifle (3.1 kg). These extra items were requested to be included by the officer/professor in the Army ROTC program at the University of Utah campus.

Finally, a backpack (with shoulder straps and a hip belt) was put on and adjusted for each participant. This backpack was a modified MOLLE backpack (Figure 2-1). It was created using the exterior frame of a MOLLE fitted with two rails where-on the load could be moved vertically.

As can be seen from Figure 2-1, the path of the load adjustment was kept in line with the wearer's torso when straight (comparing the yellow dashed line with the rails in Figure 2-1). The high location of the load placed the center of the load nearly even with the shoulders. The low position of the load placed its center next to the bottom of the spine. The middle location is equally distant (.23 m) from the top and bottom locations.

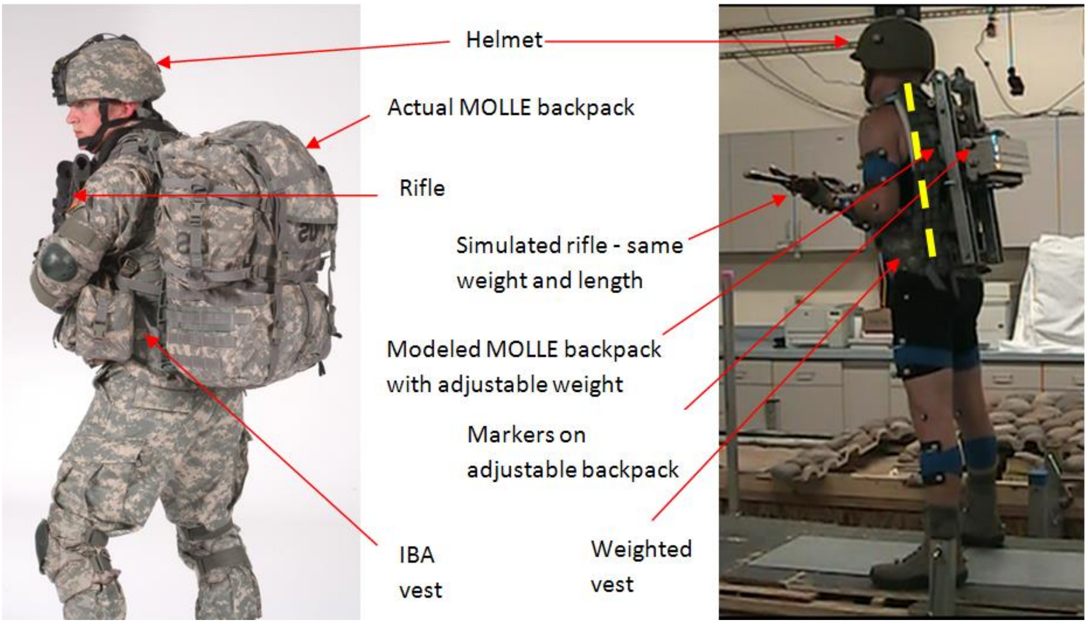


Figure 2-1 Corresponding items on participant and regular soldier

The weight of the weighted vest, the rails and the backpack support (excluding the movable load) accounted for the weight and distribution of an actual IBA.

### 2.3.3 Track Equipment

The track was a 7.3 meter long, .9 meter wide raised wooden track. The track was adjustable so it could be tilted using hand jacks from level to 10 degrees as shown in Figure 2-2 (participant is walking back from trial on track – all trials were performed walking the opposite direction from the person in Figure 2-2). Note that the maximum track angle of 10 degrees was deemed to be at the maximum of what was considered safe for the participants. Any further tilt would be considered a slipping hazard (which was noted at one point during a 10 degree cross-slope trial when one participant began to slip on the force plates – Figure 2-2 – the force plates were subsequently cleaned and further slipping was completely prevented).

Figure 2-2 Participant walking back on tilted track (markers identify body and foot location so equipment can calculate center of mass and center of pressure). Note the rectangular force plates in the middle of the track behind the participant.

## 2.4 Test Procedure

Using a formula (Formula 2-1, presented later in this report) as a basis for determining lateral stability, the process described below was established. Participants were prepared and equipment set up as follows.

### 2.4.1 Test Set-up

#### 2.4.1.1 Prior to testing

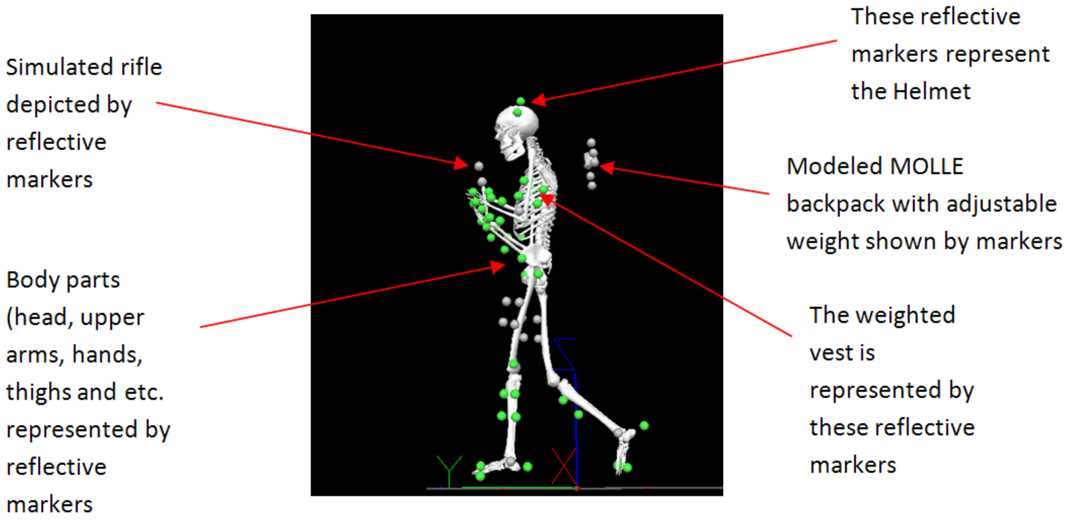
Each participant reviewed and signed a study consent form and was assured any feelings of discomfort needed to be reported and resolved before further testing. Participants were weighed and their heights measured for use in the software for computer modeling. Each participant was given a unique number to keep their personal information secure.

#### 2.4.1.2 Participant static capture

Participants were asked to stand in the middle of the motion capture image zone for a short time (approximately 6 seconds) while they were videotaped. This allowed the program to identify the body landmarks, as well as the backpack and rifle (in the program, the helmet and vest were treated as part of the head and thorax with additional weight added to the respective body parts to account for their presence) necessary to establish the body segments and determine the entire CoM for the person.

When these markers were adequately identified in the system, the markers were tracked by the motion capture equipment and each body part of the participant and item being carried could be modeled as shown in Figure 2-3.

Note that the depiction in Figure 2-3 accounts for all the mass used to determine the overall CoM.



Simulated rifle depicted by reflective markers

Body parts (head, upper arms, hands, thighs and etc. represented by reflective markers

These reflective markers represent the Helmet

Modeled MOLLE backpack with adjustable weight shown by markers

The weighted vest is represented by these reflective markers

Figure 2-3 Computer modeling of participant and items using Visual3D V5 Professional™

#### 2.4.1.3 <u>Force plate static capture</u>

The force plates (shown in Figure 2-2) were also marked to orient the motion capture system to the plates. In this way, the participant and plates could be merged into one record and the coordination of the participant stepping motion onto the force plates could be synchronized with the forces involved. Markers were removed after static capture.

### 2.4.2 Dynamic Capture

#### 2.4.2.1 <u>Participant dynamic capture</u>

After static calibration, some of the markers were removed from the participants to make their movements less restrictive (though the program was still able to track their dynamic movements with the remaining markers). They were then asked to walk along the track wearing the backpack which was set at a randomly selected load position (low, middle or high back location) with the track at a randomly selected angle (0, 5 or 10 degrees). All the load positions were walked before the track was set at the next random degree. For each condition (nine in all), the participant performed it at least four times before moving to the next condition. The participants were asked to follow small flags fixed to a loop of moving string next to the track at 4 km/hr to keep the walking pace consistent. The left foot was assigned to land only within the first force plate and the right foot the second force plate.

The set up described above allowed the measurement of each of the variables identified in Equation 2-1 below. By using the formula, a value “b” was derived for every combination of the track angle and load position for each participant subject. These “b” values were then used in a two-way (for both angle and position) random measures analyses to identify any significant effects.

## 2.5 Theory/Calculation

### 2.5.1 Formula

Walking stability has been described by one author as a state of “not falling down” [12, p. 10]. Another author defined dynamic stability as “the capacity to move the body segments in a coordinated fashion” [13, p. 1]. Still another author used stability to describe a relative condition - - a person who is walking is considered more stable in one circumstance than another if the same external influences on the first person create less of a perturbation effect than that of the second [14, p. 3].

The measurements used in this study were evaluated based on modeling human balance as an inverted pendulum.

The measure of stability given here is not a set value having a definite numerical standard, but rather is a relative term of comparison. A person experiences increased stability as they are better able to resist being “knocked off balance” by external perturbations. During standing, stability is greatest when the CoM is furthest from the perimeter (or the ultimate maximum limit - $u_{max}$) of the body's area of support. In standing position, this supporting area generally represents the base of support (BoS - area of foot to floor contact). In Figure 2-4, the silhouette of the right foot represents the BoS when the left foot is in toe-off. The center of support is referred to as the center of pressure (CoP). (Note if the BoS is in more than one area, the CoP can be between them.)

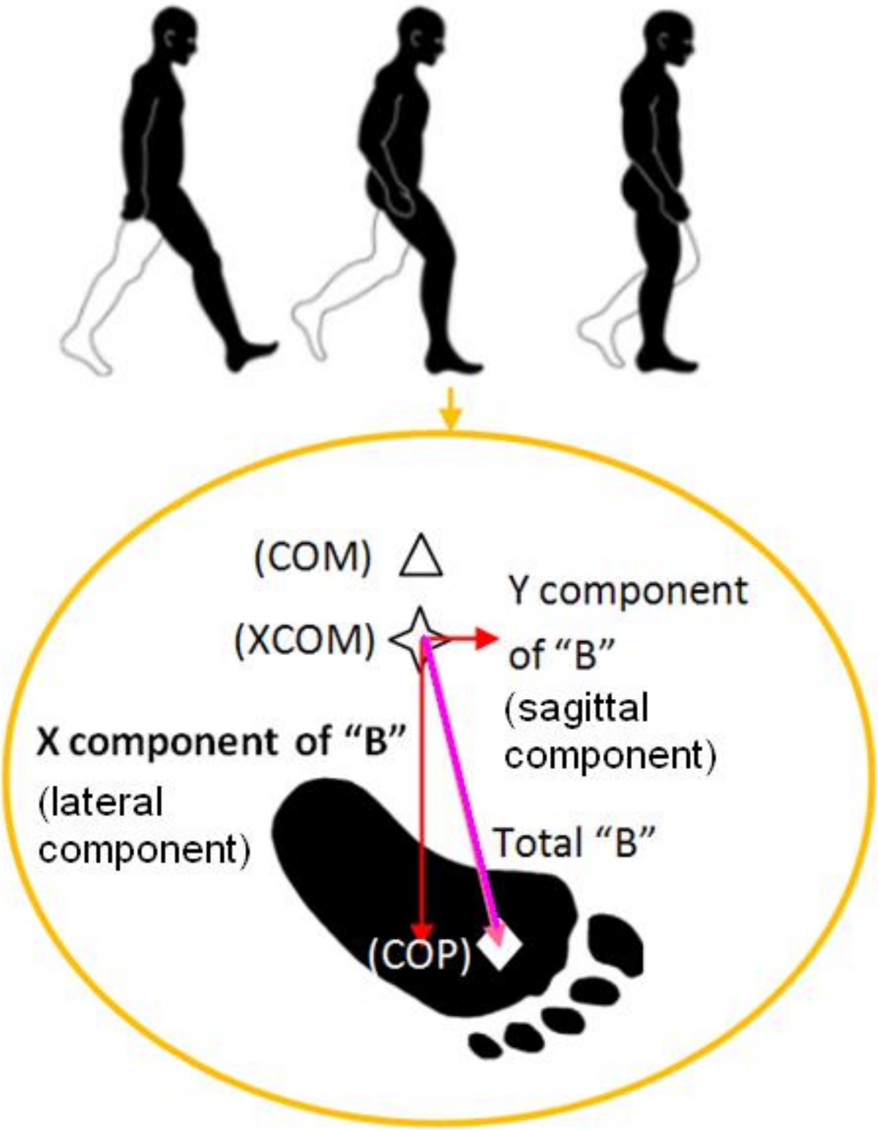


Figure 2-4 Illustration of variables [14] (Note: vector lengths are not to scale)

An analogous scenario of greater stability in one case over another would be the increased difficulty of tipping over a cone (point up) with a large diameter to a cone (point up) of a smaller diameter of the same height. The larger diameter cone is relatively more stable than the smaller diameter cone because it would be harder to tip bver.

