2018

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B.S. Exercise and Sports Science
Oregon State University-Cascades
Bend, OR 2016

Master Thesis

Presented in partial fulfillment of the requirement for the degree of:

Master of Science
Health and Human Performance, Exercise Science
The University of Montana
Missoula, Montana

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Despite extensive and ongoing scientific study into the metabolic requirements of load carriage, an understanding quantifying the effect of speed, load, sex and body mass has yet to come forth and the extent to which established models predict these requirements is largely untested. Specifically, because existing experimental efforts have typically focused on relatively modest walking speeds using loads representing a fixed portion of the subject's mass, extending the available predictions to applications where individuals complete a common task carrying an identical absolute load provides estimates of unknown accuracy. **PURPOSE:** Here, we measured the energy use in a large subject group walking at speeds surrounding the 1.8 m s^{-1} necessary to successfully complete the 4.83 km USFS wildland firefighter arduous pack (20.5kg) test, and compared these results to estimates available from the prevailing models. **METHODS**: We measured VO_2 from 61 young (age = 22.8±3.2 yrs) adults (36 males; 25 females; study range: M_b = 55.4-119.6 kg; height = 1.52-1.93 m) as they performed four, 5min trials, with a 20.5kg pack, on a level treadmill at 1.7, 1.8, 1.9 m s^{-1}, and their individual average speed from a previously administered pack test. In addition, a subset of n=10 subjects were equipped with Douglas bags during the simulated pack test to measure steady state VO_2. We used the methods of Pandolf et al. 1977 and Ludlow & Weyand 2017 to generate VO_2 estimates for the individual trials we administered. **RESULTS**: Measured values of VO_2 increased from 22.4±3.2 and 24.6±4.1 ml kg^{-1} min^{-1} at 1.7 m s^{-1}, to 31.6±5.3 and 31.0±4.5 ml kg^{-1} min^{-1} at the fastest speed administered for males and females respectively. In contrast, the accuracy of the predictive models decreased with speed and yielded prediction errors of -12.4 and -22.9% at 1.7 m s^{-1} for the Pandolf and Ludlow & Weyand methods respectively, these errors were -18.0 and -32.2% at the fastest speeds administered. When evaluated at the speed subjects used in the field trial, the prediction models underestimated energy expenditure by 5.0±4.4 and 10.4±4.9 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ respectively. **CONCLUSION**: We conclude that existing predictive models do not retain their accuracy, and substantially underestimate measured values when applied to a group of male and female subjects undertaking relatively fast walking speeds on a flat surface with a heavy load.

Supported by US Forest Service Agreement # 16-CR-11138200-005, to CP, CD, BR and MB

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Chapter 1: Introduction

Wildland Fire Fighters (WLFF) are known to expend as much as 12.6 to 26.2 $MJ \cdot d^{-1}$ of metabolic energy while engaging in fire suppression activities (Ruby *et al*., 2002; Cuddy *et al., 2015*). The duties encountered by WLFF include hiking in steep terrain, digging fire line, operating chainsaws, brush removal with hand tools over shifts that frequently extend beyond 12 hours (Heil, 2002; Rodríguez-Marroyo *et al*., 2012; Ruby *et al*., 2002), and carrying heavy loads (26.6 ± 6.9 kg) for long distances, which is frequently the most energy demanding task in WLFF (Sol *et al.*, 2018). Exposure to high ambient temperatures and frequent demands of light to moderate energy expenditure with occasional high energy outputs during arduous tasks and emergencies warrant a requirement for aerobic fitness and muscular endurance.

In 1975, the first iteration of an aerobic fitness assessment was implemented and consisted of measuring heart rate before and after a 5 minute step-test which provided an estimate of the candidate's VO_2max (Sharkey *et al.,* 1994). Concerns regarding potential for medical discrimination arising from legislation following the passage of the Americans with Disabilities Act, 1990, and subsequent legal challenges surrounding individual heart rate variability and lack of job specificity, as well as research showing that strength and lean body mass were key determinants of firefighting performance (Sharkey & Jukkala, 1980) prompted the development of a more job-related test. Thus the step-test was replaced in 1995 with a more 'job-specific' series of fitness tests, deemed the Work Capacity Tests (Sharkey & Rothwell, 1996), and includes the Arduous Pack Test (APT) which consists of walking 4.83 km on a level surface in 45 minutes or less while carrying a pack weighing 20.5 kg.

