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Establishing a Metric of Job Specific Fitness for Wildland Firefighters Using Heart Rate Response During the Arduous Work Capacity Test

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ESTABLISHING A METRIC OF JOB SPECIFIC FITNESS FOR WILDLAND FIREFIGHTERS USING HEART RATE RESPONSE DURING THE ARDUOUS WORK CAPACITY TEST

By

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Table of Contents

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The US Forest Service administers over 30,000 physical tests per year to qualify candidates for the occupational demands of wildland fire suppression. The primary assessment is the arduous pack test (APT) a 4.83 km hike that must be completed in 45 min while wearing a 20.45 kg pack. Delivery of individual feedback to guide the physical training of candidates is hampered by two factors; first, passing the pack test is widely considered the minimum performance level necessary needed for this occupation, and second, the binary nature of the assessment presents candidates with a task representing an unknown and self-selected exercise intensity. **PURPOSE:** To determine the cardiorespiratory response elicited by the APT and predict metabolic costs to assess pre-season fitness and provide physical training recommendations. **METHODS:** 62 young (age = 22.8 ± 3.2 yrs) adults (37 males, M_b = 79.5 ± 8.8 kg; 25 females, M_b = 67.5 ± 13.5 kg; study range: 55.4 - 119.6 kg) performed the APT and subsequently underwent a hiking inclined-treadmill test to VO_{2peak} while wearing a skin mounted heart rate (HR) monitor and 20.45-kg pack. **RESULTS:** 50 of the 63 subjects achieved the 45-min cutoff with a finishing time of 41.8 ± 2.1 min, the non-passers had a mean time of 47.7 ± 2.7 min. VO_{2peak} for males (49.0 ± 7.1 $mlO_2*kg^{-1}*min^{-1}$) was significantly greater than females (43.4 ± 8.3 $mlO_2*kg^{-1}*min^{-1}$). HR, %HR reserve, and & $\%HR_{peak}$ during the lab trials at 1.67 (141 ± 20 bpm; 58.2 ± 15.1%; 73.8 ± 0.1%) and 1.78 $m*s^{-1}$ (143 ± 21 bpm; 59.6 ± 15.4%; 74.7 ± 0.1%) were significantly reduced compared to HR, HR reserve, and % HR_{peak} at average field trial speed ($p<0.05$). VO_{2Index} (29.2 ± 7.6 $mlO_2*kg^{-1}*min^{-1}$) and VO_{2Field} (30.3 ± 6.0 $mlO_2*kg^{-1}*min^{-1}$) were significantly greater than $VO_{2Pandolf}$ (22.5 ± 0.8 $mlO_2*kg^{-1}*min^{-1}$) predicted during the field trial ($p<0.05$). There was a positive correlation between the overall VO_{2Field} ($r = 0.88$, $R^2 = 0.78$, $p < 0.001$) and the measured VO_2 at average field trial speed. There was a not significant correlation between the overall VO_{2Index} ($r = 0.17$, $R^2 = 0.03$, $p = 0.253$) and the measured VO_2 at average field trial speed. The standard error of the estimate (SEE) value for the overall VO_{2Field} and VO_{2Index} index values were 2.85 and 7.54, respectively. The mean difference for the overall VO_{2Field} and VO_{2Index} were -0.15 and 0.91 $ml*kg^{-1}*min^{-1}$, respectively. **CONCLUSION:** The SEE value for the overall VO_{2Field} and VO_{2Index} during the PT were 9.5% and 25.2% of the overall mean measured during the lab trial at average field trial speed. The linear model has moderately-high accuracy when predicting sustained VO_2 during the APT and may provide feedback for pre-season readiness. However, this approach is not applicable to WLFF because it requires laboratory measurements. Further, the VO_{2Index} method may be a viable prediction model due to good agreement as demonstrated in the Bland Altman analysis. These data suggest that monitoring HR during load carriage may be used to identify candidates with adequate and inadequate pre-fire season readiness.

Chapter 1 – Introduction

Wildland firefighting is classified as an arduous task under the Interagency Wildfire Qualifications Standards and requires a combination of physical components. Wildland firefighters must maintain a certain level of fitness that ensures their safety and ability to complete required job tasks. These workers are tasked with a variety of fire suppression and preparedness activities such as digging containment line, mowing, trimming, cutting and clearing trees and brush, and rock removal (3, 4, 5). Required equipment consists of a pack (12- to 20-kg) containing food, water, safety gear, and work tools (2, 3, 4, 5). Personal protective equipment (PPE) (i.e. Nomex long-sleeve shirt and pants, mid-calf leather logger boots, a 100% cotton short-sleeve undershirt, leather gloves, and hard hat) increasing their external load by approximately 5.0 – 5.5 kg (3). Environmental stressors such as high altitudes, high ambient temperatures, low humidity, and rough terrain, create additional physical challenges during work shifts that range from 12 to 16 hours (2, 3, 4). Thus, a high level of physical fitness is required for a wildland firefighter to safely and successfully complete firefighting tasks. Prior to becoming a wildland firefighter, potential employees must complete a work capacity test, which assesses load carriage and a minimum fitness requirement, denoted as the arduous work capacity test (arduous pack test).

Comprehensive job task analyses have led to the establishment of the minimum physical standards for employment for the wildland firefighter (16, 17). The pack test is a surrogate measure of strength and endurance capacity of the firefighter. The test requires individuals to complete a 4.83-km hike on flat ground with a 20.4-kg pack in 45 minutes or less (4, 16, 17, 32). This test is designed to assess the physiological capacity necessary for wildland fire suppression, particularly hiking with loads, the most common firefighting task. However, previous literature does not specify what constitutes a light load. It has been reported that firefighters are expected to carry loads ranging from 18.2 – 22.7 kg during active deployment (32). Furthermore, more recent studies report that loads range from 12 – 28 kg (3, 4, 5, 6). The established weight carried during the pack test represents the upper end of the latter spectrum, suggesting content validity of the test. Content validity is further amended because the pack test assesses physical performance rather than acquired skills, which is in accordance with the Equal Employment Opportunity Commission (EEOC) (35). The EEOC prevents the assessment of physiological measures such as HR response, thus, developing a robust physical test that is an accurate surrogate for the metabolic demand of wildland firefighting is a key component in occupational testing in this population.

In seminal studies on WLFF, researchers simulated wildfire suppression tasks to estimate the metabolic costs of working on actual fires. With the use of indirect calorimetry, various firefighter task related procedures have been developed to determine energy cost, production rate, and efficiency (34). Previous research has demonstrated that during steady-state activity on the fire-line, workers expend roughly 7.5 $kcal*min^{-1}$, which corresponds with a relative VO_2 of 22.5 $ml*kg^{-1}*min^{-1}$ (32), and sustain approximately 50% of their maximal aerobic capacity (32). A modest method for the estimation of energy expenditure during work on the fire-line is the use of electronic activity monitors (e.g. Actical Monitors). The raw activity data ($counts*min^{-1}$) when converted to average $kcals*min^{-1}$ has been reported as great as 4768 $kcal*day^{-1}$ (33). Energy expenditure has also been estimated by calculating metabolic rates during wildfire hiking segments with a prediction equation in accordance with Pandolf et al (1). However, data collected on workers during actual wildfire suppression with the use of doubly labeled water (DLW) provide more accurate values of total energy expenditure (TEE) (3, 6). This procedure involves the consumption of oral doses of H and O isotopes. Isotope loss is quantified using analyses of periodic urine sample collections during the measurement period as previously described (2, 3). In WLFF TEE has been reported to range from 2868 – 6214 $kcal*day^{-1}$ and 2946 – 5811 $kcal*day^{-1}$ with the use of this technique (2, 3). These values are approximately 2.5 – 3.0 times basal metabolic rate (3).

As previously stated, hiking with light to moderate load carriage is the most common task during wildfire suppression. Moreover, depending on the urgency of the hike and the terrain, load carriage demonstrates the highest metabolic challenges of the operational work shift (4). Wildland firefighters with competence in load carriage work more effectively and efficiently by allowing them to focus on suppression activities (e.g. digging containment line). Many studies have demonstrated the energy cost of walking with a load from at varied paces (1, 8, 10, 14), on inclined (1, 14, 31) and declined (10, 14, 29) surfaces, and a variety of terrains (10, 15). Indeed, the literature shows that metabolic rates can increase by 4-fold when walking with a given load at the same speed and grade during unloaded walking (14). The most widely used equations to estimate the metabolic demands of load carriage being those in accordance with the American College of Sports Medicine (13) and Pandolf et al. (1). However, both formulas tend to under- or over-predict metabolic rates, do not predict a large spectrum of surface grades (i.e. declined conditions), and lose predictive accuracy with increases in walking speed. More recently, a predictive equation has been developed which improves upon the accuracy of estimating metabolic rates using three basic mechanical variables (speed, surface grade, and the total weight supported against gravity) (14).

The predictive formulas previously described have robust breadth and are viable when applied in scenarios that require load carriage involving grades, walking at slower speeds, and have only been assessed in laboratory settings. Further, there may be discrepancies with their calculations in the application of the arduous pact test. Thus, determining fitness with the use of activity heart rate creates a pragmatic opportunity for wildland fire-fighters to calculate metabolic rates during sustained load carriage. These values can better prepare individuals to work on the fire-line by comparing them to the highest metabolic rates estimated in the field (4).