This stability value is expressed in terms of a distance. In the cone example, the large cone radius represents the stability value to be compared to the small cone radius.

An additional factor affecting stability is the inertia of the object's mass tending away from the center-point of support. If, in the cone example, the point of the cone already had some momentum toward the side to which it would be tipped, it would be less stable than when it was static. This is its dynamic characteristic. Consequently, when a standing person starts to lean, they become less stable and must adjust in order to remain standing.

The method, then, of mathematically quantifying the degree of stability can be developed from the formula by Hof [14, p. 3] using CoP in place of the $U_{max}$ for walking as per Hof's later article [15, p. 251] (Equation 2-1):

$$\boldsymbol{b} = \left| \boldsymbol{CoP} - \left( \boldsymbol{x} + \frac{\boldsymbol{v}}{\left(\frac{g}{l}\right)^{1/2}} \right) \right| \qquad \textbf{[2-1]}$$

$\boldsymbol{b}$ = stability value

$\boldsymbol{CoP}$ = Center of Pressure

$\boldsymbol{x}$ = instantaneous lateral point of CoM

$\boldsymbol{v}$ = velocity in lateral direction

$\boldsymbol{g}$ = standard acceleration due to gravity

$\boldsymbol{l}$ = vertical distance from CoM to ground

In Equation 1-1, the “$v/(g/l)^{½}$”portion represents the equivalent length of the inertia of the center of mass. This formula is based on modeling the body movement as an inverted pendulum, which is why the value “$(g/l)^{½}$” is employed (Hof et al. re-identified the value “$(g/l)^{½}$” as “ω”).

Figure 2-4 illustrates the dynamic stability of Equation 2-1 in the both the sagittal plane (“y” component) and lateral plane (“x” component).

The lateral “b” component will be used for walking in this study since it can be simply and independently assessed from overall stability, being primarily separate from the sagittal component [16, p. 2656].

The factors for the CoM, CoP and a lateral velocity of the CoM are usable for the walking situation specifically when, the on-stepping foot is fully supporting the body, just after the off-stepping foot is in toe-off. Walking is notably different than static standing because when the person is walking, the BoS changes with each foot lift and subsequent placement. Consequently, the BoS area in the walking case is not used, but rather the instant center of contact pressure of the foot towards which the CoM is traveling. The image which might be used to clarify this idea is a ballerina on pointe. She is more stable after she establishes the toe onto which she is going to rise, just before she rises, than after she lifts off her supporting foot.

As noted before, in most cases, the telling indicator of stability is how perturbations affect the maintenance of the erect body, which is determined by the size of “b”, or the difference between XCoM and CoP. The greater the value of “b”, the better the stability. Again, this is assuming the XCoM is headed toward, rather than away from, the CoP. If the XCoM is moving away from the CoP, instability has already begun and a new CoP must be established ahead of the XCoM [14, p. 3] to regain better stability.

As in the example of the cone, it could be theorized that the lower backpack weight location is the most stable in all conditions. It has been reported from experience of many hikers, however, that the high location is easiest to carry on level ground.

Considering this and the suggestion of others that low is better for unstable terrain, it may be that the pack weight location is variable depending on terrain, and the high pack is best for level [8, p. 47], the low pack is best for higher cross-slope and consequently the mid-pack placement is best for terrain which is in-between.

## 2.5.2 Statistics

### 2.5.2.1 Stability data

A concerted effort was made to provide complete results for each participant with all four runs per condition. However, this was not obtainable. Either camera identification of essential markers was lost or other recording challenges occurred. Consequently, the data from the runs of each condition were averaged to produce one "b" value per condition per participant. These were then analyzed using the two-way repeated measures method of the Statistical Package for the Social Sciences (SPSS) program with an alpha of 0.05.

### 2.5.2.2 Survey data

The results of the surveys were also analyzed and the results determined. The participants were given a survey which requested them to fill in a Likert Scale according to the following, "Compared to not wearing any load, please rate how hard it was to walk with total load." For each of the nine conditions of backpack load position and cross-slope angle, the questionnaire had five levels to choose from, namely: very easy, somewhat easy, neither easy nor hard, somewhat hard and very hard.

## 2.6 Results and Discussion

### 2.6.1 Results

#### 2.6.1.1 Analyses of stability

Stability measurements were taken of each participant when they were on their left and also on their right foot at the various side sloping angles and backpack locations.

The results for the repeated measures for the left foot (right foot in toe-off) are in Table 2-2 with box and whisker descriptions illustrated in Figure 2-5.

For the left foot data analysis, no outliers were discovered with studentized residuals that were greater than ±3 standard deviations.

Normality values showed that two of the conditions were below 0.05 and therefore not normal. However, since the rest were within normal values, disparity was not considered critical. To further test this, however, analysis was performed with a square root data transformation. Results produced more normal values, but final values still did not show significance.

Mauchly’s test of sphericity showed suitable values for use of the two-way repeated measures analysis: $\chi^2(9) = 0.334$, $p = 0.254$.

Table 2-2 shows the comparison of left foot stability values between the nine various conditions to determine whether there were any significant differences. A two-way repeated measures analysis was performed for these values with the following results (tests of within-subjects effects):

There are no significant two-way interactions between cross-slope angle and backpack load position at left foot $F(4,48) = 1.039$, $p = 0.397 > 0.05$, partial $\eta 2 = 0.080$. Nor did the main effects of degree, $F(2,24) = 0.506$, $p = 0.609 > 0.05$, partial $\eta 2 = 0.040$, or position, $F(2,24) = 1.946$, $p = 0.165 > 0.05$, partial $\eta 2 = 0.140$, show significance.

Table 2-2 Two-way interactions of angle and position at left foot

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial η2 |
|---|---|---|---|---|---|---|
| Degrees | 0 | 2 | 5.13E-05 | 0.506 | 0.609 | 0.040 |
| Error (degrees) | 0.002 | 24 | 0 | | | |
| Position | 0 | 2 | 0 | 1.946 | 0.165 | 0.140 |
| Error (position) | 0.002 | 24 | 6.70E-05 | | | |
| degrees * position | 0 | 4 | 5.12E-05 | 1.039 | 0.397 | 0.080 |
| Error (degrees*position) | 0.002 | 48 | 4.93E-05 | | | |

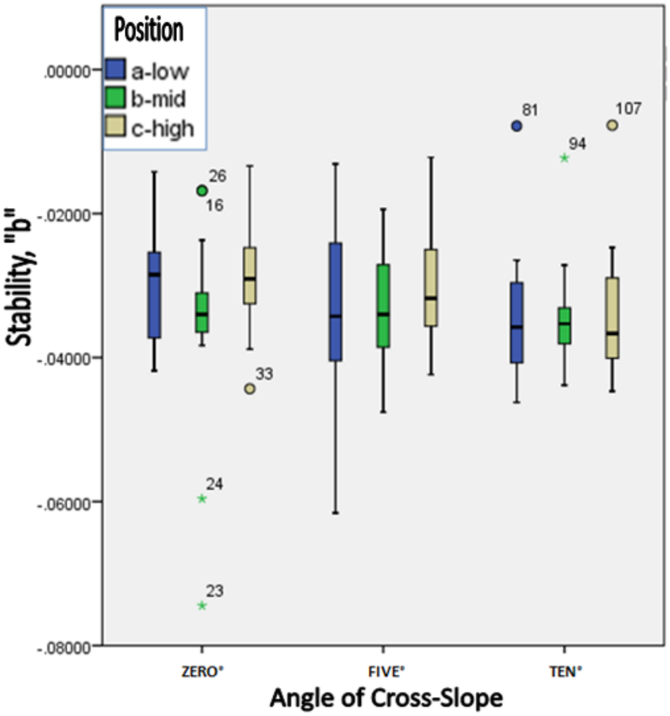


Figure 2-5 Box and whisker of left foot standing (right foot toe-off)

Note that some of the values are negative in Figure 2-5; this is due to a consistent offset of the equipment calibration which does not affect the statistical values.

Repeated measures results for the right foot (left foot in toe-off) are in Table 2-3 with box and whisker descriptions illustrated in Figure 2-6.

For the right foot data analysis, there were no outliers over ±3 standard deviations. Normality values for this foot also showed that two of the conditions were below 0.05 and therefore not normal. A data transformation was performed without test significance.

Mauchly's test of sphericity did not provide support for the right foot interaction of degrees and position sphericity: $\chi^2(9) = 0.096$, p = 0.004, so Greenhouse-Geisser adjustments were chosen to be used for all right foot analyses: 0.902 for degrees, 0.838 for position and 0.486 for the degrees*position interaction.

Table 2-3 shows the comparison of right foot stability values between the nine conditions to using a two-way repeated measures analysis (within subject effects).

There were no significant two-way interactions between degrees and backpack load position at right foot: F(1.944, 23.322) = 0.857, p=0.435 > 0.05, η2 = 0.067. Neither did main effects of degree, F(1.803, 21.64) = 1.573, p = 0.23 > 0.05, η2 = 0.116, or position, F(1.676, 20.112) = 0.537, p = 0.562 > 0.05, η2 = 0.043, show significance.

Table 2-3 Two-way interactions of angle and position at right foot

| Source | Greenhouse-Greisser value | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial η2 |
|---|---|---|---|---|---|---|---|
| Degrees | .902 | 0 | 1.803 | 0 | 1.573 | 0.23 | 0.116 |
| Error (degrees) | | 0.002 | 21.64 | 0 | | | |
| Position | .838 | 0 | 1.676 | 6.53E-05 | 0.537 | 0.562 | 0.043 |
| Error (position) | | 0.002 | 20.112 | 0 | | | |
| degrees * position | .486 | 0 | 1.944 | 7.96E-05 | 0.857 | 0.435 | 0.067 |
| Error (degrees*position) | | 0.002 | 23.322 | 9.29E-05 | | | |