In 1995, DeLorenzo-Green & Sharkey reported that the energy cost of the APT was 22.2 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$, which approximates the mean steady-state energy expenditure of 22.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ observed during common WLFF tasks on the fireline (Budd *et al.,* 1997; Sharkey, 1999). With previous literature demonstrating long-term sustainable energy expenditure approximating roughly 50% of one's VO_2max (Astrand & Rodhal, 1977; Epstein *et al.*, 1988; Hughes & Goldman, 1970; Dumke *et al.*, 2006), a VO_2max of at least 45 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ is necessary to sustain a steady-state metabolic output of 22.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for the duration of a full shift (Sharkey, 1999; Sharkey & Rothwell, 1996; Sharkey *et al*., 1994).

Load carriage contributes to increased levels of energy expenditure during WLFF (Cuddy *et al.*, 2015; Huang & Kuo, 2014) and can vary in energetic cost based on multiple factors, such as weight distribution and proximity to center of mass (Drain *et al.*, 2016). Humans expend considerably more effort when carrying backpack loads suspended posteriorly, and can double their metabolic outputs during moderate load-carriage relative to no load carried (Drain *et al., 2016;* Goldman & Iampietro, 1962; Ludlow & Weyand, 2016; Pandolf *et al.*, 1976; Soule *et al.*, 1978). Major contributors to metabolic cost during load carriage are force production performed by skeletal muscle, specifically that which is required to coordinate the body center of mass, and redirecting center of mass and load carried between successive stance phases (Huang & Kuo, 2014). Because load carriage is an inevitable task encountered by most WLFF, understanding the metabolic cost of typical WLFF load carriage scenarios would underscore the relevance of the APT as an appropriate assessment of a potential firefighter's ability to cope with the stressors typically encountered in the field.

With the implementation of global positioning systems (GPS) to monitor hiking duration, speed, and grade on actual WLFF assignments, evidence suggests that the most consistently energy demanding activity in firefighting may consist of sustained load carriage during the ingress hike (Sol *et al.,* 2018; in press). The ingress hike was defined as the morning hike on wildfire assignments from the start point, such as basecamp, to the worksite. Sol and colleagues (2018) estimated that ingress hikes among interagency hotshot crews on average required the highest metabolic demand, or 26.7±11.4 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$, compared to all other modes of hiking that was measured in the field, excluding training hikes.

The methods used by Sol and colleagues (2018) to estimate energy expenditure during the ingress hikes involved load carriage estimation equations and measured GPS data. Estimation equations such as the Pandolf equation (Pandolf *et al.,* 1976), require only a few easily attainable variables to produce an estimated energy expenditure for a given speed, grade and load. Despite being a more valid procedure, employing indirect calorimetry in the field is often impractical, timely, and expensive. Sol and colleagues (2018) captured speed, grade and distance traveled via GPS, and subsequently inserted these variables, along with body-weight, terrain, and load carried, into the Pandolf equation, thus producing the previous finding of an estimated energy expenditure totaling 26.7±11.4 $ml \cdot kg^{-1} \cdot min^{-1}$ for interagency hotshot crews during the ingress hike.

In recent literature, the Pandolf equation has been shown to be most accurate in predicting metabolic output for adult males who were carrying 22.7 kg and walking at moderate speeds (1.25 and 1.53 $m \cdot s^{-1}$); nonetheless this method produced prediction errors that underestimated VO_2 by 14 and 17%, respectively (Drain *et al.,* 2017). Similarly, other studies have found that the Pandolf equation consistently under predicts energy expenditure during load-carriage on level and declined walking conditions, while over-predicting inclined walking condition (13.4%) for a wide array of subjects (Ludlow & Weyand, 2017). This error can partially be explained by the fact that the subjects and walking conditions used in the creation of the Pandolf equation consisted of only six males with a mean body weight of 78.2±1.6 kg, mean height of 175±1.9 cm, mean age of 20±0.8 years, and only 15 speed & load combinations: 32, 40 and 50 kg; 0.2, 0.4, 0.6, 0.8 and 1.0 $m{\cdot}s^{-1}$ (Pandolf *et al.,* 1976). The narrow scope of subject anthropometrics used in creating the Pandolf equation, coupled with an inability of the equation to account for an increase in energy expenditure during prolonged load carriage of excessive weight due to fatigue (Epstein *et al.*, 1988), constrains the application of the equation to a limited number of circumstances.