Problem

The present arduous work capacity test (pack test) requires completion of a 4.83-km level grade walk in a time of 45 minutes or less. Laboratory and field tests have shown that the pack test is correlated with measures of aerobic fitness and muscular endurance (16, 17). However, heart rate response during the arduous pack test has received little attention and may assist in providing early season fitness information to better guide training procedures to gage pre-season readiness.

Purpose

The purpose of this study was to examine the cardiovascular response during the pact test to determine pre-season preparedness in wildland firefighters. HR response can be used to predict sustained load carriage oxygen consumption (VO_2) during the arduous pack test. Subsequently, these values can then be compared to VO_2 values predicted during the highest intensity wildfire suppression segments (4) to better guide physical training methods.

Significance of Study

The outcomes of this study will result in better understanding of HR response during the arduous pact test with the potential to create predictive algorithms that can be easily integrated and used by the WLFF community to provide individual assessment and training recommendations based on data collected during actual wildfire suppression tasks (4). It will attempt to develop a stronger association between load carriage and the heart rate response and facilitate additional insight into the physical fitness required for successful work on the fire-line and to improve the specificity of pre- and early-season physical readiness for wildland firefighters.

Limitations

- Subjects who participated in the study were recruited on a convenience basis and were not a random sample.

- Subjects may not have had prior experience with carrying loads, which could cause a change in gait mechanics and lead to an increased fatigue rate.
- Subjects were not paced during the pack test, rather, they were given pacing times in which they were on pace to complete the pack test in over or under the 45-minute cutoff, thus subjects could have underachieved and skewed the results.
- The pack test trials were performed on the University of Montana collegiate rubber track, which does not simulate terrain that wildland firefighters are exposed to on the job.
- Due to missing or unextractable data, a reduced number of participants were used in the final statistical analyses.

Delimitations

- Subjects included both males and females. This provided data with greater applicability since both sexes currently work as firefighters.
- The study included subjects who are active wildland firefighters or had previously worked as wildland firefighters, and had experience performing the pack test.
- The sample used represented a wide range of fitness levels, body compositions, and ages, typically observed in the WLFF community.

Key Terms

- **Wildland Firefighting –** Physically demanding labor that requires duties such as prescribed burning, wildfire suppression, and fire preparedness.
- **Energy expenditure –** Daily kilocalories utilized as a function of physical activity, basal metabolic rate, and the thermic effect of ingested food.
- **Load carriage –** Carrying or bearing an external load in addition to an individual's body weight during physical activity (e.g. walking or hiking).

- **Arduous Pack Test –** Minimum standards fitness assessment required to obtain WLFF certification.
- **Algorithm –** Series of equations or step-by-step set of operations for problem-solving.
- **Wildfire suppression -** All work and activities connected with control and fire-extinguishing operations, beginning with discovery and continuing until the fire is completely extinguished.

Chapter 2 – Review of Literature

Work Capacity Test (Pack Hike Test): Development

To determine the fitness requirements to perform arduous wildland firefighting tasks and develop a test to assess a candidate's fitness, The Missoula Equipment Development Center, and colleagues from the University of Montana Human Performance Laboratory conducted field measurements, beginning in 1965, during controlled burns to collect data on the physiological demands of firefighting tasks (32). It was demonstrated that workers expended an average of 7.5 kcal*min^{-1}, indicating that the most pertinent physiological component to successful work was aerobic capacity (VO_{2max}) (32). Additional field studies elucidated the relationship of strength and lean body mass to firefighting performance (36). Job task analyses and data from previous field tests indicated that two work capacity tests were best correlated with performance: Pulaski Test (fire-line construction) and Pack Test (load carriage). However, adverse effects on females and a higher administrative cost of the Pulaski Test eliminated it as a potential work capacity assessment. Thus, the Pack Test became the standard for wildland firefighter fitness assessment.

In the final phase of the development and implementation of the pack test, Sharkey and Rothwell (16) related the muscular and aerobic demands of work on the fire-line to those during the field assessment. Male (n = 10) and female (n = 10) subjects performed three different trials: the 4.83-km (3-mile) level grade hike with a 20.4-kg (45-lb) pack, a course that had a hill (0.23 miles with 17.5%

grade), and a 15-min simulated fire-line construction test with a hand tool. There was no significant difference between male and female finish times during the pack test (39.2 vs 42.4 min, respectively). Males and combined subjects (male/female) pack hike times between the flat and hill versions were not significantly different, however, pack hike times for females was significantly slower ($p < 0.01$) than males and combined subjects. There was a strong correlation ($r = 0.87$) between the flat and hill pack hike tests. With the use of regression analysis, a finish time of 45 min approximated a VO_{2max} of 45 $ml*kg^{-1}*min^{-1}$. This approximation remains the current cut-off score.

Energy Expenditure and Aerobic Fitness during WLFF

Over the years, the arduous work of WLFF and the physiological stresses incurred during the job have been elucidated in a plethora of comprehensive studies (2, 3, 4, 6, 12). Previous research has provided insight into the rigors of a laborious task that requires workers to meet physical standards that are unprecedented amongst other manual labor work.

With the use of doubly labeled water (DLW) methodology, which assesses total body water turnover by quantification of H and O isotope loss, Ruby et al. (3) investigated the TEE of seventeen (n = 8 men, n = 9 women) wildland firefighters from three interagency Hot Shot crews from Western Montana and Idaho during 5 days of wildfire suppression. The wildfire suppression activities included hiking and fire-line construction on rough and steep (20-40% grade) terrain. Load carriage ranged from 14 to 27 and 17 to 31% of body weight for males and females, respectively. Each individual wore personal protective equipment (PPE) adding 5.0 to 5.5 kg to their external load. Prior to fire suppression duties, the subjects were given oral doses of doubly labeled water (0.39 g*kg estimated TBW^{-1} $H_2^{18}O$, 0.23 g*kg estimated TBW^{-1} ^2H_2O). Urine samples were collected daily at 4:00am and 6:00am and TBW was calculated from the change in isotopic enrichment (i.e. background sample vs. the second void urine). TEE was calculated for days 1-3, 1-5, and estimated for days 4-5 using three components: thermogenic effect of the dietary intake (DIT), basal metabolic rate (BMR), and the energy expenditure of physical activity (EEA). The results showed a significant correlation between TEE and pre-experimental fat-free mass ($r = 0.53$, $p < 0.05$), and no significance between TEE and pre-experimental total body weight ($r = 0.34$, $p > 0.05$). TEE was 17.4 ± 3.7 and 17.5 ± 6.9 $MJ*day^{-1}$ (for days 1-3 and 4-5, respectively. The data demonstrated a consistently high daily energy expenditure (2868 – 6214 $kcal*day^{-1}$) during wildland fire suppression. Moreover, the TEE is approximately 2.5-3.0 times basal metabolic rates. More recent research replicated these findings in energy expenditure during similar WLFF deployments.

Cuddy et al. (2) set out to contrast 1997-98 data with data collected 15 years later by monitoring 15 participants (n = 12 males, n = 3 females) from two Type I Interagency Hot Shot fire crews for 3 days. Workshifts involved wildfire suppression activities including hiking, line digging, laying hose, chain sawing, clearing brush, lookout, and scouting. Subjects ingested a dose of DLW (1.82 g $^{18}O*kg$ body $mass^{-1}$, 0.13 g $^{2}H_2*kg$ body $mass^{-1}$) the evening before beginning their workshift. Participants were equipped with a physiological and activity monitor, provided urine samples and ingested a temperature transmitter each morning before deployment. Total energy expenditure (TEE), water turnover, core and chest skin temperature, physical activity (≤ 99, 100-1499, and ≥ 1500 for sedentary, light, and moderate/vigorous, respectively), and heart rate were measured throughout the workshifts. Mean core and chest skin temperatures were 37.6° ± 0.2°C and 34.1° ± 1.0°C, respectively. Mean heart rate and physiological strain index score were 112 ± 13 beats/min and 3.3 ± 1.0, respectively. Most of the physical activity was sedentary (49 ± 8%), followed by light (39 ± 6%) and moderate-vigorous (12 ± 2%) activities. Activity was higher on day 1 compared with days 2 and 3, and day 2 was higher than day 3 ($p < 0.05$). The main finding from this study was the TEE of 19.1 ± 3.9 $MJ * d^{-1}$, which was similar to the 1997 data set (17.5 ± 6.9 $MJ*d^{-1}$). The subjects 3-day average TEE ranged from 2946-5811 $kcal*day^{-1}$, comparable to TEE values (12-26 $MJ\cdot day^{-1}$; 2868 – 6214 $kcal\cdot day^{-1}$) described by Ruby et al. (3).

Although these studies determined the TEE during workshifts, the methodology does not allow for the evaluation of individual fire suppression tasks that elicit the greatest energy expenditure. Sol et al. (4) evaluated male (n = 116) and female (n = 15) workers from Type I and II Interagency Hotshot Crews (IHC) during fire suppression activities. Workshifts consisted of a morning hike to the work site (ingress hike), hikes that occurred during the workshift (shift hikes), and evening hikes back to camp or vehicles at the end of the workshift (egress hikes). Training hikes, in which the subjects self-selected the duration and intensity of the hike, were assessed only when they were equipped with active duty equipment (i.e. personal protective equipment (PPE), line gear pack, hand tool). The researchers measured HR and core temperature continuously throughout the 12-hour workshift with a HR monitor and wireless thermometer capsule, respectively. Terrain, body weight, load weight, speed, and grade (0-25%) metrics were used to estimate sustained load carriage oxygen consumption using the equation developed by Pandolf et al. (1) and individual GPS systems. For negative grades, estimates were calculated with the equation described by Santee et al. (10). The researchers concluded that the highest metabolic demand while hiking and working on actual fires occurred during the ingress hikes (26.7 ± 11.4 $ml*kg^{-1}*min^{-1}$), where heart rate was also greater ($p < 0.05$) during this hiking segment than egress and shift hikes, but less than during routine training hikes. These data are in close approximation with the estimated metabolic cost of the arduous pack test (22 $ml*kg^{-1}*min^{-1}$) (16).