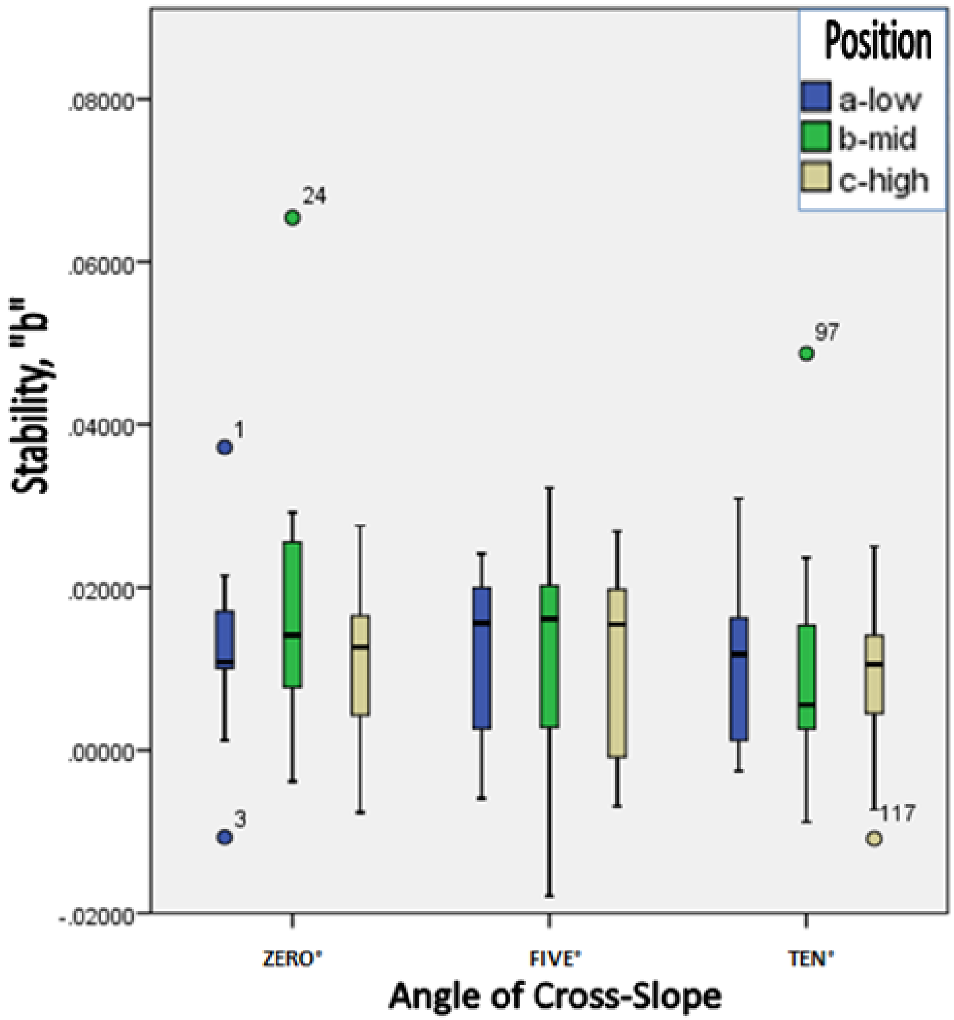


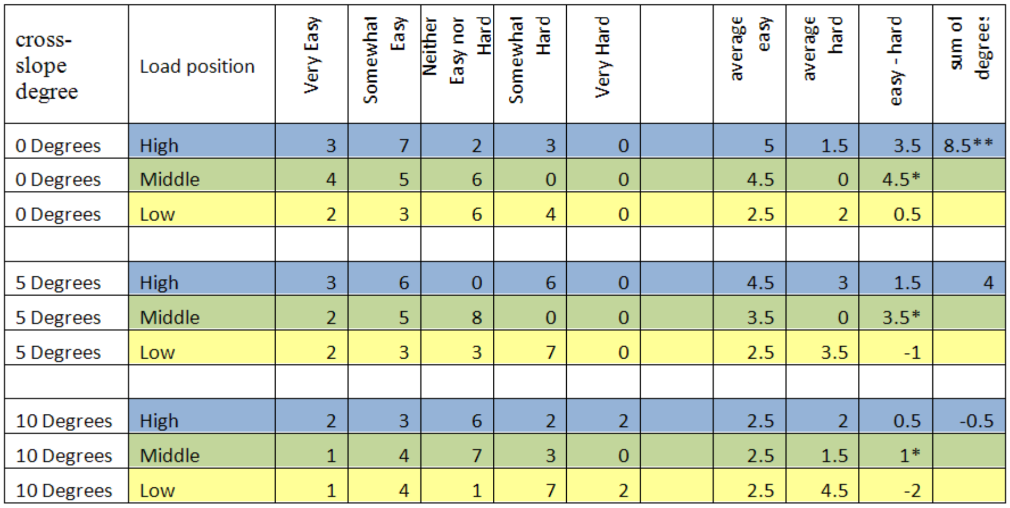
Figure 2-6 Box and whisker of left foot standing (right foot toe-off)

2.6.1.2 <u>Analyses of questionnaire</u>

The surveys showed an overall sense, on average from the participants, that carrying the backpack was between “somewhat easy” and “neither easy nor hard”.

The statistical analysis of the survey indicates that participants believed the cross-slope at 0 degrees (level) was easiest, as expected. The middle backpack location was also noted as being easiest at all slope angles (Table 2-4).

Table 2-4 Questionnaire results for ease of backpack at different positions and angles



| cross-slope degree | Load position | Very Easy | Somewhat Easy | Neither Easy nor Hard | Somewhat Hard | Very Hard | | average easy | average hard | easy - hard | sum of degrees |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 Degrees | High | 3 | 7 | 2 | 3 | 0 | | 5 | 1.5 | 3.5 | 8.5** |
| 0 Degrees | Middle | 4 | 5 | 6 | 0 | 0 | | 4.5 | 0 | 4.5* | |
| 0 Degrees | Low | 2 | 3 | 6 | 4 | 0 | | 2.5 | 2 | 0.5 | |
| | | | | | | | | | | | |
| 5 Degrees | High | 3 | 6 | 0 | 6 | 0 | | 4.5 | 3 | 1.5 | 4 |
| 5 Degrees | Middle | 2 | 5 | 8 | 0 | 0 | | 3.5 | 0 | 3.5* | |
| 5 Degrees | Low | 2 | 3 | 3 | 7 | 0 | | 2.5 | 3.5 | -1 | |
| | | | | | | | | | | | |
| 10 Degrees | High | 2 | 3 | 6 | 2 | 2 | | 2.5 | 2 | 0.5 | -0.5 |
| 10 Degrees | Middle | 1 | 4 | 7 | 3 | 0 | | 2.5 | 1.5 | 1* | |
| 10 Degrees | Low | 1 | 4 | 1 | 7 | 2 | | 2.5 | 4.5 | -2 | |

*Highest load position ratings for the easiest carry at the various cross-slope angles

** Highest easy cross-slope angle (the highest average score for degrees was at 0)

### 2.6.2 Discussion

The indications from this study support the null hypotheses that backpack load location does not have a significant effect on the lateral stability of the carrier when walking on various cross-sloped angles from 0 to 10 degrees, whether interactions or main effects of degree and angle are considered (supporting null hypotheses 1, 2 and 3).

This study was performed on a cross-slope maximum angle of 10 degrees on a continuous hard surface. The value of testing a person in this condition was repeatability and consistency. The results, showing that neither position nor angle significantly affected the stability of the participant, were not expected.

One of the suggested causes of this outcome is due to the ability of the body to sufficiently compensate for both the backpack weight location (height) and angle of surface within the condition limits of this study. Evidence of this ability is indicated by Hof in his comment “In a study on unperturbed walking (Hof et al., 2007) it was confirmed that the minimum distance $b=|u_z-\zeta_{max}|$ is indeed remarkably constant” [16, p.

2655], where $u_Z – \zeta_{\max}$ is equivalent to Equation 2-1. While cross-slope walking has been considered a perturbation [17, p. 24], in this case, it may be that the cross-slope perturbation is well handled by the person.

Furthermore, Dixon and Pearsall show that walking on a cross-slope results in a decrease in step width [17, p. 18] to help minimize the difference in height between the legs. In the lateral plane, the legs also change, with the uphill leg being more adducted and the downhill leg being more abducted [17, p. 18]. This change is noted in the current study (Figure 2-7 and Table 2-5) and seems to accommodate body modifications that allow the stability value “b” to remain constant.

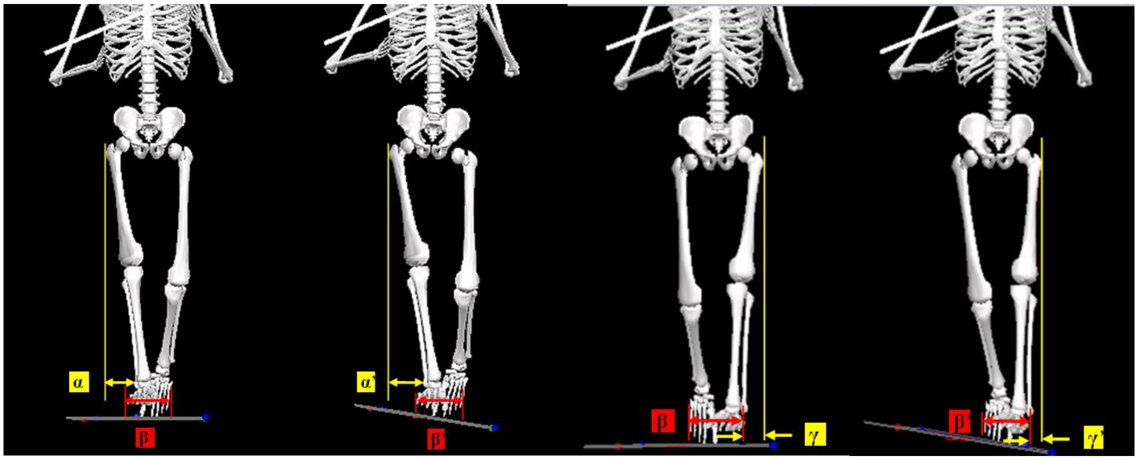


Figure 2-7 Illustrating distance: right hip adduction, foot width and left hip abduction

Table 2-5 Showing the values of one participant and the x measured differences between hip and ankle on each side when on level surface and on most inclined surface.

| | Level low bp | 10 deg lo bp | Level high bp | 10 deg hi bp |
|---|---|---|---|---|
| Right hip | 0.0975 | 0.1078 | 0.0985, **α** | 0.1174, **α’** |
| Left hip | 0.0849 | 0.0889* | 0.0776, **γ** | 0.0644, **γ’** |
| Average step width | 0.1234 | 0.0910 | 0.1421, **β** | 0.1095, **β’** |

The illustration is given for the difference as measured for the high backpack location as an example. The values in Table 2-5 indicate that the uphill foot moves in more medially when walking on a cross slope, than on a level surface and the downhill foot moves more laterally when walking on a cross slope, than on a level surface (with a backpack and regardless of the height of the pack load – note that the starred value "*" is from a set of values, one of which appeared to be a high outlier).

Additionally, participants were somewhat seasoned in backpacking, having experience marching with standard loads [10, p. 865], [18, p. 28]. Lateral stability is actively controlled by humans [19, p. 1433] and this control may dictate a set stability limit, one to which a healthy individual is accustomed and to which an able body will adapt whether on level or angled cross-slopes or even with additional loads, loaded in various locations on the back.

#### 2.6.2.1 Comparison to similar studies

Compensating for asymmetrical walking to maintain accustomed stability is noted by Hof, Vermerris and Gjaltema [16, p. 2655]. In their study report, they explain that lateral perturbations are resolved by maintaining a fixed "b" distance (reference Equation 2-1 for "b"). Since lateral stability is actively controlled by humans [19, p. 1440], this control may dictate a set stability limit, one to which a healthy individual is accustomed and to which an able body will adapt whether on level or angled cross-slopes.

No specific studies have been done on the stability of walking along various cross-slopes with differently positioned backpack loads. A best comparison can only be made to studies which examined the difference in walking stability of wearing a backpack load at various vertical locations on a level surface.

The vertical position of the load was determined by some authors to be more stable in a higher location [2, p. 189] while others supported lower placed backpack loads [18, p. 27], [20, p. 21], [21, p. 9]. Additionally, other authors indicated that load placement stability depended on the terrain [8, p. 47]. This study showed no significant difference in stability for load location.

#### 2.6.2.2 Limitations of this study

There are several issues affecting the outcome of this study. The study population had training in backpack wearing, the sample size was limited, and not all four trial runs of the data sought were available. Also, the length of time and distance of the activities of the study were limited.

#### 2.6.2.3 Recommendations for future study

One such future consideration is to perform the study with a larger and more diverse group. Also, more time and distance experience might prove a more significant discriminator.

Another area to review is to consider greater loads to test, to match more closely the current field experience of soldiers. The loads included in the study, however, seemed to be close to the maximum manageable for some of the study participants.

### 2.6.3 Conclusion

The results of this study show that there are no significant changes in lateral stability due to vertical location of backpack load or angle of cross-slope. This seems to indicate that the body can adapt to differing conditions while maintaining a similar pattern of lateral stability, at least for the population participating who are experienced in walking with backpacks of similar weight.

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# 3 DETERMINING THE LATERAL STABILITY OF PERSONS WALKING ON CROSS-SLOPED SURFACES[3]

## 3.1 Abstract

Cross-slopes (or side tilting surfaces) occur along roadsides, hill edges, some pathways and sidewalks. Such surfaces are exceptions to level walking and may challenge stability. To determine the magnitude of instability associated with cross-slope walking, 15 participants were recruited and subsequently recorded walking along a track laterally tilted at 0 degrees, at 5 degrees and at 10 degrees. Using the data obtained from these track trials, a formula was employed to compare the stability of the participants under these various conditions. The results of this study indicate that stability during lateral walking is not significantly affected by cross-sloped angles of 5 and 10 degrees compared to level ground.