A recently published estimation equation, known as the Minimum Mechanics Equation (MME), has reportedly achieved a significantly lower SEE (1.08 vs. 1.71 $mlO_2{\cdot}kg^{-1}{\cdot}min^{-1}$) across six different grades during load carriage when compared to the Pandolf equation (Ludlow & Weyand, 2017). Here, we tested the accuracy of the energy expenditure estimates available from the prevailing load-carriage predictive models (Ludlow & Weyand, 2017; Pandolf *et al.*, 1976) on a large group of subjects whose sex and body masses differed. Subjects were also assessed during a simulated arduous pack test (APT) with load carriage (20.5 kg), and were analyzed as pass and non-pass groups. Energy expenditure was measured during field trials via Douglas bags, and during laboratory tests on a level treadmill with simultaneous indirect calorimetry.

Moreover, peak VO_2 was measured during a graded exercise test with load carriage (20.5 kg), while energy expenditure during the first two, 3-minute stages (10% grade, 0.76 $m \cdot s^{-1}$; 12% grade, 1.12 $m \cdot s^{-1}$) was compared with estimates derived from two prevailing prediction equations (Ludlow & Weyand, 2017; Pandolf *et al*., 1976). We evaluated load carriage predictions among the diverse group of subjects, as well as the possible difference in metabolic cost between treadmill and all-weather track surface walking. Furthermore, we aimed to discover possible discrepancies in metabolic cost of load carriage due to differences in anthropometric traits such as weight and height.

Problem

Recent estimates derived with the Pandolf equation suggest that the highest sustained metabolic demands during wildland fire suppression occur during the ingress load carriage hikes into the active fireline. The current standard for qualification to work on the fireline requires the applicant to complete the arduous pack test (APT) in 45-minutes or less, which previous literature suggests costs ~22.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$; a lower metabolic requirement than the previously observed ingress hike (26.7±11.4 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$). Using estimation equations such as the Pandolf and MME, it may be possible to produce a more personalized current level of fitness, or seasonal readiness, than simply passing the APT in under 45 minutes. These equations require further investigation regarding their ability to accurately estimate energy expenditure for speed, grade and load combinations encountered on the fireline and during the APT.

Purpose

The purpose of this study was to examine the criterion validity of two load-carriage estimation equations to accurately predict load-carriage VO_2 during walking speeds that resemble typical paces observed during the arduous pack test which is walked on a flat surface, as well as slower speeds walked on inclined grades that are common in the field.

Null Hypotheses

1. No significant difference between estimated energy expenditure derived from the Pandolf and MME equation, and measured energy expenditure using indirect calorimetry.
2. No significant difference in estimated energy expenditures between the two estimation equations.
3. No significant difference in estimated energy expenditure between equations when applied to different sexes.
4. No significant difference in estimated energy expenditure between equations when applied to different weight ranges.

Significance of Study

The findings of this study will contribute to the implementation of a more refined methodology that individualizes current level of aerobic fitness, and quantifies season readiness in a more meaningful fashion. Receiving a 'pass' in the current APT is only indicative of the firefighter possessing the bare minimum level of aerobic fitness to sustain ~22.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for three miles. Validation of the more accurate estimation equation could ensure its application in a future methodology that will designate the previously estimated metabolic demand (26.7±11.4 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$) as the qualifying baseline for sustainable aerobic capacity, ideally equating to 50% of the firefighter's VO_2max.

Limitations

- Subjects were recruited upon willingness and convenience to participate, and may not be an accurate representation of would-be firefighter applicants.
- Diet, exercise, music and other potential physiological influences were not controlled for before, during or between submaximal trails and maximal testing.
- Certain subjects may not have approached the field test with the intensity that they otherwise would have if applying for a firefighting position.
- Subject's walking speed during the APT may have varied considerably throughout their individual trial due to pacing times which were provided to them every 200 m.
- Potentially inaccurate treadmill-angles during maximal testing may have influenced comparisons between measured and estimated VO_2 in the first two stages of the test.

Delimitations

- Diverse subject population resembled the wide array of typical WLFF candidates regarding sex, weight, and height. This diversity challenges the ability of the estimation equations to accurately predict energy expenditure due to variation in variables that are required for the equations.