These previous studies elucidate the energy expenditure and metabolic rate of single workshifts; however, very few studies have evaluated the aerobic capacity of wildland firefighters throughout the fire season. Gaskill et al. (49) measured pre- and post-season aerobic capacity and body composition with different WLFF crews across four separate fire seasons (2002, 2006, 2008 and 2012). 78 of 84 crew members participated in the study prior to their perspective fire season, and data from 65 subjects were used in the final calculations. Expired gases were collected during a maximal graded exercise treadmill protocol to assess maximal aerobic capacity (VO_{2max}) where subjects walked with a 22-kg backpack until volitional fatigue. After a 5-minute warm-up (2.5 mph, 0% grade), subjects began the test at 4.0 mph and 0% grade. Grade then increased by 1% each minute until 16% grade. Subsequently, grade remained constant and speed was increased by 0.2 mph each minute until volitional exhaustion. VO_2 ventilatory threshold (VO_2vt) was determined with the combination of three graphical methods (V-slope, excess CO_2, and ventilatory equivalents). The results of this study indicate that there was a reduction in body weight ($p < 0.01$), a product of both a significant loss in fat mass and fat free mass across the fire season. VO_{2max} values (absolute and relative) were lower in females both at pre- and post-season ($p < 0.01$) but did not change across the fire season in all crewmembers. The large variation in pre-season VO_2vt noticeably reduced across the season for each crew, where the post-season standard deviation was less than half of the pre-season standard deviation. The fact that a more homogenous VO_2vt is observed in crew members post-season is indicative of wildland firefighters engaging in similar physical activities throughout the season, and that lower fit individuals might benefit from pre-season physical training to alleviate disparities in fitness from the highest fit individuals.

Metabolic Cost of Load Carriage in Humans

The energy requirements for walking at various speeds, grades, and terrains have been comprehensively elucidated in a myriad of studies (1, 10, 20, 21, 25). The energy cost for short periods of walking increase systematically with increasing body mass, load mass, speed, and grade (21, 28). The type of terrain has also been shown to have considerable influences on energy expenditure (10, 15).

Previous literature has established a linear relationship between the metabolic cost of walking and the weight of the body (21). It has also been demonstrated that walking with external loads is similar to walking with additional body weight and the energy cost of walking up a given grade is the sum of the energy cost of level walking at the given speed, plus an additional cost for the elevation of the total weight (39). Based on these studies, Givoni and Goldman (38) developed a predictive model to calculate the metabolic cost of walking with and without loads, on level or graded surfaces (i.e. 0 - 24%).

Following extensive analysis of preceding studies (21, 39, 40), the researchers suggested a predictive formula that was applicable for both genders at walking speeds of 2.5 $km*hr^{-1}$ or greater with loads carried close the center of mass. To test the accuracy of the formula, the researchers compared the predictions with the results from published experimental studies (21, 39, 40). Statistical analysis showed a correlation of 0.99, showing internal consistency. However, this formula was limited to predicting the metabolic cost of walking on treadmills. Further evaluation of loaded walking was required to elucidate the energy cost of walking on other surfaces.

Soule et al. (15) investigated the energy cost of walking while carrying loads at varying terrains and compared the results to predicted treadmill costs for the same loads and speeds. Eight men walked at speeds of 0.66 and 1.1 $m*s^{-1}$ for heavy brush, swampy bog, and loose sand, and 1.1 and 1.55 $m*s^{-1}$ for blacktop road, dirt road, and light brush carrying three different loads (8, 20, or 30 kg) for all six terrains. The subjects were paced by checked times every 400 meters of each course. Their expired air was measured using a Max Planck gasometer for three minutes at the 8, 16, and 25 minutes of the 30-min tests. The ratios of the measured energy cost to the corresponding treadmill costs predicted for the same loads and speeds provided the terrain coefficients for the six terrains. The mean ratio energy cost for blacktop, dirt, light brush, heavy brush, swamp, and sand were 1.0, 1.1, 1.2, 1.5, 1.8, and 2.1. There was no significant difference between the dirt and light brush coefficients ($p > 0.05$); however, the blacktop, heavy brush, swamp, and sand all differed significantly ($p < 0.05$). These coefficients provide the capability to predict energy expenditure while walking on any of the level terrains with a moderate pack load (10 – 40 kg). Although, this study does not evaluate the metabolic cost of a larger spectrum of walking at speeds (i.e. lower than 0.7 $m*s^{-1}$).

Pandolf et al. (1) investigated the energy expenditure of walking at very slow speeds and standing with backpack loads to develop a new formula that included a spectrum of walking speeds from standing. In the first study, six men completed 15 trials of walking for a duration of 15 min with a combination of speeds (0.2, 0.4, 0.6, 0.8, and 1.0 $m*s^{-1}$) and loads (32, 40, and 50 kg). Douglas bags were used to collect expired air from the 5-7th, 9-11th, and 13-15th min of each trial. An experimenter paced the subjects with a metronome to maintain the specified speed for each trial. The second study included 10 male subjects that completed 4 trials consisting of standing for 20 min with backpack loads of 0, 10, 30, and 50 kg. Expired air was collected from the 5-8th, 11-14th, and 17-20th min. The researchers found that energy expenditure during walking increased with increasing external load, which barely reached significance ($p = 0.05$). There was a statistically significant difference between speeds ($p < 0.05$). The energy costs for standing with loads were significantly different ($p < 0.01$) in all the trials except between no load and the 10-kg trial. These findings led to the revision of a previous predictive formula (38) with consideration for load carriage, grade, and terrain. The new predictive model encompasses the entire range of walking speeds down to standing, and is currently one of the most widely used formulas to predict energy expenditure. Following the conclusion of this study, researchers have continued to build upon the predictive model in an attempt at increasing its precision.

The fact that the Pandolf equation (1) does not accurately predict the energy cost of downhill walking may be a limitation to the predictive formula. Pimental and Pandolf (28) investigated the accuracy for predicting the energy expenditure of loaded standing and walking at very slow speeds on negative and positive grades. Eight male subjects stood or walked at speeds of 0.5 or 0.9 $m*s^{-1}$ for 20 min on grades of -10 up to 25% with loads of 20 or 40 kg. (each load at -10 and +10% at both speeds for walking, and +10 and +25% for standing). Each subject was tested one session per day for ten days in random order. Energy expenditure was determined by collecting steady-state expired air during the 5-8, 11-14, and 17-20 min time periods. The results showed that walking at 0.9 $m*s^{-1}$ on a -10% grade was lower than the walking 0.5 $m*s^{-1}$ on a +10% grade, which was lower than walking 0.9 $m*s^{-1}$ on a +10% grade ($p < 0.01$). Energy costs of walking with the 20-kg load were significantly lower than the costs of walking with the 40-kg load at all speeds and grades ($p < 0.01$). The predicted values were significantly lower than measured for walking 0.5 m*s^{-1} on a +10% grade ($p < 0.01$ for 20 kg loads, $p < 0.001$ for 40 kg loads), but were not significantly different for walking 0.9 m*s^{-1} on a +10% grade. Indeed, the discrepancy between the measured and predictive values as well as the inability of the Pandolf prediction equation to predict energy expenditure for negative grades indicates the need for a more accurate model that includes a wider range of grades.

To quantify the metabolic cost of load carriage over uphill, level, and downhill slopes, Santee et al. (10) conducted a field study to collected oxygen consumption data to compare energy costs with data derive from a prior laboratory study in which a model was developed for uphill and downhill load carriage metabolic costs. Eight male subjects attempted 3 load carriage tests with no load 13.6 kg and 27.2 kg for 7 conditions including: level paved airstrip, 3 uphill and 3 downhill (gravel roads) on grades of 4, 8.6, and 12%. Participants were paced at 1.34 m*s^{-1} at sites that were 1300 – 1500 m in length to allow for collection of 15 – 20 min of expired air. Oxygen uptake, heart rate, and core temperature were recorded every minute during the bouts using a portable oxygen consumption monitor, sports watch heart rate monitor, and telemetric temperature pill, respectively. The results demonstrated no significant difference between the measured and predicted values for the negative grades with no load ($p = 0.66$), 13.6 kg ($p = 0.10$) and 27.2 kg ($p = 0.94$) loads. No significance was found for the uphill slope values ($p = 0.46$) except for the data obtained from the 8.6% uphill grade ($p < 0.001$). In conclusion, the model was a good fit for predicting energy costs of unload or load downhill walking and uphill walking with the exception for loaded walking on an 8.6% grade. The values were calculated in conjunction with terrain factors (15) which shows the need for terrain specificity when predicting metabolic costs of walking. However, a prediction model was recently developed to calculate human walking energy costs with minimal variables.