## 3.2 Introduction

According to Winter [1, p. 193], 50% of falls occur during some form of locomotion. This value represents a major area of concern for certain sectors of the society. According to OSHA, slips, trips and falls cause a majority of general industrial accidents and are the next highest cause of accidental deaths after motor vehicle deaths [2]. Not all these accidental falls are from the differing levels, and may occur during walking for example

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[3] Elliott R (2016) Determining the Lateral Stability of Persons Walking on Cross-Sloped Surfaces with Backpacks Loaded at Various Levels. J Ergonomics 6:160. doi:10.4172/2165-7556.1000160

(fatal falls not to a lower level, account for 3% of all fatal occupational injuries [3]). However, for the elderly (65 years and older), the number one cause of reported non-fatal injury is from unintentional falls [4].

Loss of balance can lead to a fall to the ground. Such loss of balance while walking, or dynamic instability, may be caused by poor traction, bumping into objects, body coordination issues or external perturbations. One such perturbation is considered the cross-slope of the walking surface [5, p. 24].

Cross-slopes exist in many places outdoors. They occur, for example, at the foot of hills and are also encountered on the camber of roads, and along railroad tracks, among other manmade sites. When the cross-slopes are very steep, they defy foot travel due to slippage, but even at lower angles, they may present significant changes in adaptation [6, p. 188]. According to Dixon and Pearsall [5, p. 21], cross-slope walking decreases step width. Since increased step width may improve stability [7, p. 219], a decreased step width may reduce stability. This suggests that cross-slope walking may potentially create greater instability because it narrows the step width.

However, as also noted in the Damavandi, Dixon and Pearsall study, high ground reaction forces from the down slope leg of a person walking on a cross-slope may be keep the CoM within normal laterally stable walking bounds [6, p. 187]. Consequently, it is uncertain if cross-slope walking causes a significant increase in instability.

Note that none of these previous cross-slope studies numerically quantified stability in the same manner as this study.

Outside of the more obvious evidence of instability, given when a body unintentionally falls down [8, p. 10], one method of determining stability is to use a formula given by At Hof [9, p. 112] (discussed in more detail in the Theory/Calculation section below). This formula is based on modeling the human body as an inverted pendulum. It uses the difference in distance between the dynamic center of mass (CoM) and the center of pressure (CoP) of the supporting structure (of the feet) to establish stability. The concept of this formula is that the larger the distance between the dynamic CoM and the supporting CoP, the greater the ability of the body to withstand external perturbations. For walking, this formula is used only to determine stability in the lateral plane (side to side).

Actual trials with Air Force and Army Reserve Officers' Training Corps (ROTC) personnel and other military-related participants were performed for this study. The data from these trials were collected using a motion capture system and force plates. Results were prepared according to the stability formula previously mentioned. Statistical analyses were carried out on the results to determine if significant differences existed between left foot, right foot and angle of cross-slope.

### 3.2.1 Hypothesis

This study was conducted to determine if walking along ever more angled cross-slopes results in increased instability.

Hypothesis**:** The null hypothesis is that the angle of slope (from 0, 5, 10 degrees) of a cross-slope has no significant effect on the lateral stability of a person walking thereon.

## 3.3 Materials and Methods

To quantify the stability of an individual walking along a cross-sloped surface, an adjustable track was set up at the University of Utah Ergonomics and Safety Laboratory in the Merrill Engineering Building.

### 3.3.1 Participants and Materials

Participants were requested by announcements on the University of Utah campus. Eligible people were to be between the ages of 18 - 50, the heights of 153 - 193 cm, and the weights of 48 - 91 kg. Fifteen individuals (including both genders - 11 males and 4 females), acceptable to the requirements, participated. These individuals were either currently members or officers of the Army ROTC or Air Force ROTC programs on campus or were Army Reservists. Each participant signed a consent document verifying their voluntary participation in this study. Participants were compensated for their time.

### 3.3.2 Personnel Equipment

#### 3.3.2.1 Personnel markering

Each participant had small reflective marker balls (Figure 3-1) attached to them at specific body locations. These locations were the same for each participant and represented the landmarks of shoulders, elbows and wrists and so on. By using the reflective markers, each body segment was defined to the computer system and provided information for determining the overall center of mass for the participant.

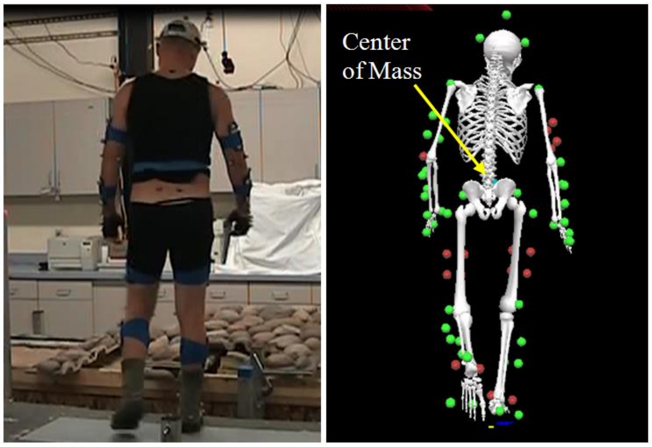

Figure 3-1 Participant with markers and a similarly modeled participant in software

#### 3.3.2.2 Personnel apparel

Participants were asked to wear tight fitting biker shorts, a tank top shirt, and military style boots (with one exception of running shoes being used - because the boots available were too large – it is recognized that extra weight on the feet is comparable to about 6 times the weight if on the back [10, p. 433] , however this exception proved acceptable since no outliers in the data were discovered from this participant).

### 3.3.3 Track Equipment

The track was a 7.3 meters long and 0.9 meters wide raised wooden track. The track was adjustable so it could be tilted using hand jacks from level to 10 degrees as shown in Figure 3-2 (all trials were recorded while participants walked in the other direction from that shown in the figure).

## 3.4 Test Procedure

To test the stability of the participants walking at various cross-slope angles, the following process was established using the apparel and the track equipment described.

### 3.4.1 Test Set-up

#### 3.4.1.1 Prior to testing

Each participant reviewed and signed a study consent form and was assured any feelings of discomfort needed to be reported and resolved before the testing was resumed.

Participant’s heights were measured. Each participant was given a unique number to keep their personal information secure.

Figure 3-2 Participant walking back on tilted track (wearing markers) program to identify the body landmarks necessary to establish the body segments and determine the entire CoM for the person.

### 3.4.1.2 Participant static capture

Participants were asked to stand stationary in the middle of the motion capture image zone for a short time (approximately 6 seconds) to be video recorded. This allowed the

### 3.4.1.3 Force plate static capture

The force plates were also statically captured with markers to orient the motion capture system to the plates. In this way, the participant and plates could be merged into a single record and the action of the participant's stepping motion (onto the plates) could be synchronized with the associated forces involved.

### 3.4.2 Dynamic Capture

#### 3.4.2.1 Participant dynamic capture

Some of the markers were removed from the participants to make their movements less restrictive (though enough were left on to follow the body segments in the computer). Participants were then asked to walk along the track at a randomly selected angle (0, 5 or 10 degrees). Trials at each of these angles were repeated at least four times going in one direction and following a loop of moving string beside the track with small flags to help participants keep the pace consistent. The left foot was assigned to land only within the first force plate and the right foot the second force plate.

The set up described above allowed the measurement of each of the variables identified in Equation 3-1 below. By using the formula, a value "b" was derived for each track angle of every participant subject. These "b" values were then used with the track angles in a one-way random measures analyses to identify any significant effects.

## 3.5 Theory/Calculation

### 3.5.1 Formula

Walking stability has been described by one author as a state of "not falling down" [8, p. 10]. Another author defined dynamic stability as "the capacity to move the body segments in a coordinated fashion" [11, p. 1]. Still another author used stability to describe a relative condition -- a person who is walking is considered more stable in one circumstance than another if the same external influences on the first person create less of a perturbation effect than that of the second [12, p. 3].

The measurements used in this study were evaluated based on modeling human balance as an inverted pendulum.

The measure of stability given here is not a set value having a definite numerical standard, but rather is a relative term of comparison. A person experiences increased stability as they are better able to resist being “knocked off balance” by external perturbations. During standing, stability is greatest when the CoM is furthest from the perimeter (or the ultimate maximum limit - $u_{max}$) of the body’s area of support. In standing position, this supporting area generally represents the base of support (BoS - area of foot to floor contact). In Figure 3-3, the silhouette of the right foot represents the BoS when the left foot is in toe-off. The center of support is referred to as the center of pressure (CoP). (Note if the BoS is in more than one area, the CoP can be between them.)

An analogous scenario of greater stability in one case over another would be the increased difficulty of tipping over a cone (point up) with a large diameter to a cone

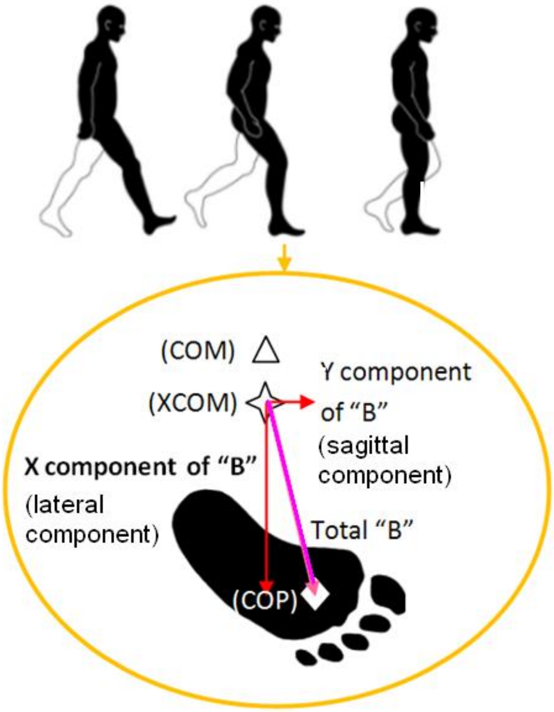

Figure 3-3 Illustration of variables [12] (Note: vector lengths are not to scale)

(point up) of a smaller diameter of the same height. The larger diameter cone is relatively more stable than the smaller diameter cone because it would be harder to tip over.

This stability value is expressed in terms of a distance. In the cone example, the large cone radius represents the stability value to be compared to the small cone radius.

An additional factor affecting stability is the inertia of the object's mass tending away from the center-point of support. If, in the cone example, the point of the cone already had some momentum toward the side to which it would be tipped, it would be less stable than when it was static. This is its dynamic characteristic. Consequently, when a standing person starts to lean, they become less stable and must adjust in order to remain standing.

Using these concepts, the method of mathematically quantifying the degree of stability can be developed from the formula by Hof [12, p. 3] using CoP in place of the $U_{max}$ for walking as per Hof's later article [13, p. 251] (Equation 3-1):

$$\boldsymbol{b} = \left| \boldsymbol{CoP} - \left( \boldsymbol{x} + \frac{\boldsymbol{v}}{\left(\frac{\boldsymbol{g}}{\boldsymbol{l}}\right)^{1/2}} \right) \right| \qquad \textbf{[3-1]}$$

***b*** = stability value

***CoP*** = Center of Pressure

***x*** = instantaneous lateral point of CoM

***v*** = velocity in lateral direction

***g*** = standard acceleration due to gravity

***l*** = vertical distance from CoM to ground

In Equation 1-1, the "$v/(g/l)^{1/2}$" portion represents the equivalent length of the inertia of the center of mass. This formula is based on modeling the body movement as an inverted pendulum, which is why the value "$(g/l)^{1/2}$" is employed (Hof et al., re-identified the value "$(g/l)^{1/2}$" as "ω").

Figure 3-3 illustrates the dynamic stability of Equation 3-1 in the both the sagittal plane ("y" component) and lateral plane ("x" component).

The lateral "b" component will be used for walking in this study since it can be simply and independently assessed from overall stability, being primarily separate from the sagittal component [14, p. 2656].