Chapter 2: Review of Literature

Field Observations Highlight the Importance of Aerobic Fitness

Wildland firefighters (WLFF) encounter a wide array of energy demands during a typical shift. Depending on the geographic location and aggression of the fire, firefighters must be fit enough to safely carry out a shift which may require energy expenditures ranging from approximately 12.6 to 26.2 $MJ \cdot d^{-1}$ (Cuddy *et al*., 2015; Ruby *et al*., 2002). Ruby and colleagues (2002) used the doubly labeled water (DLW) technique to quantify total energy expenditure of male and female firefighters during fire suppression in a variety of geographical locations. The DLW method is preferable to the more common method of indirect calorimetry during field work due to possible instrumental errors, and indirect calorimetry may also not be representative of the common work:rest cycle occurring each hour over prolonged work shifts, possibly distorting the average energy expenditure over prolonged periods of time.

Aerobic Fitness and Heat Related Injuries

High energy demands, maintaining fluid and energy balance and facilitating glycogen resynthesis are not the only obstacles encountered by firefighters. Heat related injuries, although relatively uncommon in WLFF (Bonauto *et al.*, 2007; Cuddy & Ruby, 2011), are still worthy of concern within occupations such as WLFF and military operations due to cost of work missed and treatment. Thermoregulation during fire suppression can be challenged by a combination of high ambient and radiant temperatures, and high metabolic demand during arduous tasks in the field. In addition to wearing the required personal protective equipment, carrying heavy packs or loads (10-20 Kg) can further increase the required energy demands, causing a disproportionate rise in heat production relative to the ability to offload that heat.

Studies have shown a direct relationship between high aerobic fitness levels and better thermoregulation (Lisman *et al.*, 2014; McClelland *et al.*, 2017; Mora-Rodriguez, 2012). Lisman and colleagues (2014) conducted a Heat Tolerance Test (n= 34 males; n= 12 females) which consisted of subjects walking on a treadmill at 1.39 $m \cdot s^{-1}$ with a 2% grade for 120 minutes at 40°C and 40% RH. The authors found that: 1) n = 32 subjects were classified as Heat-Tolerant and n = 14 were classified as Heat-Intolerant. 2) Body fat percentage was significantly different between those classified as Heat-Tolerant (20.7±SD 6.3%) and Heat-Intolerant (25.4±SD 8.0%) and 3) Aerobic capacity (VO_2max) was significantly different between those classified as Heat-Tolerant (51.4±SD 7.7 $ml \cdot kg^{-1} \cdot min^{-1}$), and Heat-Intolerant (45.2±SD 6.9 $ml \cdot kg^{-1} \cdot min^{-1}$) (Lisman *et al.*, 2014).

The findings by Lisman and colleagues, specifically the correlation between VO_2max and heat tolerance classification, further support the need for aerobic fitness. The sustainable aerobic output required to pass the APT (VO_2 ~22.5 $ml \cdot kg^{-1} \cdot min^{-1}$) approximates half of the maximal aerobic capacity of the individuals who were deemed 'Heat-Intolerant' (45.2±SD 6.9 $ml \cdot kg^{-1} \cdot min^{-1}$), while the average VO_2max for those deemed 'Heat-Tolerant' (51.4±SD 7.7 $ml \cdot kg^{-1} \cdot min^{-1}$) closely resembles what the VO_2max would equate to if applying the findings from Sol and colleagues (2018) of 26.7 $ml \cdot kg^{-1} \cdot min^{-1}$ equating to 50% (Astrand & Rodhal, 1977; Epstein *et al.,* 1988; Hughes & Goldman, 1970) of a firefighter's VO_2max. In attaining a sustainable aerobic output of 26.7 $ml \cdot kg^{-1} \cdot min^{-1}$ as 50% VO_2max before qualifying as a WLFF, firefighters may reduce their risk for HRI, with simultaneous reduction in cost of medical treatment and work missed.

Emergency Situations Require High Energy Demands

It is important to consider possible emergency situations requiring extraordinary amounts of energy output. In a study that took place on Storm King Mountain, Ruby and colleagues (2000) demonstrated the importance of peak aerobic fitness during emergency evacuation procedures. Thirteen subjects (n= 8 males, n= 5 females) navigated a simulated escape route approximating a distance of 660 meters with an average grade of 20.75% with and without a 15.9 kg pack. The authors found a significant negative correlation between body mass and slower times during the pack trials (r = -0.64), indicating that larger subjects were less affected by the pack. Most importantly was the high correlation (r = 0.82 for pack trial; r= 0.87 for no pack trial) between peak VO_2 and transit rates, or time to completion (Ruby *et al*., 2000). These findings demonstrate the importance of building and maintaining a high level of aerobic fitness for the fire season, as well as the increased metabolic cost of carrying a load.