Ludlow et al. (14) conducted a study to predict the walking economy of adult humans using three mechanical variables: speed, surface grade, and the total weight supported against gravity. The researchers used a two-step approach to develop a more accurate predictive equation. In the first part, 20 subjects (n = 12 males, n = 8 females) performed 5-min unloaded treadmill walking at 0.4, 0.7, 1.0, 1.3, and 1.6 $m*s^{-1}$ on six gradients (-6, -3, 0, 3, 6, and 9 degrees). In the second part of the study, 20 subjects performed 5-min torso-loading (no-load, +18, and +31% body weight) treadmill walking at the same speeds and grades. Nine of the 20 subjects completed two negative grade trials at 1.8 $m*s^{-1}$. Loads varied based on the subjects' body mass and were rounded to the nearest ten-pound increment. Steady-state rates of oxygen consumption were measured during the trials by indirect calorimetry. Rates of oxygen uptake were obtained from the last two min of each trial. Resting, sitting and standing measurement were taken during a 30-min test period and were determined as the lowest 10-min segment average within the trials. These measured values were compared to the minimum mechanics model of walking metabolism that the researchers developed (VO 2-gross = [VO 2-rest + ((C 1 • G) + VO2-walk-min) + (1 + (C2 • G)) • (C 3 • V 2))]]), as well as direct comparison with the predictive models of the American College of Sports Medicine (ACSM, 13) and Pandolf et al. (1). Findings indicated that there was no effect of load on the mass-specific (per kg_{-total}) metabolic rates across any combination of speed and grade for each of the three load conditions ($p = 0.05$). In part I, the overall error of individual prediction (SEE value) of the minimum mechanics model for the measured metabolic rates corresponded to 7.4% of the overall mean measured. The SEE values for the ACSM and Pandolf equations corresponded to 15.7 and 13.4%, respectively, of the overall mean measured for the validation group subjects. Consistently, the prediction values from the minimum mechanics model for loaded walking in part II were similar to the values obtained under the unloaded conditions. The prediction values for the ACSM and Pandolf equations declined and improved, respectively, from the unloaded values in part I.

The Effect of Load Distribution during Walking

Indeed, it has been shown that the metabolic cost of walking increases with increasing external loads (20, 23); however, the capacity of these loads rarely exceeded 50 kg (41). Furthermore, the location of the load may alleviate some of the energy required to support it while walking. A follow up study by Pandolf and colleagues was conducted to address walking economy with heavy loads. Soule et al. (30) studied fourteen subjects walking on a treadmill for 20 minutes at 3 different speeds (32, 48, or 64 km * h^{-1}) while carrying 35, 40, 45, or 50 kg loads. A second set of subjects (n = 10) walked for 45 minutes at the same speeds carrying 60, 65, or 70 kg external loads. Energy expenditure ($cm^3O_2*kg^{-1}*min^{-1}$) was measured through indirect calorimetry and expressed as the net energy expenditure (EE of locomotion – no load cost). The researchers concluded that there were no statistical differences ($p > 0.05$) in EE per kg with increasing loads at 32 and 48 $km*h^{-1}$. At 64 $km*h^{-1}$, there was statistical difference ($p < 0.05$) in EE while carrying 70 kg compared to 35 kg; however, the measured cost of carrying 40 and 65 kg at the same speed was statistically similar. This constant measure in energy cost led the researchers to conclude that the positioning of the load may be more causative to the increase in energy expenditure rather than the increase in weight. Correspondingly, lower energy cost is seen when the load is located as close to the center of mass of the body as possible.

To assess the metabolic costs of varying load distribution during uphill and downhill walking, Lloyd and Cooke (26) studied nine subjects using both a traditional backpack and a new backpack design which balances the load with weighted front pockets. The participants walked on a treadmill at 3 $km*h^{-1}$ at negative gradients of 27, 22, 17, 12, and 5 for 3 minutes. After a rest period, subjects walked at the same speed at inclined gradients of 0, 5, 10, and 20% for 3 minutes without a load and carrying a load of 25.6 kg in each of the backpacks (traditional pack, new pack with short back length, new pack with long back length). Oxygen consumption (VO_2) was measured throughout the exercise bouts. Statistical analysis showed that VO_2 was significantly higher ($p<0.001$) in both loading conditions than the no-load walking at all the downhill gradients. No significance was observed between the two loaded walking conditions; however, VO_2 with the new backpack design was significantly lower ($p<0.05$) than that associated with the traditional backpack during uphill walking. The overall VO_2 average for the entire protocol was 5% lower for the innovative design than the traditional pack.

Heart Rate Response during Load Carriage and WLFF

Previous research has shown that competency with walking with load carriage is associated with a high aerobic capacity (26, 47, 48). Aerobic fitness can be assessed through physiological indices such as maximal oxygen consumption, walking economy, and heart rate (9, 13, 25, 51). With the use of wearable technologies, heart rate can be easily measured during physical activities. To measure the cardiovascular demands of load carriage, Lyons et al. (46) studied twenty-eight healthy male volunteers during simulated load carriage on a treadmill at 1.11 $m*s^{-1}$ for 60 minutes on varying grades of 0, 3, 6, and 9%. Subjects carried backpack loads of 0, 20, and 40 kg for 5-min bouts on each grade. Heart rate was continuously monitored during each exercise bout. Results indicated that the mean increase in heart rate was significantly greater ($p < 0.01$) from carrying 20 to 40 kg on the 0% (9.5 bpm), 3% (12.4 bpm), 6% (18.1 bpm) and 9% (22.5 bpm) gradients, compared with the mean increase from 0 to 20 kg on the 0% (5.5 bpm), 3% (6.8 bpm), 6% (9.6 bpm) and 9% (12.7 bpm) gradients. These values suggest that an increase in external load and gradient ameliorates cardiovascular responses as demonstrated by absolute HR.

Cardiovascular measures, such as heart rate response, can be used to quantify the physiological demand of wildland firefighting. Rodriquez et al. (53) analyzed the heart rate response in 160 Spanish wildland firefighters during 200 wildfire suppression activities of varying durations: < 1h, between 1 and 3h, between 3 and 5h, and > 5h. The mean heart rate observed during these activities were 133 ± 2 bpm, 128 ± 1 bpm, 120 ± 3 bpm, and 116 ± 2 bpm, respectively. Statistical analysis indicated that mean heart rate during < 1h wildfire suppression was significantly greater than mean heart rate measured during suppression duration of 3 and 5h and > 5h ($p < 0.05$). Similarly, mean heart rate response during 1 and 3h wildfire suppression was significantly greater than mean heart rate during 3 and 5h as well as > 5h mean heart rate responses ($p < 0.05$). Exercise intensities as demonstrated by maximal heart rate (62 – 71% HR_{max}) were similar to those recommended by the ACSM (55) intensity zones to improve the cardiorespiratory fitness of subjects who are unfit (55 – 64% HR_{max}). These results indicate that wildland firefighters must maintain moderate to high levels of exercise intensities for long durations, and that aerobic fitness is imperative to safe and successful wildfire suppression.

Previous studies have comprehensively demonstrated the metabolic requirements necessary to perform wildland firefighting (2, 3, 4). Although wildland firefighters spend a substantial portion of the job being sedentary, moderate to high aerobic capacities are needed during fire suppression activities (2). The current primary assessment to qualify for the occupation of wildfire suppression attempts to measure this aerobic capacity, however, it is limited by a couple of factors: first, the pack test is considered the minimum performance level necessary for this occupation, and second, the binary nature of the assessment makes it difficult to measure individual fitness. Individuals undergoing the pack test self-select exercise intensities, resulting in unfit individuals that walk at a high percentage of their overall fitness while others walk at low relative intensities. Thus, HR response during the pack test may be useful in the identification of wildland firefighters with adequate and inadequate pre-season readiness, and subsequently, physical training can be recommended.

Chapter 3 – Methodology

Participants

Recreationally active males and females from the University of Montana community (N = 62; n = 37 males, n = 25 females) were recruited to participate in this study. Inclusion criteria included: age range between 18 and 40 years old, and weight between 140 and 250 lbs. To access cardiovascular disease factors, the subjects filled out a Physical Activity Readiness Questionnaire (PAR-Q) and signed an informed consent in accordance with the University of Montana Institutional Review Board.

Preliminary Testing

Peak Aerobic Capacity (VO_{2peak})

VO_{2peak} was determined by use of a modified Bruce Protocol. Subjects were equipped with a 20.4-kg line gear pack on a motorized treadmill in which speed and grade increased every stage until volitional exhaustion (Table 1). The incremental test consisted of three-minute stages for the first two stages, followed by two-minute stages in which expired gases were collected via a metabolic cart (Parvomedics, Inc., Sandy, UT). Three of four criteria were met to reach VO_{2peak}: 1) Rate of perceived exertion (RPE) > 17 on the Borg Scale (6-20 prior to fatigue) (44); 2) Heart rate (HR) within 10 bpm of the subjects' predicted HR max (11); 3) Respiratory exchange ratio (RER) > 1.10; 4) Plateau in VO_2 despite an increase in workload.