The factors for the CoM, CoP and a lateral velocity of the CoM are usable for the walking situation specifically when the on-stepping foot is fully supporting the body, just after the off-stepping foot is in toe-off. Walking is notably different than static standing because when the person is walking, the BoS changes with each foot lift and subsequent placement. Consequently, the BoS area in the walking case is not used, but rather the instant center of contact pressure of the foot towards which the CoM is traveling. The image which might be used to clarify this idea is a ballerina on pointe. She is more stable after she establishes the toe onto which she is going to rise, just before she rises, than after she lifts off her supporting foot.

As noted before, in most cases, the telling indicator of stability is how perturbations affect the maintenance of the erect body, which is determined by the size of "b," or the difference between XCoM and CoP. The greater the value of "b", the better the stability. Again, this is assuming the XCoM is headed toward, rather than away from, the CoP. If the XCoM is moving away from the CoP, instability has already begun and a new CoP must be established ahead of the XCoM [12, p. 3] to regain better stability.

### 3.5.2 Statistics

#### 3.5.2.1 Stability data e

The data given from the participants who walked the track were evaluated using a repeated measures analysis. Since some of the data were not available from the four trials for each condition, the "b" values for each condition were averaged per participant. These values were then analyzed using the repeated measures method in the Statistical Package for the Social Sciences (SPSS) program with an alpha of 0.05

## 3.6 Results and Discussion

### 3.6.1 Results

#### 3.6.1.1 Analyses of stability

Stability measurement data for the three cross-slope angles (0, 5 and 10 degrees – Table 3-1) for each subject was statistically analyzed using a repeated measures method.

For the repeated measures analysis for the left foot, the results showed (Table 3-1):

Normality – one of the three data sets for the left foot was not normal – this data set was for walking on a level surface. These data will be used because the values for the right foot showed normality for the level surface walking, indicating that due to symmetry with the right foot and all other data sets normal, the results are acceptable.

Outliers – the absolute values of the maximum and minimum studentized amounts are less than ±3 standard deviations; consequently, there are considered to be no outliers.

Mauchly's Test of Sphericity was acceptable.

There is no significant effect between stability and cross-slope at left foot $F(2,22) = 0.179$, $p = 0.837 > 0.05$, partial $\eta 2 = 0.016$.

A box and whisker chart for the left foot (right foot in toe-off) is shown in Figure 3-4.

Table 3-1 Repeated measures analysis of angle at left foot

| Source | Type III Sum of Squares | Df | Mean Square | F | Sig. | Partial η2 |
|---|---|---|---|---|---|---|
| degrees | 1.764E-5 | 2 | 8.818E-6 | 0.179 | 0.837 | 0.016 |
| Error (degrees) | .001 | 22 | 4.931E-5 | | | |

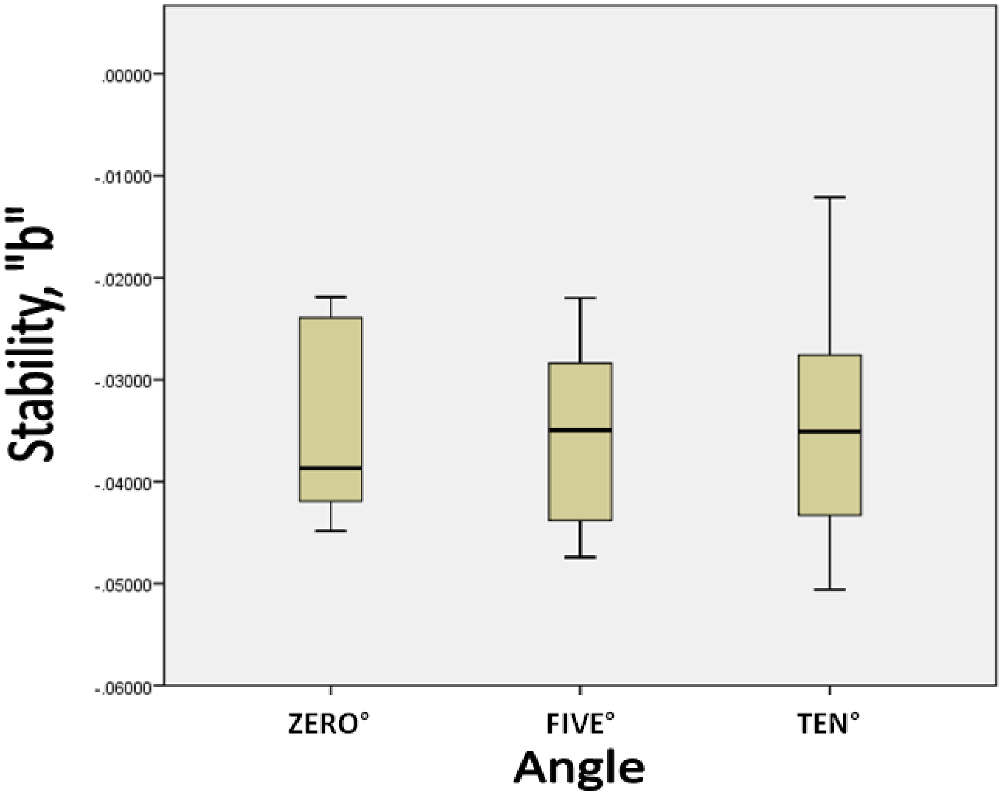

Figure 3-4 Box and whisker chart for left foot (right foot in toe-off)

For the repeated measures analysis for the right foot, the results showed (Table 3-2):

Normality – the results are acceptable.

Outliers – the absolute values of the maximum and minimum studentized amounts are less than 3; consequently, there are no outliers.

Table 3-2 Repeated measures analysis of angle at right foot

| Source | Type III Sum of Squares | Df | Mean Square | F | Sig. | Partial η2 |
|---|---|---|---|---|---|---|
| degrees | 0.000 | 2 | 9.384E-5 | 1.064 | 0.361 | 0.081 |
| Error (degrees) | 0.002 | 24 | 8.816E-5 | | | |

Mauchly's Test of Sphericity was acceptable.

There is no significant effect between stability and cross-slope at left foot F(2,24) = 1.064, p = 0.361 > 0.05, partial η2 = 0.081.

A box and whisker chart, of the left foot (right foot in toe-off), is shown in Figure 3-5.

### 3.6.2 Discussion

The indications from this study support the null hypothesis as cross-slope angle (from 0 to 10 degrees) does not have a significant effect of the lateral stability of the walker. This study was performed on a cross-slope maximum angle of 10 degrees on a

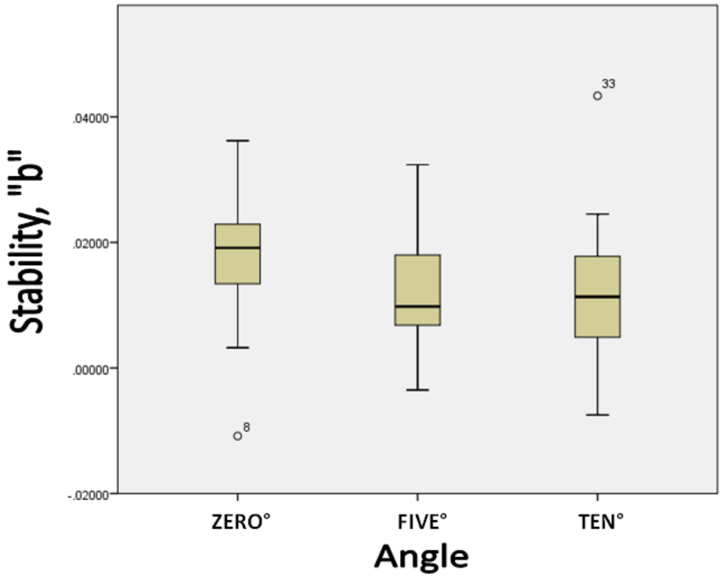

Figure 3-5 Box and whisker chart for right foot (left foot in toe-off)

continuous hard surface. The value of testing a person in this condition was repeatability and consistency. The results showing that surface angle did not affect the stability of the participant were unexpected.

One of the suggested causes of this outcome is due to the ability of the body to sufficiently compensate for the angle of surface within the condition limits of this study. Evidence of this ability are indicated by Hof in his comment, “In a study on unperturbed walking (Hof et al. 2007) it was confirmed that the minimum distance $b=|u_Z-\zeta_{max}|$ is indeed remarkably constant” [14, p. 2655], where $u_Z-\zeta_{max}$ is equivalent to Equation 3-1. While cross-slope walking has been considered a perturbation [5, p. 24], in this case, it may be that the cross-slope perturbation is well handled by the person.

Furthermore, Dixon and Pearsall show that walking on a cross-slope results in a decrease in step width [5, p. 18] to help minimize the difference in height between the legs. In the lateral plane, the legs also change, with the uphill leg being more adducted and the downhill leg being more abducted [5, p. 18]. This change is noted in the current study (Figure 3-6 and Table 3-3) and seems to accommodate body modifications that allow the stability value “b” to remain constant.

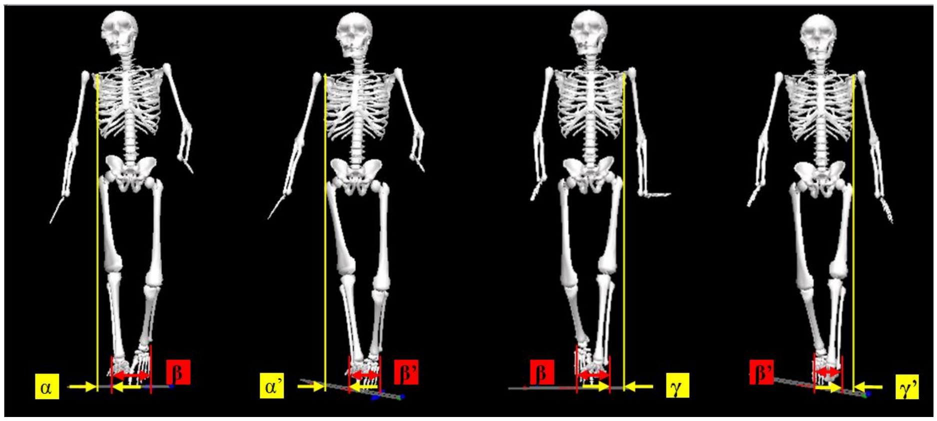

Figure 3-6 Illustrating distance: right hip adduction, foot width and left hip abduction

Table 3-3 Showing the values of one participant and the x measured differences between hip and ankle on each side when on level surface and on most inclined surface.

| | Level | 10 deg |
|---|---|---|
| Right Foot | | |
| Right hip | 0.0873, α | 0.1138, α’ |
| Left Foot | | |
| Left hip | 0.0884, γ | 0.0775, γ’ |
| Average step width | 0.1218, β | 0.1029, β’ |

### 3.6.2.1 Comparison to similar studies

Compensating for asymmetrical walking to maintain accustomed stability is noted by Hof, Vermerris and Gjaltema [14, p. 2655]. In their study report, they explain that lateral perturbations are resolved by maintaining a fixed “b” distance (reference Equation 3-1 for “b”). Since stability (specifically lateral stability) is actively controlled by humans [15, p. 1440], this control may dictate a set stability limit, one to which a healthy individual is accustomed and to which an able body will adapt whether on level or angled cross-slopes.

### 3.6.2.2 Limitations of this study

While there are several variables affecting the outcome of this study, from use of a population that has training in hiking along various terrains, to the fact that the sample size is limited and not all the data sought were totally available, there seemed to be sufficient statistical support that the results were obtained from acceptable data.

### 3.6.2.3 Recommendations for future study

One area for future study is to perform the study with a larger and more diverse group. This study was intended to provide usable information on cross-slope walking stability. If lateral stability remains constant for healthy trained walkers, it would be useful to know if the same be said for the elderly [5, p. 24].

With the report by Dixon and Pearsall [5, p. 21] that cross-slope walking decreases step width, an additional study would be required to compare significant step width changes to changes in the stability distance.

Another area to review is to discover what specific parts of the body respond to provide a consistent lateral stability.

### 3.6.3 Conclusion

This study supported the null hypothesis that cross-slopes of 0, 5 and 10 degrees do not affect the lateral stability of the walkers of this study as determined by Equation 3-1.