The capability of firefighters to withstand high energy demands, arduous conditions, energy and thermoregulation imbalances and a multitude of other challenges are heavily influenced by aerobic fitness. It is therefore beneficial to the firefighter to adopt a prudent standard of aerobic and muscular competence, as well as a dependable, and accurate method of assessing the firefighter's aerobic capacity. Ideally, the firefighter in pre-season training would have the ability to simply calculate their percent of 'readiness', and have a better idea of where they currently are and how much additional training they require. Before implementation of such an interactive methodology, the equations that comprise this newly proposed procedure must be deemed accurate.

Load-Carriage Estimation Equations

Pandolf Equation

One of the most widely used predictive equations to determine energy expenditure with and without loads is known as the 'Pandolf Equation'. A revised version of the equation was published in 1976 which accommodated slower walking speeds, beginning at 0.7 $m \cdot s^{-1}$ and descending down to the standstill level (Pandolf et al., 1976). Pandolf and colleagues tested the validity of their revised equation by comparing the predicted with the measured energy expenditure of subjects from a previous study (Goldman & Iampietro, 1962). Both studies used walking speeds of 0.7 – 1.8 $m \cdot s^{-1}$, load carriages of 10 – 30 kg, and percent grades of 3 – 9%. The correlation coefficient was identical to that calculated using the original formula ($r = 0.96$). Despite the high correlation observed between measured and predicted energy expenditures, the scope of walking conditions employed during these experiments proved relatively narrow, thus failing to encompass an array of walking conditions commonly encountered in occupational settings such as military and WLFF.

It is well known that the accuracy of the Pandolf Equation in predicting energy expenditure for different speed, grade and load combinations can vary widely among different individuals (Drain *et al*. 2016; Drain *et al*. 2017; Duggan & Haisman, 1992; Pimental *et al.* 1982; Soule *et al.*, 1978). In 1982, Pimental and colleagues observed an under-prediction of energy expenditure (5 – 16%) during slow (≤ 1.12 $m \cdot s^{-1}$) walking conditions at multiple external loads and grades, including an under-prediction of 14-33% at level walking. The Pandolf equation has been shown by Drain and colleagues (2017) to be most accurate for adult men at moderate speeds (14-17% error rate).

Drain and colleagues (2017) conducted a military-focused experiment that compared measured energy expenditure to estimated energy expenditure that was derived using the Pandolf Equation. Sixteen male subjects (VO_2peak 51.3±SD 5.0 ml·kg^{-1}·min^{-1}) completed 10 walking bouts of 15 minutes under different speed and load conditions: five walking speeds (0.7, 0.97, 1.25, 1.5, 1.8 m·s^{-1}) and two external loads (22.7, 38.4 Kg). After analysis, the Pandolf Equation was found to under-predict the metabolic rate across all 10 walking speed and load combinations by 12-33%. The moderate walking speeds produced less prediction error across both load conditions when compared to the slower and faster walking speeds. An interesting observation was the error rate of 22% associated with the speed and load combination of 1.8 m·s^{-1} while carrying 22.7 kg. This speed and load combination approximates conditions of the arduous pack test.

If applying the most modest under-prediction error of 12% to the estimated energy expenditure of the firefighters from Sol *et al*. (2018), their energy expenditure during the ingress hike may have been closer to 30 ml·kg^{-1}·min^{-1}. It is important to note that the external loads used by Drain and colleagues were distributed between hands, feet and torso. In contrast, experimental data that contributed to the development of the Pandolf equation was based upon backpack load carriage. It has been shown that load carried on the feet (2.0-5.0 kg) is associated with a 6-9 fold increase in energy cost, compared to an equivalent backpack load when walking at 1.25-1.33 m·s^{-1} (Legg & Mahanty, 1986; Taylor *et al.*, 2012), and would likely increase further in our experiments given the more frequent limb oscillations required at the APT speed of 1.8 $m \cdot s^{-1}$.

Minimum Mechanics Equation

The Minimum Mechanics Equation (MME) has just recently been published by Ludlow and Weyand (2017), and has already been compared with the Pandolf equation, as well as the ACSM equation (*ACSM*, 2013; Ludlow & Weyand, 2017). The original version of the Ludlow and Weyand equation, deemed the 'Height-Weight-Speed' model, predicted energy requirements of level human walking using height, weight, and walking speed (Weyand *et al*., 2013). Their approach was to create a generalized predictive equation for human walking economy that more fully incorporated the influence of body size. In contrast, the Pandolf and ACSM equations used regression analyses with limited incorporation of established knowledge or theory, and without incorporating the influence of gait mechanics.