Stage	Speed (mph)	Grade (%)
1	1.7 (0.76 m*s^{-1})	10
2	2.5 (1.11 m*s^{-1})	12
3	3.2 (1.42 m*s^{-1})	14
4	3.5 (1.56 m*s^{-1})	16
5	3.5 (1.56 m*s^{-1})	18
6	3.5 (1.56 m*s^{-1})	20

Table 1: Speed and Grade per stage of the Bruce Protocol

Experimental Trials

Arduous Pack Test (Field)

Study participants arrived at the University of Montana track located at the South St. and Higgins Ave. intersection, where they were equipped with an Actiheart heart rate monitor (CamNtech, Cambridgeshire, UK) and a 20.4-kg line gear backpack. They then were instructed to complete a 4.83-km flat submaximal hike in under 45 minutes (United States Fire Service work capacity test). The subjects walked at a self-selected pace but were given pacing times at 200 and 400 meters of each lap at which they were over/under the 45-min cutoff time. Heart rate was continuously recorded throughout the test. Body weight and pack weight were measured before and after the trial, and finish time was recorded following the trial. Data collection consisted of 8 days over the span of 3 weeks. The average temperature over the course of the 8 experimental trials was 46.0 ± 5.7 °F.

Submaximal Load carriage Trials (Lab)

Submaximal treadmill trials took place in the Healthy Heart Lab at the University of Montana, where subjects were weighed and equipped with an Actiheart monitor when they arrived. A 10-min resting HR was measured while subjects were seated prior to the treadmill trials. Following the rest period, subjects donned a 20.4-kg line gear pack and walked on a treadmill at varying speeds (1.67, 1.78, 1.87 $m*s^{-1}$, as well as the average speed each individual subject walked during the pack test) for 5 min each. These speeds correspond to common hiking speeds observed during the APT in previous literature as well as in the current study. VO_2 was continuously measured for the duration of the trials via a metabolic cart and the last 2-min of each trial was averaged for data analysis. A seated resting HR was recorded for 10 min following the trials.

Metabolic Load Carriage Calculations During the Field Test

Sustained load carriage VO_2 was calculated with heart rate and VO_2 measured during the lab trial at the average speed that subjects walked during the field trial. As described in the APT, heart rate was continuously monitored during the trials using an Actiheart monitor. Data was recorded in 15-second intervals and average heart rate values for the 1st, 2nd, and 3rd 15-minutes of the field trial and the overall average heart rate was used for calculations. With the use of HR and VO_2 measured in the lab trial at average speed during the field trial, VO_2 was estimated from the corresponding HR measured in the field trial. By assuming a linear relationship between HR and VO_2 during the trial, oxygen consumption can be calculated during the APT using HR response:

$$\mathbf{VO_{2Lab}/HR_{Lab} = VO_{2Field}/HR_{Field}}$$
$$\mathbf{VO_{2Field} = HR_{Field}*(VO_{2Lab}/HR_{Lab})}$$

VO_{2Lab} is the oxygen consumption measured during steady-state load carriage in the laboratory on a motorized treadmill at the average speed that participants walked during the field trial.

HR_{Lab} is the heart rate measured during steady-state load carriage in the laboratory on a motorized treadmill at the average speed that participants walked during the field trial.

HR_{Field} is the heart rate measured during the APT.

VO_{2Field} is the oxygen consumption estimated during the field trial.

VO_2 load carriage was also calculated using HR index in accordance to Wicks et al. (45). HR response during the APT was divided by resting HR, measured during the 10-min period prior to the lab trials, to calculate HR index:

$$\mathbf{HR_{Field}/HR_{Rest} = HR_{Index}}$$

HR_{rest} is the resting heart rate measured during the lab trial prior to beginning loaded-walking.

HR_{Field} is the heart rate measured during the field trial.

HR_{index} was then used to calculate METs as described by Wicks et al. (45):

$$\mathbf{METs = 6.02 \times HR_{Index} - 4.93}$$

Subsequently, METs was used to calculate sustained VO_2 during the field trial:

$$\mathbf{VO_{2Index} = 3.5\ ml*kg^{-1}*min^{-1} \times METs}$$

VO_{2Index} is the oxygen consumption estimated using HR_{Index} in accordance with Wicks et al. (45).

The third prediction values were calculated using the equation developed by Pandolf et al. (1):

$$\mathbf{VO_{2Pandolf} = 1.5\ W + 2.0\ (W + L)(L/W)^2 + \eta(W + L)[1.5\ V^2 + 0.35\ VG]}$$

where M = metabolic rate, watts; W = subject weight, kg; L = load carried, kg; V = walking speed, m/s; G = grade, %; η = terrain factor (terrain factor: 1.0).

$VO_{2Pandolf}$ is the oxygen consumption estimated using the equation described by Pandolf et al. (1).

VO_2 values were predicted for each speed during the lab trials, as well as for the 1st, 2nd, and 3rd 15-min segments of the field trials, and overall field oxygen consumption.

Statistical Analysis

Physical characteristics between males and females of 53 subjects were analyzed using t-tests of unequal variance.

HR response, % HR reserve, and % Peak HR for field and lab data were analyzed using a single factor analysis of variance (ANOVA), followed by a Tukey post-hoc analysis for between group differences. 47 subjects were used in the field analysis, and 41 subjects were used in the lab analysis.

Predicted VO_2 and % VO_{2peak} during the lab trial were analyzed using a 2-way ANOVA ($VO_{2Pandolf}$ vs. Measured VO_2 and lab trials; % VO_{2peak} vs. % Measured VO_{2peak} and lab trials). Predicted VO_2 during the field trial was analyzed using a 3-way ANOVA (VO_{2Field} vs. $VO_{2Pandolf}$ vs. VO_{2Index} and 15-min segments during field trial).

Statistical analyses for the VO_{2Field} and VO_{2Index} were completed using linear regressions to calculate correlations. 47 subjects were used in the linear regression analyses. The standard error of the estimate (SEE) was calculated to measure the accuracy of the predictions. Data was subsequently plotted using Bland Altman analyses to measure the agreement between predicted and measured VO_2 values. All values are presented as mean ± SD and significance set at $p < 0.05$.

Chapter 4 – Results

Subject Descriptive Data

Sixty-two subjects were initially enrolled in the study and completed both the field and lab trials. However, due to missing or unextractable HR and VO_2 data during the field and lab trials, and subjects who could not perform the higher speeds during the lab trials, 53 subjects were included in the final descriptive analysis. 47 subjects were included in the field trial analysis, and 41 subjects were included in the lab trial analysis due to missing or unextractable data.

Table 1: Number of subjects used in each data analysis.

Data Analysis	Number of Subjects
Descriptive	53
Field Trial HR Response	47
Lab Trial HR Response	41
VO_2 Correlations	47

Descriptive data is presented in Table 2. Fifty-three subjects were included in the physical characteristics analysis. Weight ($p < 0.001$) and VO_{2peak} ($p < 0.05$) were significantly different between males and females, but age ($p = 0.260$), measured HR_{peak} ($p = 0.267$), estimated HR_{peak} ($p = 0.142$), and HR_{rest} (0.641) were not.

Table 2: Physical characteristics for 53 subjects. Data represented as mean ± SD. * p < 0.05

Subject Characteristics

	All (n = 53)	Males (n = 32)	Females (n = 21)
Age (yrs.)	22.7 ± 3.1	23.0 ± 3.3	22.0 ± 2.7
Weight (kg)	73.6 ± 11.1	79.0 ± 8.4	64.5 ± 7.8*
VO_{2peak} *(mlO2*kg^{-1}*min^{-1})*	46.8 ± 8.0	49.0 ± 7.1	43.4 ± 8.3*
Measured HR_{peak} *(bpm)*	191 ± 9	193 ± 8	190 ± 11
Estimated HR_{peak} *(bpm)*	192 ± 3	192 ± 2	193 ± 4
HR_{rest} *(bpm)*	73 ± 11	72 ± 10	74 ± 13

Lab Data

The physiological responses collected under laboratory conditions are presented in table 3. Forty-one subjects were included in the analysis due to missing HR and VO_2 data.

Table 3: Physiological characteristics for 41 subjects during the lab trials. VO_2 data (below dotted line) expressed as $mlO_2*kg^{-1}*min^{-1}$. Data represented as mean ± SD. * p<0.05: vs. Average Field Trial Speed.
** p<0.05: vs. VO_2 Measured. # p<0.05: vs. % $VO_{2peakMeasured}$.

Lab Data

	$1.67\ m*s^{-1}$	$1.78\ m*s^{-1}$	$1.87\ m*s^{-1}$	Average Field Trial Speed
HR Response				
HR (bpm)	141 ± 20*	143 ± 21*	156 ± 20	155 ± 18
HR Reserve (%)	58.2 ± 15.1*	59.6 ± 15.4*	70.8 ± 15.0	70.0 ± 12.4
% HR_{peak} (%)	73.8 ± 0.1*	74.7 ± 0.1*	81.8 ± 0.1	81.8 ± 0.1
Measured VO_2	22.4 ± 3.0	25.4 ± 3.6	28.7 ± 4.1	29.9 ± 5.0
$VO_{2Pandolf}$	19.9 ± 0.8**	22.5 ± 0.9**	24.3 ± 0.9**	25.3 ± 2.6**
% $VO_{2peakMeasured}$	50.3 ± 13.5	57.1 ± 16.5	64.3 ± 17.1	67.2 ± 19.8
% $VO_{2peakPandolf}$	49.4 ± 1.9#	55.7 ± 2.1#	60.2 ± 2.3#	62.7 ± 6.5#

HR Response

There was a main effect for speed ($p < 0.001$) during the lab trials. HR response during the 1.67 $m*s^{-1}$ and 1.78 $m*s^{-1}$ trials were significantly lower compared to the HR response during the average field trial speed (both $p < 0.001$). HR response during the 1.87 $m*s^{-1}$ trial was not significantly different compared to the average field trial speed ($p = 0.738$).