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# 4 DETERMINING THE ENERGY USE OF PERSONS WALKING ON CROSS-SLOPED SURFACES WITH BACKPACKS LOADED AT VARIOUS LEVELS[4]

## 4.1 Abstract

There are times when firefighters, hunters, outdoor guides as well as military personnel traverse uneven terrains while wearing a loaded backpack. The type of uneven terrain reviewed in this study is the cross-slope type terrain which might be encountered on the side of a road or along the edge of a hill or mountain. Such a side sloping surface may create an increase in overall energy expenditure as the walker manages an atypical body configuration to maneuver the path. Furthermore, walking along a cross-slope with a load positioned high on the back may require that the carrier expend more energy to keep balance than if the load in the backpack were placed lower on the back. To determine the answers to these, and related, unknowns, this study recruited 15 participants who walked along a track at randomly selected cross-slopes of 0, 5 and 10 degrees, while wearing a modified military backpack and carrying additional military load. The backpack supported a 20.4 kg weight which was also randomly located at positions of low back, middle back or high back. Each participant's respiration was measured and the energy expenditure was calculated for the participants in the various conditions.

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[4] Elliott R (2016) Determining the Lateral Stability of Persons Walking on Cross-Sloped Surfaces with Backpacks Loaded at Various Levels. J Ergonomics 6:160. doi:10.4172/2165-7556.1000160

The results of this study indicate that overall, no significant metabolic differences exist between combinations of load positions, at low, middle or high back locations, and cross-slope angles of 0, 5 or 10 degrees.

## 4.2 Introduction

Cross-slope walking in this study is defined as walking along a surface that is tilted in the lateral plane. Cross-slopes are a part of the walking, marching and hiking terrain existing in cities, country sides and mountains. By rough calculation, a 1.8 meter tall adult male with a center of gravity located at his pelvis and standing with the outer edges of his feet at .45 m (about shoulder width) would, without adjusting his posture, fall if tilted sideways at 15 degrees or more. To avoid falling sideways in such a situation, this man would naturally make asymmetrical lateral adjustments to his body to maintain his stability. Experience and common observation indicate that there is a tendency for most individuals to stand with their torsos as upright as possible when on a cross-slope. During walking, this effort to stay vertical may require additional energy expenditure as the body's center of mass (CoM) shifts laterally back and forth. Hollerbach and Checcacci explain that in theory, lateral stability adds no additional energy demand for forward movement [1, p. 5], but this does not consider extra energy demands which may be needed to maintain stability. Additionally, while an added load on a body has been shown to increase energy usage [2, p. 76], the position of that load with respect to the body's CoM may significantly raise that demand. Such an increase may be due to the energy needed to assure the body's accustomed stability.

Some research is available describing the energy a person expends while wearing a backpack with the pack's load located at various positions [3]–[9]. The similarity among all these studies is the participants were asked to walk on level surfaces with loads located either high or low on their backs while being metabolically tested. Some of these studies also had participants walk with the load in the mid-back area or perform separate efforts such as walking up or down sagitally oriented inclines. Of the seven studies which were found, none tested the energy expenditure of participants with different load locations at differing cross-slopes.

The trials performed in the studies mentioned above tested heart rate and/or oxygen consumption to determine if there was a significant difference in the physiological effects of load placement. Two tests measured both the oxygen consumption and heart rate values [6, p. 756], [7, p. 786]. The heart rate analysis for the different positions of load placement (along level ground) was not significant in three of the studies [3, p. 71], [6, p. 757], [7, p. 787]. In the studies where oxygen consumption was measured on level ground, two indicated the load position was not significant [5, pp. 4–5], [6, p. 757], but in three others, the significant difference in oxygen consumption was in favor of a high load placement compared to lower load placements. [7, p. 787], [8, p. 396], [9].

Still other researchers performing similar studies -- which placed the load either on the shoulders or equally spaced around the waist -- and recording the oxygen consumption of the participants walking up a 5% (2.9°) incline showed less oxygen consumption when the load was on the waist [10, p. 27]. This result may show that the body is sensitive to minor variations in backpack positioning, such as where the load of the backpack is placed.

Since individuals who need to transport materials by foot typically use a backpack, the amount of inefficient energy they expend may be of concern to their overall job. As noted in the NATO/OTAN manual for Common Military Task Marching: “A successful foot march is when troops arrive at their destination at the prescribed time and they are physically able to execute their mission" [11, p. 1]. If troops are expected to be physically able to execute their mission upon arrival at their destination, employing energy-saving tactics would be beneficial.

Backpacks come in various types. This particular study focused on the military Modular Lightweight Load-carrying Equipment (MOLLE) backpack (Figure 4-1).

For this study, backpack load position is defined as the location of the CoM of the load with respect to its location on the back – low (at the bottom of the spine), middle (midway between the low and high locations) or high (shoulder height). In an effort to find a possible benefit to cross-slope walking demands, this study was conducted to determine if a specific load location was less taxing at each one of three cross-slope angles (0, 5 or 10 degrees).

Figure 4-1 A soldier wearing a MOLLE backpack (from commons/Wikimedia.org)

### 4.2.1 Hypotheses

Energy expenditure may follow stability, as the more unstable the individual, the more effort would be demanded to maintain balance. For example, it is supposed that if the high load location is most stable on level ground, any other load location on level ground will produce higher energy expenditure.

Hypothesis 1: the null hypothesis for this study indicates there is no significant difference in the energy expenditure of a person, who is walking with a backpack, regardless of the interaction between the backpack load location (whether at a location low, middle or high on the back) and angle of cross-slope (whether a level surface or tilted at 5 degrees or at 10 degrees).

Hypothesis 2: the null hypothesis for this study indicates there is no significant difference in the energy expenditure of a person, who is wearing a backpack, regardless of the main effect of cross-slope degree (whether on a level surface or at 5 or at 10 degrees).

Hypothesis 3: the null hypothesis for this study indicates there is no significant difference in the energy expenditure of a person, who is wearing a backpack, regardless of the main effect of backpack load position (whether at low, middle or high).

## 4.3 Material and Methods

### 4.3.1 Participants

Participants were recruited by announcement and flyers on the University of Utah campus. Eligible people were to be between the ages of 18 - 50, the heights of 153 - 193 cm, and the weights of 48 - 91 kg. Fifteen eligible people (11 males and 4 females) participated. These individuals were either currently members or officers of the Army

ROTC or Air Force ROTC programs on campus or were current members of the Army Reserves.

### 4.3.2 Equipment

#### 4.3.2.1 Personnel apparel/equipment

Participants were asked to wear tight fitting biker shorts, a tank top shirt, and military style boots. (The smallest boots available were too large for one participant so alternative shoes were used, the effect being minimal in the statistical analysis as it did not create an outlier.) Participants also donned a weighted vest (at 11.6 kg) to help simulate Interceptor Body Armor (IBA), an Army helmet (1.8 kg) and carried a simulated rifle (3.1 kg).

Finally, a backpack was put on and adjusted for wear. This backpack was a modified MOLLE backpack (Figure 4-2). It was created using the exterior frame of a MOLLE (with the carry bag removed) and fitted with two rails on which a weight (load) could be moved vertically.

The combined weight of the weighted vest, the rails and the backpack support (excluding the movable load) accounted for the weight and distribution of an actual IBA.

As can be seen, the path of the load was kept in line with the wearer's torso when straight (comparing the red line with the load support rails in Figure 4-2).

The top, or high, location of the load places the center of the load approximately even with the shoulders. The bottom, or low, position of the load places its center approximately even with the bottom of the spine. The middle location is equidistant between the top and bottom locations (.23 m).

The total extra weight on the participant, including the backpack frame, the adjustable load, the simulated rifle, the vest, helmet and portable oxygen sensor, was 37 kg.

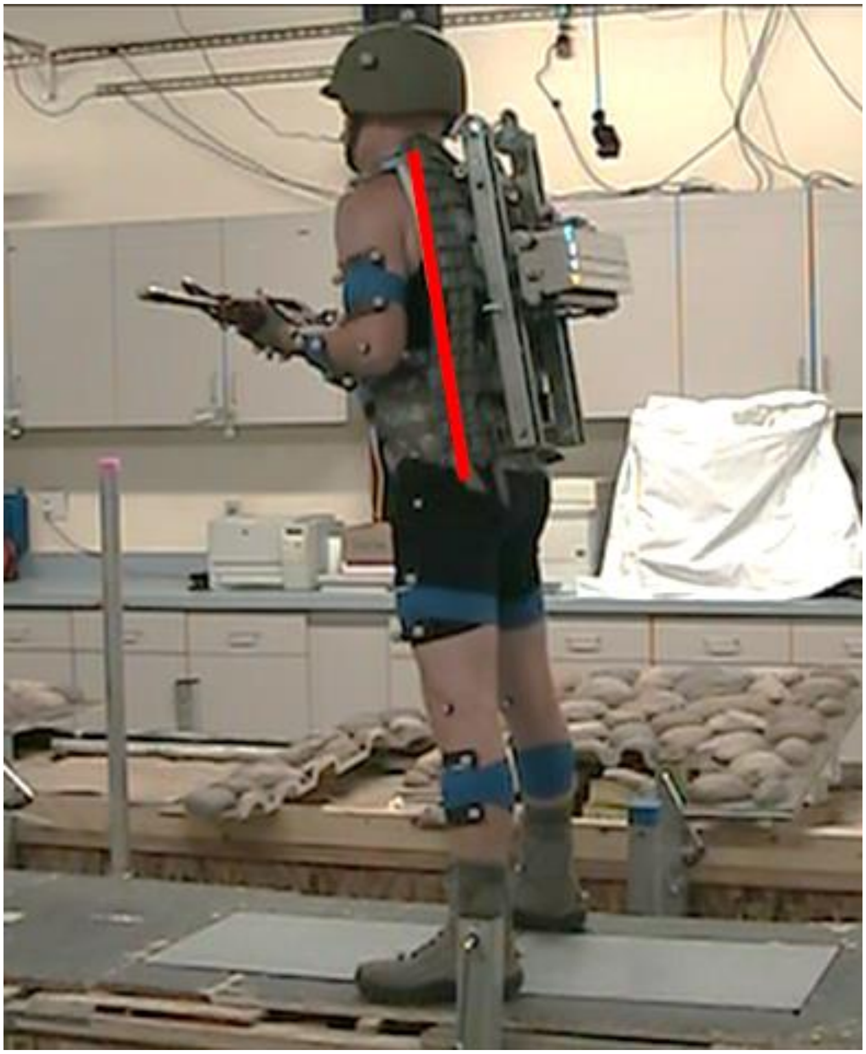

Figure 4-2 Participant with backpack (note: markers not part of metabolic test)

### 4.3.2.2 <u>Track equipment</u>

The track was a 7.3 m long, .9 m wide raised wooden track. The track was adjustable so it could be tilted using hand jacks from level to 10 degrees as shown in Figure 4-3. Please note the track angle was deemed to be at the maximum of what was considered safe for the participants - any further tilt would be considered a slipping hazard (which was noted at one point during a 10 degree cross-slope trial with one participant until the force plates were adequately recleaned).