Weyand and colleagues (2013) partitioned gross walking metabolic rates into three compartments: 1) resting metabolism 2) minimum walking metabolism and 3) speed-dependent walking metabolism. The authors ultimately tested 78 subjects (n= 45 males; n= 33 females) between the ages of 5 and 48 years of age. Subjects ranged in height nearly twofold (1.07-2.11 m) and sevenfold in weight (15.9-112.8 kg). Walking speeds were 0.4, 0.7, 1.0, 1.3, 1.6, and 1.9 $m \cdot s^{-1}$. This broad range of walking speeds and subject anthropometrics was critical in creating a predictive equation that could accurately predict energy expenditure during level walking. Measured VO_2 was then compared to estimated VO_2, derived from the Height-Weight-

Speed model. Results showed that the SEE of the model was 1.34 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$, compared to 3.35 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ and 3.23 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for the ACSM and Pandolf equation, respectively.

In 2017, Ludlow & Weyand refined the Height-Weight-Speed model, and subsequently published a new equation referred to as the 'Minimum Mechanics Equation' (MME). This model encompasses three basic mechanical variables: speed, surface grade, and total weight supported against gravity. The new model successfully achieved an R^2=0.99, and SEE=1.06 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ when measured and estimated aerobic outputs were compared. With the recent findings of Ludlow & Weyand (2017), application of the MME model in predicting energy expenditures of walking with load can be applied to occupational situations where indirect calorimetry isn't feasible, and alternate estimation equations present as unreliable for certain body-weights, speeds, grades and loads.

Chapter 3: Methodology

Participants

Sixty three subjects (Males n=37; females n=26; M_b = 74.6±12.5 kg; Height = 1.75±0.09 m; Age = 22.8±3.2 y/o; Study range: 55.4--119.6 kg; 1.52--1.93 m) were recruited from the University of Montana and local community and completed their written informed consent in accordance with the guidelines of the University of Montana's Institutional Review Board prior to any testing. Inclusion criteria included an age range between 18 and 40 years of age. Three subjects who failed to complete the laboratory protocol were excluded from the study.

Simulated Arduous Pack Test

Subjects reported to Dornblaser Field on the University of Montana campus, Missoula, MT (elevation 978.1 meters), and engaged in an APT on a 400 meter all-weather surface track. Participants were equipped with the 20.5 kg pack, and walked a distance of 4.83 km at a self-selected pace. Pacing feedback was provided at the 200 and 400 meter points of the track, and times were announced with respect to a finishing time of 45 minutes. This ensured that subjects knew whether they were ahead or behind the necessary completion time to successfully pass the pack test. Each subject's lap-time and completion time was recorded.

Douglas Bag Trials

A sub-group of subjects (n=10) were fitted with a mouth piece that directed their expired air into Douglas Bags (Consolazio *et al.,* 1963). Expired gasses were collected for 90 seconds at the 5, 20 and 35 min time points (figure 1A). Gas fractions were measured using the

Parvo Medics oxygen and carbon dioxide analyzers (True One 2400, Parvo Medics Sandy, Utah), and volumes were measured using a dry gas meter.

Submaximal Treadmill Trials

During the second phase of the experiment, subjects reported to the laboratory, and completed a series of treadmill walking trials while wearing the 20.5 kg WLFF backpack. These tests consisted of walking at four different speeds for 5-minutes each on a level treadmill. The speeds for three of the bouts were 1.7, 1.8 and 1.9 $m \cdot s^{-1}$, while the fourth bout was administered at the mean speed that the subject maintained during their APT (Figure 1B). The order in which the four trial speeds were administered varied between subjects depending on their predetermined APT speed. In the laboratory, metabolic output (VO_{2lab}) was measured using the previously described metabolic cart. Submaximal steady-state VO_{2lab} for each bout was calculated by averaging measures from the last two minutes of the respective stage.

Loaded Maximal Trial

Following a self-selected rest period, we administered a graded test for aerobic fitness capacity. Subjects wore the 20.5 kg pack, and proceeded with the test while expired gasses were measured as previously described. Average VO_2 for stages one and two of the modified Bruce protocol was determined using the last 30 seconds of each three-minute stage, and VO_2peak was recorded as the highest attained measure before failure.