% HR Reserve

There was a main effect for speed ($p < 0.001$) for % HR reserve during the lab trials. % HR reserve during the 1.67 $m*s^{-1}$ and 1.78 $m*s^{-1}$ trials were significantly lower compared to the average field trial speed ($p < 0.001$). There was no significant difference in % HR reserve between 1.87 $m*s^{-1}$ and average field trial speed ($p = 0.629$).

% Peak HR

There was a main effect for speed ($p < 0.001$) for % peak HR during the lab trials. Percent peak HR during the 1.67 $m*s^{-1}$ and 1.78 $m*s^{-1}$ trials were significantly lower compared to the average field trial speed ($p < 0.001$). There was no significant difference in % peak HR between 1.87 $m*s^{-1}$ and the average field trial speed ($p = 0.685$).

Oxygen Consumption (VO_2)

$VO_{2Pandolf}$ was significantly lower compared to the VO_2 measured at 1.67 $m*s^{-1}$ ($p < 0.001$), 1.78 $m*s^{-1}$ ($p < 0.001$), 1.87 $m*s^{-1}$ ($p < 0.001$), and the average field trial speed ($p < 0.001$).

Field Data

Pack Test Completion

Fifty of the 62 subjects achieved the 45-min cutoff (passing rate of 80.6%) with a finishing time of 41.7 ± 2.1 min, the non-passers had a mean time of 47.7 ± 2.6 min. Non-passers were 77% female and 23% male. There was a significant difference in completion time between passers and non-passers ($p < 0.001$).

Forty-seven subjects were included in the analysis due to missing HR data.

Table 4: Physiological characteristics for 47 subjects during the pack test. VO_2 data (below dotted line) expressed as $mlO_2*kg^{-1}*min^{-1}$. Data represented as mean ± SD. * $p<0.05$: vs. Overall HR. † $p<0.05$: vs. 3rd 15-min HR. ‡ $p<0.05$: vs. 2nd 15-min HR. # $p<0.05$: vs. $VO_{2Pandolf}$.

Field Data				
	1st 15-min	2nd 15-min	3rd 15-min	Overall
Speed ($m*s^{-1}$)	1.83 ± 0.2	1.88 ± 0.8	1.93 ± 0.4	1.88 ± 1.1
HR Response				
HR (bpm)	150 ± 19*†‡	159 ± 18*‡	166 ± 18*	158 ± 18
HR Reserve (%)	64.6 ± 14.1*†‡	72.6 ± 12.6*‡	78.2 ± 12.3*	71.3 ± 12.3
% HR_{peak} (%)	78.2 ± 0.1*†‡	82.3 ± 0.1*‡	86.7 ± 0.1*	82.3 ± 0.1
$VO_{2Pandolf}$	22.2 ± 1.2	22.5 ± 0.5	23.9 ± 0.8	22.5 ± 0.8
VO_{2Index}	26.7 ± 7.6#	29.8 ± 7.9#	31.9 ± 8.1#	29.2 ± 7.6#
VO_{2Field}	28.7 ± 6.3#	30.6 ± 6.1#	31.9 ± 6.1#	30.3 ± 6.0#

Heart Rate Response

Post hoc analysis showed a significant difference between HR response during the 1st 15-min and the 2nd ($p < 0.001$), 3rd ($p < 0.001$) 15-min, and overall ($p < 0.001$) HR response. HR response during the 2nd 15-min was significantly reduced compared to the 3rd ($p < 0.001$) 15-min and overall ($p < 0.001$) HR response. There was a significant difference between the 3rd 15-min and overall ($p < 0.001$) HR response during the field trial. HR response in the passing group during the PT was not significantly different compared to the non-passing group ($p = 0.802$).

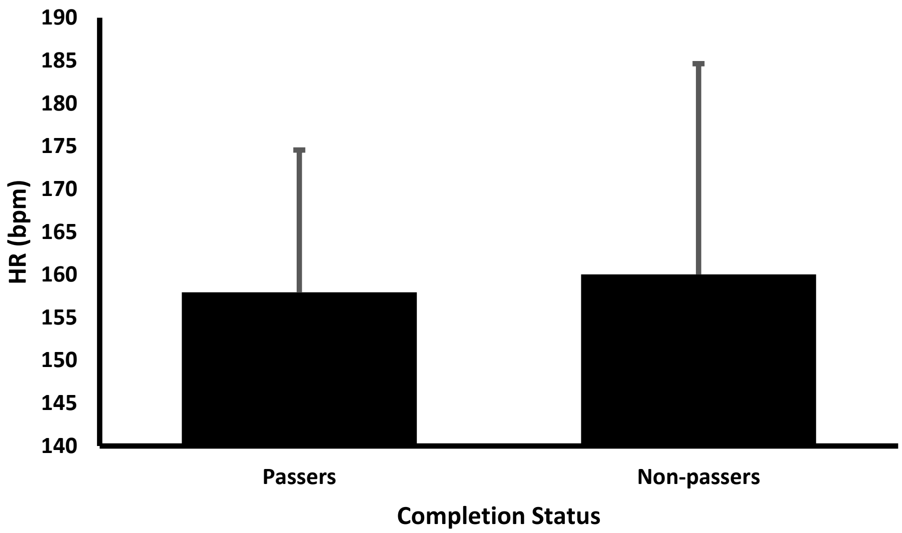

Figure 1. Average HR response for passers and non-passers over the entire APT.

% HR Reserve

Post hoc analysis showed a significant difference between % HR reserve during the 1st 15-min and the 2nd 15-min ($p < 0.001$), 3rd 15-min ($p < 0.001$), and overall ($p < 0.001$) % HR reserve. % HR reserve during the 2nd 15-min was significantly reduced compared to the 3rd ($p < 0.001$) 15-min and overall ($p < 0.001$) % HR reserve. There was a significant difference between % HR reserve during the 3rd 15-min and overall ($p < 0.001$) % HR reserve. % HR reserve during the PT was not significantly different between the passing and non-passing groups ($p = 0.565$).

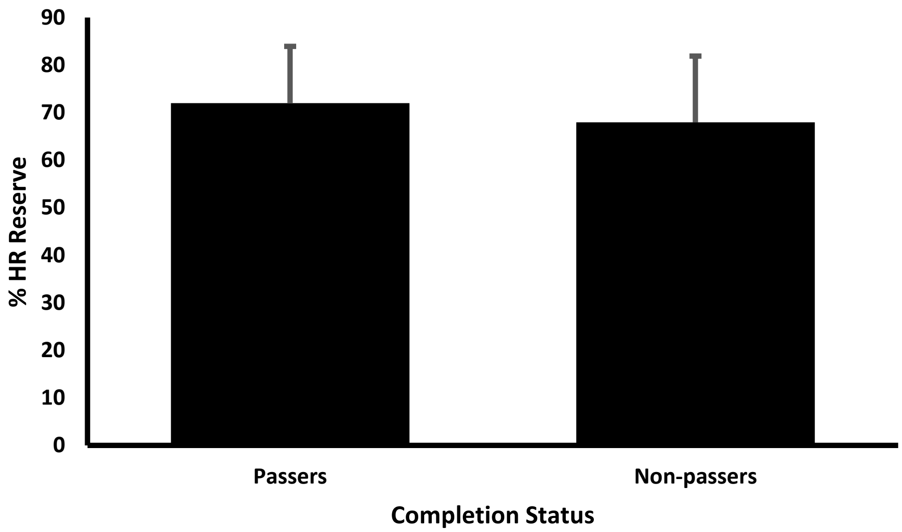

Figure 2. Average percent HR reserve for passers and non-passers over the entire APT.

% Peak HR

Post hoc analysis showed a significant difference between % peak HR during the 1st 15-min and the 2nd 15-min ($p < 0.001$), 3rd 15-min ($p < 0.001$), and overall ($p < 0.001$) % peak HR. % peak HR during the 2nd 15-min was significantly reduced compared to the 3rd 15-min ($p < 0.001$) and overall ($p < 0.001$) % peak HR. There was a significant difference between % peak HR during the 3rd 15-min and overall ($p < 0.001$) % peak HR. % Peak HR during the PT was not significantly different between the passing and non-passing groups ($p = 0.437$).

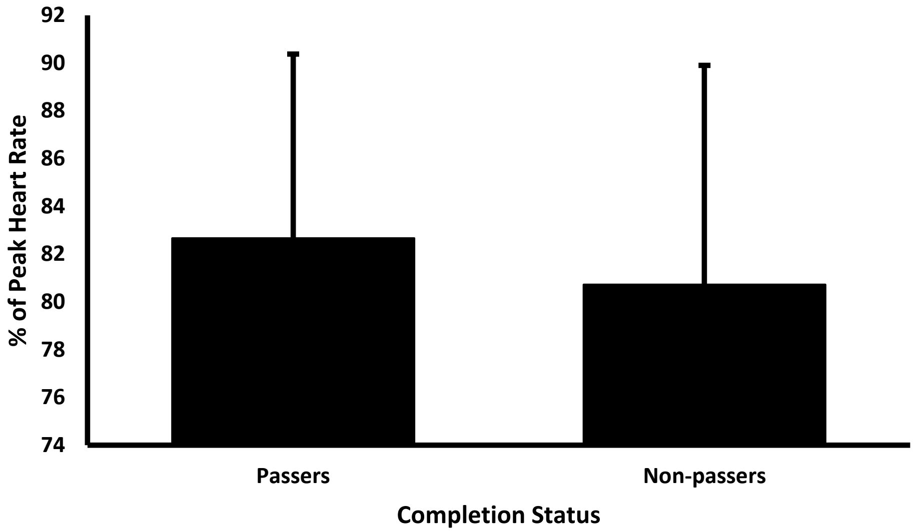

Figure 3. Percent peak HR for passers and non-passers over the entire APT.