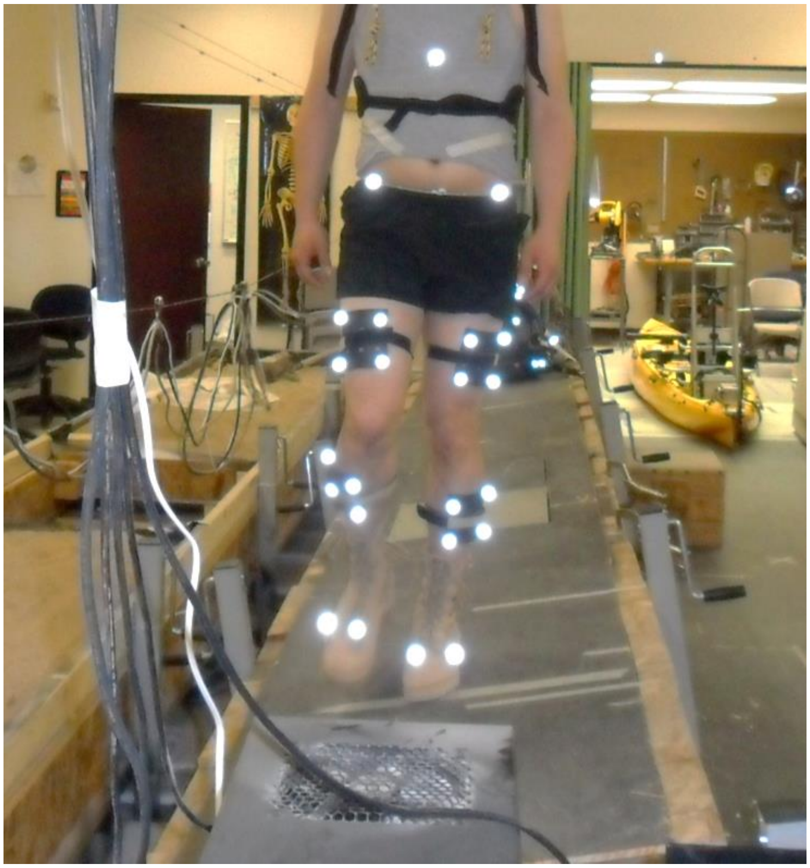

Figure 4-3 Track when tilted

4.3.2.3 Measuring equipment

A Polar heart rate monitor (Polar of Kemple, Finland) was coated with conductive gel and placed by the participant over the sternum on the bare skin. A CareFusion portable VO2 tester (Oxycon™ Mobile Device from CareFusion, San Diego, CA) mask was worn (and tested for leakage) by the participant (Figure 4-4). The mask was connected to two portable units which communicated by wireless electronics to a main unit. The main unit was connected to a laptop computer. The computer had a program for recording and analyzing the data from the heart monitor and the breath tester. The program measures metabolic energy in kilocalories per day.

Figure 4-4 VO2 respiration monitor to assess energy expenditure

### 4.3.3 Procedure

#### 4.3.3.1 Previous to testing

Participants were asked in e-mail communications, not to “…eat anything two hours before testing” and to “avoid exercise and caffeine for four or more hours beforehand.” Participants were asked to feel free to drink water as needed. Each participant reviewed and signed a study consent form and was assured any feelings of discomfort needed to be reported and resolved before testing was resumed. Participants were weighed, heights measured, resting heart rates read and ages recorded for input into the energy computation software. Each participant was given a unique number to keep their personal information secure.

#### 4.3.3.2 Testing

Each participant number was associated with a unique random set of trials. The angle of the track was randomly set at a specific value of 0, 5 or 10 degrees and the load on the backpack was randomly set at low, middle or high. The trials consisted of walking back and forth along the track while following a constantly moving loop of thread (with small flags attached) beside the track. This loop speed was set at 4 km per hour (2.5 mph). The participants walked for a total of 4 minutes (with one exception where the trial was cut short at 3 minutes and 35 seconds due to a recording problem). The track angle was not changed until all levels of the backpack were tested in random order. This process was repeated until all nine combinations of track angle and load location were tried. The participant was allowed to return to a chair to rest until their heart rate was within 10 beats per minute of their resting heart rate. Originally, the goal was to have the heart rate fall to within 5 beats per minute of resting before retesting. However, due to the length of the testing and anxiety created by this expectation, 10 beats per minute were chosen – part of the justification for this value is participants typically increased their heart greater than 10 beats per minute in simply mounting the track to perform another trial.

#### 4.3.3.3 Analysis

The CareFusion Ergospirometry "Breath by Breath" manual explains the method used to determine the energy expenditure (EE) (Equation 4-1).

$$EE = 1.59 \bullet VCO2 + 5.68 \bullet VO2 - 2.17 \bullet UN \qquad [4\text{-}1]$$

EE is the energy expenditure in kilocalories/day (these are units of the equipment)

VCO2 is the volume of CO2 in ml/min/kg

VO2 is the volume of O2 in ml/min/kg

UN is the urinary nitrogen which is given a value of 15 (since obtaining the urinary nitrogen was outside of the Institutional Review Board (IRB) set for this testing, the given standard value of 15 was used instead of obtaining the UN for each participant)

The EE is calculated by the CareFusion "Breath by Breath" program. The Ergospirometry testing equipment records the averages of every 5 seconds of breath, both the volume of the oxygen and volume of the carbon dioxide. These two variables are mentioned above in Equation 4-1. To characterize the energy expenditure of the participants, averages are taken of the last part of the EE recordings. The very last 5 seconds of each trial is disregarded due to some end effects occurring when the measurements are stopped. Data from the 25 seconds previous to the very last 5 seconds of the trial are averaged to determine energy usage of the trial. The reason only the last portion of the trial is used for determining the metabolic rate is to allow the body to reach a better steady state condition which is more representative of the energy expenditure.

#### 4.3.3.4 Questionnaire

The participants were asked to fill out a questionnaire rating each trial. The questionnaire covered testing done by the participants while wearing the loads in other trials (stability trials were performed using the same nine conditions previous to the metabolic testing). The participants were given a survey which requested them to fill in a Likert Scale according to the following, "Compared to not wearing any load please rate, how hard it was to walk with total load." For each of the nine conditions of backpack load position and cross-slope angle, the questionnaire had five levels to choose from, namely: very easy, somewhat easy, neither easy nor hard, somewhat hard and very hard.

## 4.4 Results and Discussion

### 4.4.1 Results

#### 4.4.1.1 Analysis of energy expenditure

Energy expended by the participants in the nine different configurations of angle and backpack location was analyzed with a two-way repeated measures method (Table 4-1) using the Statistical Package for the Social Sciences (SPSS) program with alpha at 0.05.

No outliers emerged with studentized residuals greater than ±3 standard deviations.

Normality values were normal.

Mauchly's test of sphericity showed suitable values for use of the two-way repeated measures analysis $\chi^2(9) = 8.607$, $p = 0.479$.

Table 4-1 shows the comparison of energy usage values between the nine various conditions to determine significant differences. A two-way repeated measures analysis was performed with the following results (tests of within-subjects effects):

There are no significant two-way interactions between cross-slope angle and backpack load position: $F(4,52) = 0.738$, $p = 0.570 > 0.05$, partial $\eta 2 = 0.054$. Neither did the main effects of degree (using the Greenhouse-Geisser value due to an abnormal Mauchly value for degree): $F(1.298,16.875) = 0.673$, $p = 0.461 > 0.05$, partial $\eta 2 = 0.049$, or position: $F(2,26) = 0.361$, $p = 0.700 > 0.05$, partial $\eta 2 = 0.027$, show any significance.

Pairwise comparisons of the level walking with the backpack load placed at low, middle or high locations show no significant differences (Table 4-2).

Additional comparison using a box and whisker chart is shown in Figure 4-5.

Table 4-1 Two-way interactions of angle and position

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. | Partial η2 |
|---|---|---|---|---|---|---|
| degrees | 2765381.772 | 2 | 1382690.886 | 0.673 | 0.519 | 0.049 |
| Error (degrees) | 53430454.588 | 26 | 2055017.484 | | | |
| degrees (Greenhouse-Geisser) | 2765381.772 | 1.298 | 2130425.823 | 0.673 | 0.461 | 0.049 |
| Error (degrees) (Greenhouse-Geisser) | 53430454.588 | 16.875 | 3166334.833 | | | |
| position | 249264.841 | 2 | 124632.420 | 0.361 | 0.700 | 0.027 |
| Error (position) | 8976184.046 | 26 | 345237.848 | | | |
| degrees * position | 1209061.227 | 4 | 302265.307 | 0.738 | 0.570 | 0.054 |
| Error (degrees*position) | 21303117.906 | 52 | 409675.344 | | | |

Table 4-2 Pairwise comparisons of load positions and energy expenditure at 0 slope

| load position | | load position | p = .05 | level of significance |
|---|---|---|---|---|
| low | vs | mid | p< | 0.1368 |
| low | vs | high | p< | 0.2201 |
| mid | vs | high | p< | 0.8353 |

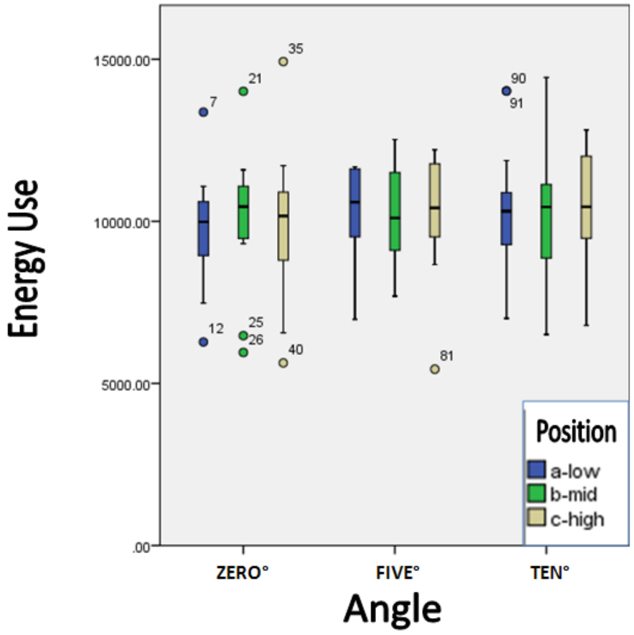

Figure 4-5 Box and whisker chart of energy compared to angle/load position

#### 4.4.1.2 Questionnaire

The surveys showed an overall sense, on average from the participants, that carrying the backpack was between “somewhat easy” and “neither easy nor hard”.

The statistical analysis of the survey indicates that participants believed the cross-slope at 0 degrees (level) was easiest, as expected. The middle backpack location was also noted as being easiest at all slope angles (Table 4-3).

### 4.4.2 Discussion

#### 4.4.2.1 Comparison to other similar studies

The trials performed in the other studies mentioned in the introduction tested heart rate and/or oxygen consumption to determine if there was a significant difference in the physiological effects of load placement. As noted, a few of these studies concluded there was no significant difference in metabolic energy expenditure walking on a level surface

Table 4-3 Questionnaire results for ease of backpack at different positions and angles

| cross-slope degree | Load position | very easy | Somewhat easy | neither easy nor hard | somewhat hard | very hard | | average easy | average hard | easy - hard | sum of degrees |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 degrees | high | 3 | 7 | 2 | 3 | 0 | | 5 | 1.5 | 3.5 | 8.5** |
| 0 degrees | middle | 4 | 5 | 6 | 0 | 0 | | 4.5 | 0 | 4.5* | |
| 0 degrees | low | 2 | 3 | 6 | 4 | 0 | | 2.5 | 2 | 0.5 | |
| | | | | | | | | | | | |
| 5 degrees | high | 3 | 6 | 0 | 6 | 0 | | 4.5 | 3 | 1.5 | 4 |
| 5 degrees | middle | 2 | 5 | 8 | 0 | 0 | | 3.5 | 0 | 3.5* | |
| 5 degrees | low | 2 | 3 | 3 | 7 | 0 | | 2.5 | 3.5 | -1 | |
| | | | | | | | | | | | |
| 10 degrees | high | 2 | 3 | 6 | 2 | 2 | | 2.5 | 2 | 0.5 | -0.5 |
| 10 degrees | middle | 1 | 4 | 7 | 3 | 0 | | 2.5 | 1.5 | 1* | |
| 10 degrees | low | 1 | 4 | 1 | 7 | 2 | | 2.5 | 4.5 | -2 | |

*Highest load position ratings for the easiest carry at the various cross-slope angles

** Highest easy cross-slope angle (the highest average score for degrees was at 0) when the load in the pack was worn high or low. This study showed the same results for level walking (pairwise comparisons shown in Table 4-2).

Also, as previously referenced, other studies indicate that there is a significant difference in metabolic energy use for the person who is wearing a low placed backpack load compared to a high placed load. This study did not confirm the same findings.

#### 4.4.2.2 Comparison to studies of load carrying metabolic rate

The rate of energy expenditure, measured in this study as kilocalories/day, has been estimated by Bastien et al. [2, p. 78] for level walking with a load. In their study, the rate was discovered to be proportional to the total load (both the body mass and the load mass if under 75% of the body mass) at specific speeds. For 4 km/hr (1.1 m/s in their study), the power was 4 Watts/kg.; Comparing their study to the present study there is on average a close approximation to the recorded energy rates (the Bastian as well as other metabolic calculations are shown in Table 4-4 -- Figure 4-6 is a graphical display of Table 4-4).

In comparison to level walking with a load, if it is assumed that the energy expenditure of walking with the same load is greater for walking on a cross-slope at potentially less efficient load positions, then the “Measured” values in Table 4-4 should perhaps show an average value greater than 6% (as it should show not only a similarity to the Bastien values but an increase due to effort). Overall, they are less than the Garg values, but again greater than the Pandolf values.