Experimental Protocol (n=10)

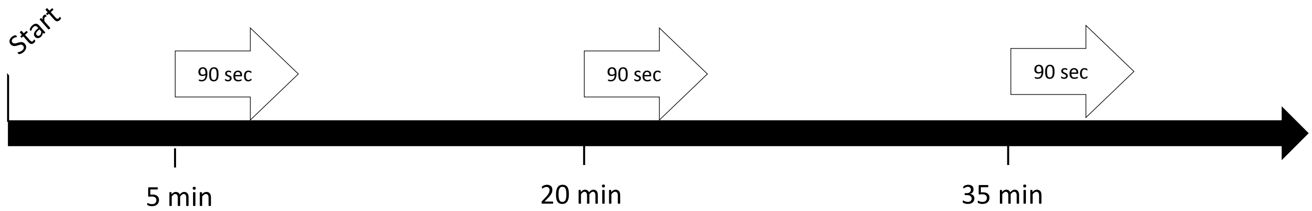

Figure 1A. Douglas Bag-trial protocols during the simulated APT. Expired gasses were collected for 90 seconds at three time periods.

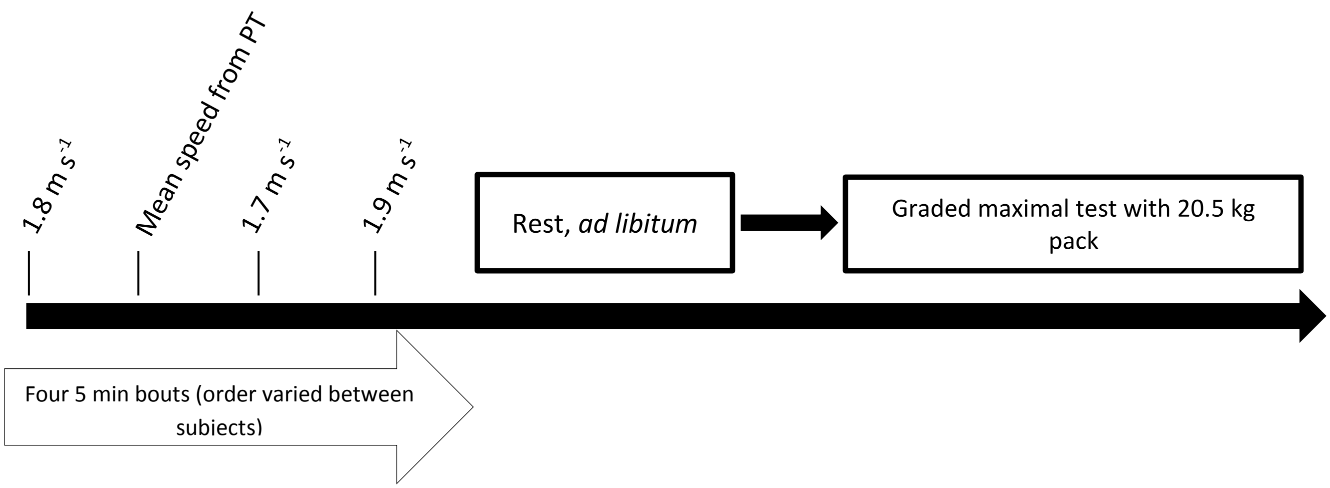

Figure 1B. Experimental protocol for subsequent laboratory visit (n=60).

Estimation Equations

After attainment of each subject's VO_2peak, estimated VO_2's for the submaximal trials and inclined stages one and two of the maximal test were calculated using the Pandolf (Pandolf et al., 1976) and Minimum Mechanics load-carriage equations (Ludlow & Weyand, 2017). **See Appendix 1 for a description of equations.**

Data analysis

Pearson correlations were performed to assess the relationship between measured and predicted metabolic rates for all conditions. Prediction error was calculated for both estimations, while Paired T-test and one-way ANOVA were used in analyzing measured and predicted values. Data are reported as mean ± SD, and significance was determined at $P \leq 0.05$.

Chapter 4: Results

Simulated Arduous Pack Test

Of sixty subjects kept for analysis, 48 (80%) finished the simulated APT in 45 minutes or less (table 1). Mean speed walked during the simulated pack test trials was 1.88±0.14m·s^{-1}, study range was 1.52--2.24 m·s^{-1}. Body mass did not significantly differ between pass and non-pass groups. Height however was significantly ($p=0.006$) less for the non-passers.