Oxygen Consumption (VO_2)

There was a significant difference between $VO_{2Pandolf}$ and VO_{2Field} values ($p < 0.001$). There was a significant difference during the 1st ($p < 0.001$), 2nd ($p < 0.001$), and 3rd ($p < 0.001$) 15-min segments, and overall pack test ($p < 0.001$).

There was a significant difference between VO_{2Index} and $VO_{2Pandolf}$ ($p < 0.001$). There was a significant difference during the 1st ($p < 0.001$), 2nd ($p < 0.001$), and 3rd ($p < 0.001$) 15-min segments, and overall pack test ($p < 0.001$).

Oxygen Consumption Correlations

VO_{2Field}

Correlations between VO_{2Field} and measured VO_2 during the lab trial at average field trial speed is presented in figure 1. Forty-seven subjects were included in the analysis due to missing HR data.

There was a strong positive correlation between the measured VO_2 and overall VO_{2Field} values (r =0.88, $R^2 = 0.78$, $p < 0.001$). The SEE for the overall VO_{2Field} value was 2.85 $mlO_2*kg^{-1}*min^{-1}$, respectively.

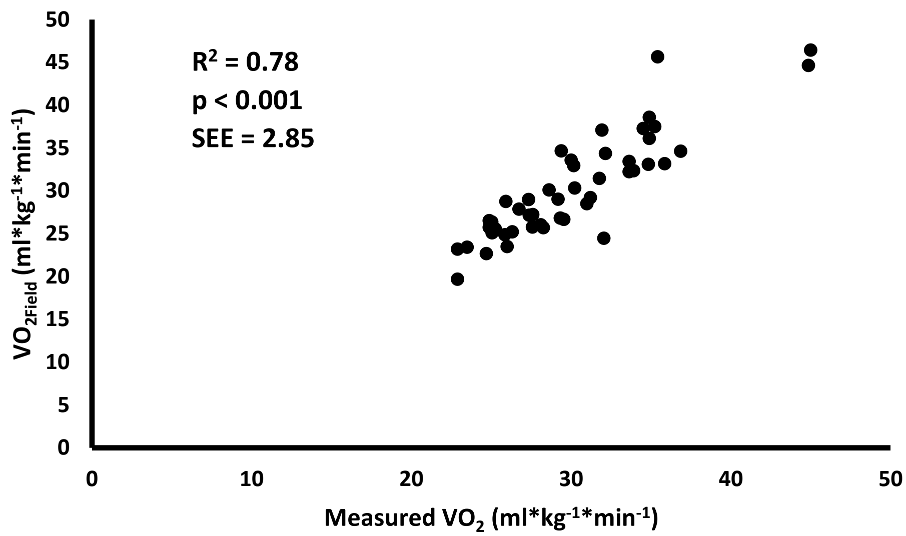

Figure 4: Overall VO_{2Field} predicted during the field trial vs. measured VO_2 during the lab trial at the average field trial speed. N = 47.

Bland Altman Analysis

Bland Altman plot is presented in figure 2 displaying the difference between VO_{2Field} and the measured VO_2. The mean difference for the overall VO_{2Field} value was -0.15 $ml*kg^{-1}*min^{-1}$. The upper and lower limits of agreement were 5.45 and -5.73 $ml*kg^{-1}*min^{-1}$, respectively.

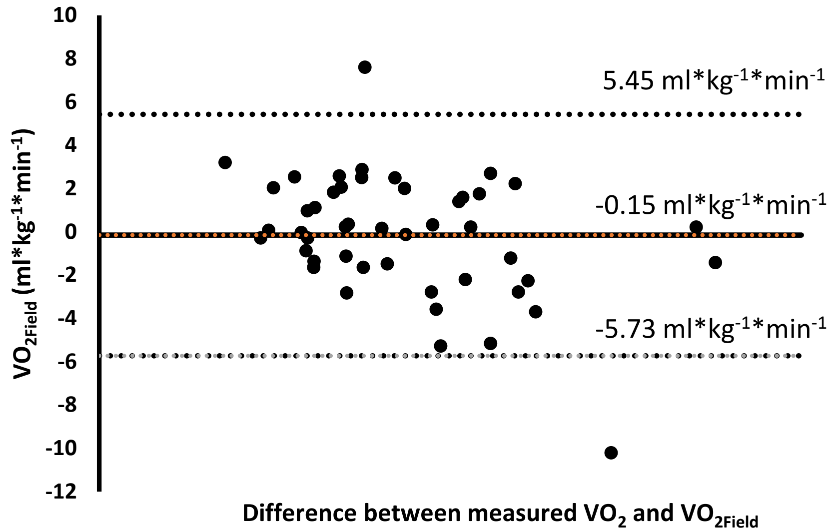

Figure 5: Bland Altman plot illustration the agreement between the overall VO_{2Field} and the measured VO_2 during lab trial at the average field trial speed. N = 47.

VO_{2Index}

Correlations between VO_{2Index} and measured VO_2 during the lab trial at average field trial speed are presented in figure 3. Forty-seven subjects were included in the analysis due to missing HR and VO_2 data.

There was not a significant correlation between the overall VO_{2Index} and measured VO_2 values (r =0.17, R^2 = 0.03, p = 0.253). The SEE for the overall VO_{2Index} was 7.54 $mlO_2*kg^{-1}*min^{-1}$.

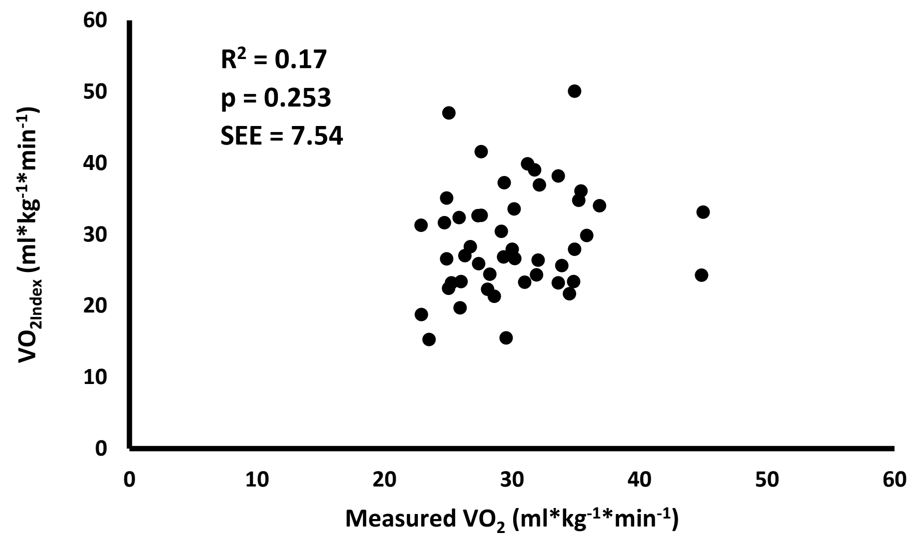

Figure 6: Overall VO_{2Index} predicted during the field trial vs. measured VO_2 during the lab trial at the average field trial speed. N = 47.

Bland Altman Analysis

Bland Altman plot is presented in figure 4 displaying the difference between the VO_{2Index} and the measured VO_2 during the lab trial at average field trial speed. The mean difference for the overall VO_{2Index} value was 0.91 ml*kg^{-1}*min^{-1}. The upper and lower limits of agreement were 17.2 and -15.4 ml*kg^{-1}*min^{-1}, respectively.

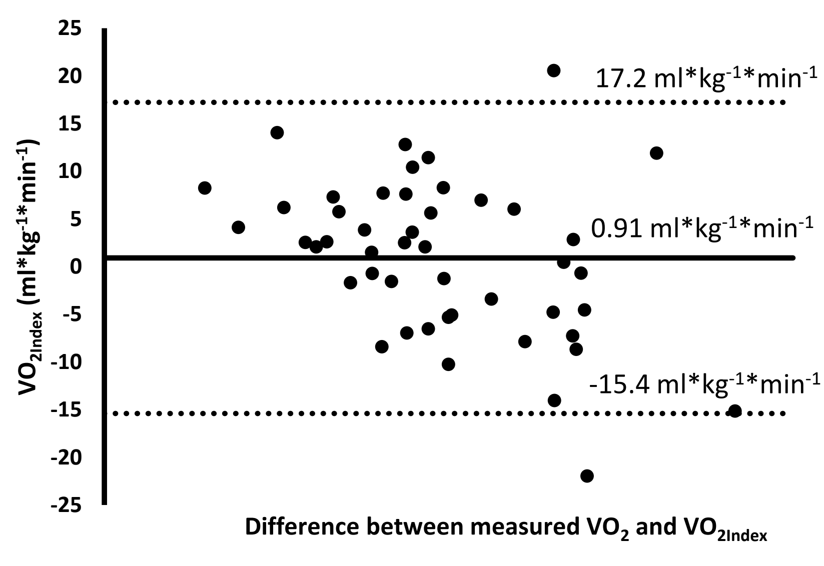

Figure 7: Bland Altman plot illustrating the agreement between the VO_{2Index} for the field trial and the measured VO_2 during the lab trial at the field trial speed. N = 47.