The comparisons show that the energy expended by the participants was realistically measured (being within range of the calculated values) and helps to show that assumed extra energy expenditures, due to the conditions tested, may account for no more work than level walking with the same load.

Table 4-4 Averages for all conditions and level walking with same load calculations

| Measured | | Garg | | | Bastian | | | Pandolf | |
|---|---|---|---|---|---|---|---|---|---|
| Kcal/day | | Kcal/day | Measured /Garg | | Kcal/day | Measured /Bastian | | Kcal/day | Measured /Pandolf |
| 11095.778 | | 16234.203 | 68.34815 | | 9871.306 | 112.40435 | | 8094.6147 | 137.07605 |
| 9754.1111 | | 15944.97 | 61.173595 | | 9571.5724 | 101.90709 | | 7901.0367 | 123.45356 |
| 8900.0222 | | 15872.661 | 56.071393 | | 9496.639 | 93.717601 | | 7853.6777 | 113.32299 |
| 10205.933 | | 15438.81 | 66.105699 | | 9047.0386 | 112.80966 | | 7579.6612 | 134.64894 |
| 10522.533 | | 16559.592 | 63.543435 | | 10208.506 | 103.07613 | | 8319.3885 | 126.48205 |
| 11953.089 | | 15547.273 | 76.882222 | | 9159.4387 | 130.50023 | | 7646.4047 | 156.323 |
| 13313.067 | | 15872.661 | 83.874195 | | 9496.639 | 140.18714 | | 7853.6777 | 169.51379 |
| 11092.911 | | 16270.358 | 68.178655 | | 9908.7727 | 111.9504 | | 8119.2449 | 136.62491 |
| 11338.778 | | 16342.666 | 69.381444 | | 9983.7061 | 113.57283 | | 8168.7737 | 138.80636 |
| 8911.6889 | | 15691.89 | 56.791686 | | 9309.3055 | 95.728827 | | 7737.2868 | 115.17847 |
| 6781.6889 | | 15908.815 | 42.628497 | | 9534.1057 | 71.130834 | | 7877.3022 | 86.091516 |
| 7772.7111 | | 15673.813 | 49.59043 | | 9290.5721 | 83.662352 | | 7725.8138 | 100.60702 |
| 10179.956 | | 15908.815 | 63.989401 | | 9534.1057 | 106.7741 | | 7877.3022 | 129.2315 |
| 10131.089 | | 16089.587 | 62.966745 | | 9721.4392 | 104.21388 | | 7997.0304 | 126.68564 |
| | | | 63% ave | | | 106% ave | | | 128% ave |

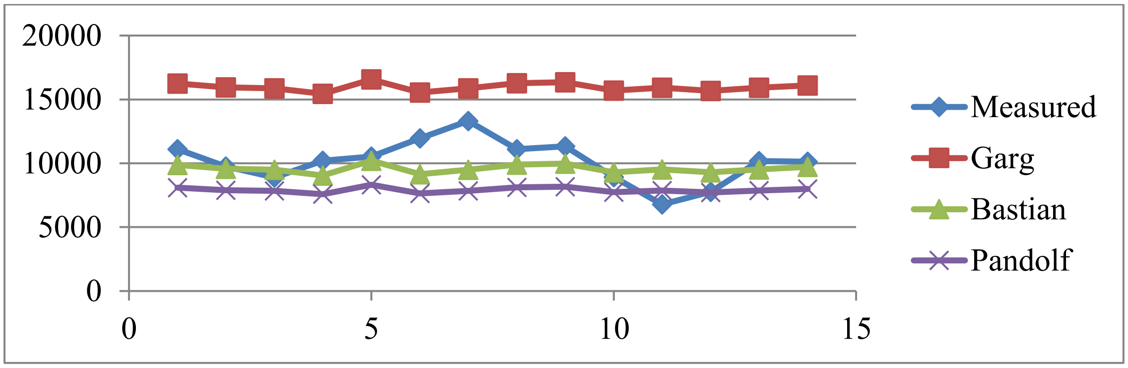

Figure 4-6 Graphical comparison of values in Table 4-4

#### 4.4.2.3 Shortcomings of this study

Three aspects may have affected the results of this study. These are not unusual in a study, but need to be addressed. These are participant make-up and unplanned events.

The participant make-up may have been the most influential shortcoming of this study as all participants had military backgrounds and were accustomed to marching with a loaded backpack. Of the previous studies performed to determine if there is a difference between load placement and energy usage (whether energy usage was calculated by heart rate or oxygen use), the majority of the ones which showed no significant difference specifically used military personnel (who had experience with wearing a backpack). The majority of those studies which did not specify that the participants in those studies had experience in using backpacks (Stuempfle's study specifically selected people with minimal backpacking experience [7, p. 785]) showed a significant difference. It may be that the difference in finding a significant effect between high and low load placement is related to the experience level of the participants.

Finally, unplanned events were resolved using best judgments and relying on the outcome of statistically determined significant outliers, of which none were discovered.

Two such unplanned events which occurred were that some of the participants did not recover to within an intended heart rate of 5 beats per minute of their resting heart rate between testing conditions and only 25 of the intended last 30 seconds of metabolic data for each trial walk was considered usable.

To provide a fresh start for each condition trial, the participant was to wait until their heart rate was within 5 beats per minute of their resting heart rate. This value was based on laboratory tradition, but was modified as noted to 10 bpm as some participants were unable to meet that level of rest. It was noted that when participants stood and donned the backpack before another trial their heart rates naturally increased to levels beyond the 10 bpm level of resting heart rate.

Following, for example, other studies [13], the participants were to walk a minimum of 3 minutes to assure a steady metabolic state had been reached. The last 30 seconds of the 4-minute walk was to be averaged to acquire the intended steady state value. It was noted, however, in some cases, that participants became aware of the last few seconds of the test and would slow down, making the final 5 seconds unusable. Consequently, only the first 25 seconds of the last 30 seconds of the walking data was averaged. In one case, the time to begin the 25 sec recording was after 3 minutes and 5 seconds (instead of 3 minutes and 30 seconds). Since this was still over the precedent of 3 minutes for the Parker study, it was determined to be acceptable [13].

#### 4.4.2.4 Recommendations for future study

Participants became exhausted participating in this study, not always from over-exertion, but from other aspects of the study related to the length of time involved. The metabolic test was only part of a larger study sequence involving these same participants. The study protocol meant that subjects would not return for a second time to complete another portion of the study, so they were asked to perform everything consecutively. Consequently, they often were fatigued at the end of the trials. In light of this, it is recommended that in conducting a similar study, only two angles be used (the level and the 10 degree angle) and that only two load placements be tested (low and high). In this way, participants may be expected to perform with more exactness and they will be less drained.

Also, it is suggested that a similar study be performed with two groups, one experienced in backpacking and another with no experience.

### 4.4.3 Conclusion

The results of this study indicate that no significant metabolic differences exist between combinations of load positions, at low, middle and high back locations, and cross-slope angles of 0, 5 and 10 degrees within a confidence level of 95%. The null hypothesis cannot be rejected.

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# 5 CONCLUSION

## 5.1 Backpack Load Location and Cross-Slope Walking Stability Assessment

Walking along a cross-slope presents a perturbation to normal gait and can consequently be a challenge to stability [1]. To determine if there is adequate compensation for this challenge, human trials were performed with participants walking along 0, 5 and 10 degree cross-slopes. Some testing was also performed with the participants while wearing backpacks loaded at various height locations to determine if along with slope adjustments, there were significant changes in stability and metabolism.

In the first test, participants wore boots, helmet and weighted vest while holding a simulated rifle and were asked to carry a backpack with a 20 kg weight, which could be adjusted from a low position on the back to the middle of the back to a high position near the shoulders. Participants were to try each of these positions four times for each of three cross-slope track positions, namely: 0, 5 and 10 degrees.

Several authors have indicated that load carrying on an uneven surface is best done with a backpack loaded in the lower position [2], [3]. Some have evidenced that more stability is maintained in a motionless state (standing still) with the backpack load placed high on the back [4, p. 189]. However, from this study in dynamic trials, there is no support that dynamic side to side or lateral stability is significantly affected by load position (low, middle or high) on cross-slopes of 0, 5 and 10 degrees.

The results of the survey questionnaire given the participants, however, indicate that the 0 degree (or level) walking surface is easiest (which is expected) and that the middle backpack location for the load is the easiest load position for all cross-slope angles. This is in some contrast to indications of no significant differences in lateral stability, which may have to do with a comfort factor that is not revealed by this study's stability calculations.

Future studies to investigate why the backpack load location and cross-slope angle do not affect the lateral stability of the wearer (at least within the experimental conditions included in this study) could concentrate on the adaptability of the body to conform to the cross-slope and added load while maintaining consistent patterns of stability with normal walking. Additionally, the experience of the walker may have a major effect in determining whether or not the body is adaptable [5, p. 865]. In the current study, the participants were physically fit and experienced in wearing backpacks and hiking on hilly terrain.

Some method of relating forward speed and step length, or similar evaluation in the future, may determine more completely the forward/aft level of stability for someone walking, and therefore provide more information concerning overall stability of individuals walking with increased loads and loads placed at various locations on the back. The forward/aft (sagittal) control of walking is considered primarily separate from lateral stability [6, p. 2656].

### 5.2 Cross-slope Walking without a Load Stability Assessment

In the second set of trials (performed by the same participants and at the same time as the backpack trials noted above), the participants simply walked along the track at various cross-sloped angles. These tests were done to determine the stability of the walkers without load on cross-slopes.

The results of the second set of trials showed the same basic results as the first, that lateral stability was not significantly affected by cross-slope angle for cross-slopes of 0, 5 and 10 degrees. In fact there was no significant difference in means of lateral stability between the two analyses. Consequently, it is believed that the lack of load did not change the body's adaptability, or visa versa, to maintaining the same lateral stability at the cross-slope angles between level and 10 degrees.

Though, as noted in Chapter 3, wider step widths may produce more stability, the reverse may not be true in that there may be a minimum stability distance between the XCoM and CoP so that the body tends to maintain stability to provide balance under abnormal conditions. Consequently, the body will adjust and adapt as needed to maintain this established stability level. This concept is supported by a study report which says lateral perturbations are managed by keeping a fixed stability distance between the dynamic CoM and the CoP [6, p. 2656].

### 5.3 Backpack Load Location and Cross-Slope Walking Metabolic Assessment

The third set of trials (also performed in the same sessions as the previous trials) measured the metabolic rate of energy usage for the participants as they wore the backpack loaded at various load positions and walked on the track tilted at various cross-sloped angles. The participants wore all the gear from the first test (helmet and weighted vest along with the backpack and carried a simulated rifle) and were also fitted with a portable oxygen sensor which transmitted measurements of the participant's oxygen and carbon dioxide volumes to a central processing unit. The participants also wore a heart monitor. The participants in this third set of tests walked at a specified speed of 4 m/s back and forth on the track for 4 minutes to determine their total energy expenditure under the nine different combinations of conditions.

The results of the metabolic testing showed no significant differences in energy usage between the various conditions.

The lack of significant differences between the combinations of load location and cross-slope angles may be due to several factors. Among these factors are that the energy needed to maintain dynamic lateral stability [7] is not significantly different under the load position, and the cross-slope angles mentioned were too small to register within the limitations of the study and the combinations of body weight and load weight. Other researchers have had similar findings with backpack position, though no cross-slope walking was included [8].

Another possible contributing factor is the relatively high experience level of the participants who may have developed methods of minimizing energy needs on non-level terrain through repeated exposure, so the differences may be explainable by the body’s superior ability to adjust to the slopes included in this project.

## 5.4 Survey Questionnaire Results

The participants were given a survey which requested them to fill in a Likert Scale according to the following, “Compared to not wearing any load please rate, how hard it was to walk with total load.” For each of the nine conditions of backpack load position and cross-slope angle, the questionnaire had five levels to choose from, namely: very easy, somewhat easy, neither easy nor hard, somewhat hard and very hard.

The results of the questionnaire indicated that of the cross-slope options level walking was easiest and the middle backpack location was the easiest of the backpack load positions.

## 5.5 References

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