Chapter 5 - Discussion

The current study was designed to measure the HR response during load carriage commensurate with the arduous work capacity test for WLFF. A secondary purpose was to use HR response during the PT to estimate sustained VO_2, which could subsequently be used to compare to values predicted in the field (4). This may be used to indicate pre-season readiness and allow for training recommendations.

The pack test was designed to assess minimal levels of operational fitness of wildland firefighter candidates and to identify candidates who are ready to perform WLFF job-specific tasks. Sharkey et al. (37) demonstrated that energy costs during the pack test are correlated to those required on the job. However, fitness was assessed by measures of oxygen consumption in these studies, and measures of HR response were absent in all field evaluations of the pack test. Therefore, this study is novel in that HR was the primary physiological parameter evaluated.

A study conducted by Rodriquez et al. (54) measured HR during wildfire suppression on incident according to the type of attack performed (direct, indirect or mixed). Mean HR in the direct, mixed and indirect attacks were 128 ± 2 bpm, 126 ± 2 bpm, and 111 ± 3 bpm, respectively, which were decreased compared to the HR values presented in this study. When expressed as % of maximal HR, values reported by Rodriquez et al. (54) were also reduced compared to the current study. Comparable to those HR values, Sol et al. (4) monitored HR throughout wildfire suppression work (e.g. ingress, egress, and shift hikes) and demonstrated HR values of 122 ± 1 and 129 ± 1 bpm for in 131 Type II and Interagency Hotshot crews, respectively. The highest HR values were measured during the ingress hike, which were significantly greater than the egress hike ($p > 0.05$), with a mean HR of 128 ± 29 bpm. This is in conjunction with the highest estimated metabolic rate, predicted using the Pandolf equation (1).

The highest maximal HRs recorded during direct, mixed, and indirect attacks were comparable to HRs recorded during the pack test. Results from a study conducted by Budd et al. (50) measuring physiological responses in Australian wildland firefighters during bushfire suppression, demonstrated average HR values of 152 bpm, which was also lower than the values seen in the current study. Although, these were experimental fires and the observed HR responses could have been a result of the Hawthorne effect (i.e. modified behavior in response to awareness of being observed). Cuddy et al. (2) demonstrated that wildland firefighters spent 33 ± 10% and 38 ± 9% of workshift time in HR ranges of 100-120 and 120-140 bpm, respectively. A lower percentage of workshifts were spent in the 140-160 and 160-180 bpm ranges (17 ± 7% and 2 ± 2%, respectively). This suggests that wildland firefighters generally work at lower heart rate intensities than is seen during the pack test, but because maximal HR responses during fire suppression (i.e. 160 – 180 bpm) are in accordance with HR responses during the pack test, this may be a viable approach to determining job-specific readiness.

Results from the current study demonstrate that there is considerable inter-subject variation in HR response during the pack test. This variance may be accounted for by a myriad of physiological and biological characteristics including aerobic (i.e. cardiopulmonary function) and anaerobic (i.e. leg strength) fitness and anthropometric measures (e.g. height, weight, leg length, fat-free vs. fat mass, etc.). Other factors that may influence pack test HR response include load carriage experience and prior completion of the pack test or WLFF employment (16, 17). There was little to no association with HR response and completion of the pack test. The mean HR response between passers and non-passers was statistically similar, suggesting that all individuals undertaking the WLFF minimum physical assessment self-select comparable relative intensities**.** Additionally, there was no statistical difference in % HR reserve and % of peak HR between the passing and non-passing groups.

In correspondence with the pack test, inter-subject HR response during the submaximal load-walking treadmill trials varied to a similar degree. This variance may also be accounted for by the previously mentioned physiological and anthropometric factors, as well as previous load carriage and WLFF experience. Heart rate variability may also be a result of requiring subjects to walk at speeds beyond their fitness levels. It was common for field trial non-passers to have elevated HR responses during the 1.78 and 1.87 $m*s^{-1}$ lab trials. These subjects (n = 10) were not able to maintain the required speed (1.78 $m*s^{-1}$) to complete the PT in less than 45 minutes, consequently, they experienced high cardiovascular strain (178 ± 11 and 185 ± 10 bpm for 1.78 and 1.87 $m*s^{-1}$, respectively). Furthermore, it has been shown that treadmill walking results in a faster cadence and shorter stride length than during over-ground walking (56). This spatiotemporal difference may lead to an elevated heart rate due to increased muscle activity and energy expenditure (56).

The binary nature of the pack test makes it difficult to assess candidate fitness levels given that individuals self-select similar physical intensities, regardless of fitness level. In this study, HR response was utilized to attempt to measure fitness levels and determine pre-season readiness. By assuming a linear relationship between oxygen consumption and heart rate, sustained VO_2 during the pack test could be determined through the measurement of pack test heart rate. Results indicated a high correlation of coefficient (R^2) between the predicted and measured VO_2 values at each time point (i.e. 1st through 3rd 15-min segments and overall PT). All the R^2 values for the sustained VO_2 values predicted reached significance. In contrast, the R^2 values for the sustained VO_2 values predicted from HR index did not reach significance. These results indicate that a high percentage of the variance is accounted for in the prediction of sustained VO_2 from measured VO_2 and HR during lab trial at average field trial speed.

The lowest reported standard error of the estimate (SEE) resulted from overall sustained VO_2 values predicted (2.85 $ml*kg^{-1}*min^{-1}$, respectively). This SEE value corresponded to 9.5% of the overall mean measured during the lab trial at average field trial speed. This SEE value is slightly greater than the error of prediction for the minimum mechanics model in accordance with Ludlow et al. (14), which corresponded to 7.4%. The specificity of the lab measurements to WLFF load carriage may allow for the development and implementation of a predictive formula that has greater practical application than the leading standard in predicting metabolic rate (i.e. Pandolf (1)). As previously mentioned, the Pandolf et al. (1) equation tends to under- or overpredict metabolic rates in its calculation. Results from this study indicate that the Pandolf (1) equation predicts a significantly lower metabolic rate compared to the measured submaximal VO_2, rendering its use inviable for the pack test. VO_{2Index} values were significantly similar to VO_{2Field} values, but $VO_{2Pandolf}$ values were not. This suggests that HR_{Index} may be a better method of predicting oxygen consumption during the APT, and by comparing these values to those predicted in the field (4), it may be possible to indicate pre-season fitness and provide physical training recommendations. Also, it is important to note that VO_2 estimated in the field by Sol et al. (4) was accomplished with the use of the Pandolf (1) predictive model. Since the current study showed a significant difference with the measured lab VO_2 and VO_{2Field}, oxygen consumption estimated during ingress and egress hiking in the field may be under-predictions.

The difference between the measured VO_2 values and the predicted VO_2 values show statistical agreement, as demonstrated by the Bland Altman analyses. This statistical method is proposed to hold greater statistical power than correlations when analyzing methods of measurement (52). According to Altman and Bland (52), the correlation coefficient is not a measure of agreement, thus, it is wrong to infer that methods of measurement are interchangeable based on this analysis. Correlation analyses measure the strength of a relation between two variables, but do not indicate whether the variables lie along the line equality. They will have perfect correlation if they lie along any straight line (i.e. trendline). Furthermore, the 95% confidence interval for the assumed linear relationship predicted VO_2 is narrower when compared to HR index predicted VO_2. This may be more statistically robust in terms of biological relevance. Although, a positive implication of HR index is the use of resting HR. Resting HR is readably obtainable and, in normotensive subjects, stabilizes after 10 minutes of sitting or lying (57).

In the current study, subjects were instructed to walk at a self-selected pace. This may have implications in the outcome of VO_2 values predicted. There was a trend to increase pace from the start to the end of the pact test, which corresponded with an increase in HR and, thus, predicted VO_2. This may make it difficult to access fitness by extrapolating from the 1st or 2nd 15-min. If VO_2, and fitness, can be predicted with a truncated version of the pack test, the USFS may save valuable time and money that can be allocated to more pressing matters within WLFF. Future studies should control the varied paces at which subjects complete the pack test, measure HR response, and take field measurements of oxygen consumption. In addition, larger cohorts should be utilized within a wildland firefighter demographic to strengthen the practical application of a predictive model.

Regardless of passing status subject self-selected intensities were similar, despite hiking speeds varying considerably. These data suggest that candidates must maintain a HR reserve of 72% or less (82% of maximum HR) while walking at 1.8 m s^{-1} (4.0 mph) to complete the APT in 45 min or less. This demonstrates that measuring HR response during the APT may allow for the pre-season assessment of fitness. These data support the further development of a brief (5-10 min) hiking assessment to determine APT readiness, and potentially seasonal readiness. The reliance on measures of HR and over ground speed suggest that this test and individualized feedback could be administered and delivered at the scale of the US wild land firefighting community i.e. 30-40 000 individuals per year.

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