APT Results (80% pass)	**Passers (n=48)**	**Non-Passers (n=12)**
Completion time (min)	41.75±2.05	47.87±2.65
VO_2Peak (ml·kg^{-1}·min^{-1})	48.5±7.2	**38.7±8.5†**
%VO_2Peak	63.6±9.3	**73.3±13.7***
Sex	66% male	25% male
Body mass (kg)	74.3±11.7	75.7±15.8
Load-carried: Body mass (%)	28.3±4.5	27.9±4.6
Height (m)	1.77±0.08	**1.69±0.08†**

Table 1: Differences between subjects who either passed or failed to complete the APT in less than 45 minutes. *$p=0.04$; †$p<0.01$

Douglas Bag Trials (n=10)

Mean walking speed during Douglas bag trials was 1.87±0.09 m·s^{-1}; mean steady-state VO_2's (VO_{2db}) were 29.1±4.5, 30.1±4.5 and 31.1±4.3 ml·kg^{-1}·min^{-1} for early, mid, and late collections, respectively. There were no significant differences between VO_{2db} across the three collection points ($p>0.05$). There were no significant differences when comparing subject's mean steady-state VO_{2db} with measured steady-state VO_{2lab} during the same-speed treadmill trial (29.9±3.9 vs 29.6±5.2 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively). There was a general trend for subjects to increase their speed over the duration of the APT (figure 2), but no significance was found.

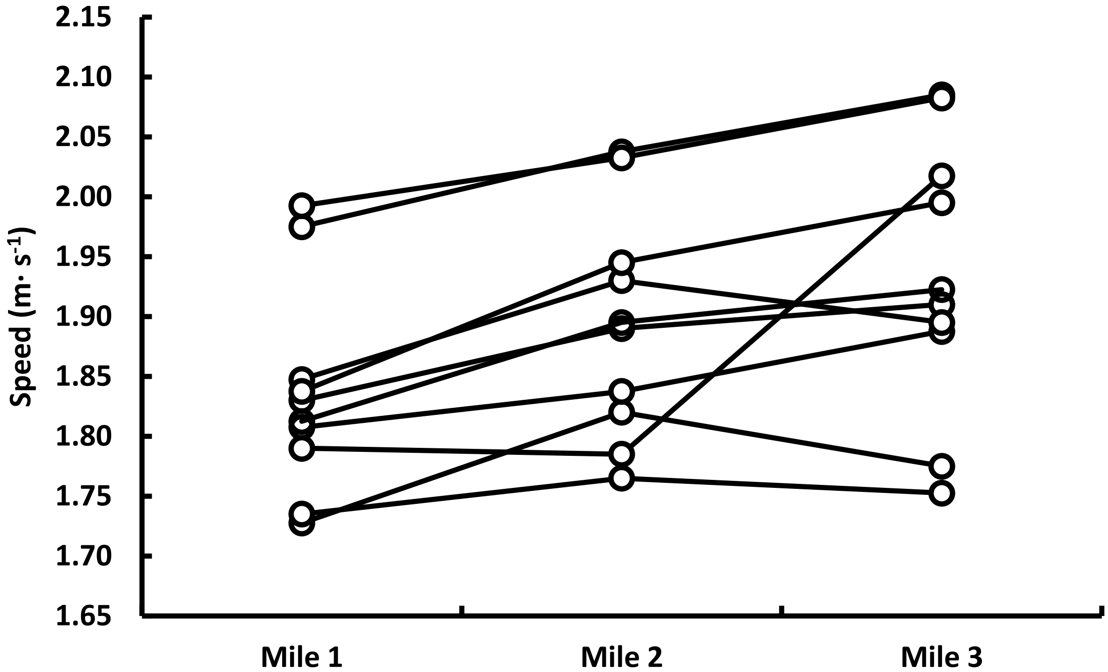

Figure 2: Mean speeds for the ten Douglas bag subjects for each mile of simulated APT (n=10).

Estimated vs. Measured Oxygen Consumption

Comparison of mean estimated and measured VO_{2db} for the ten Douglas-bag subjects is shown in Figure 3. Estimated oxygen consumption derived from the Pandolf and MME equations underestimated measured VO_{2db}, yielding prediction errors of -17.4 ($p<0.001$) and -31.1% ($p<0.001$), respectively.

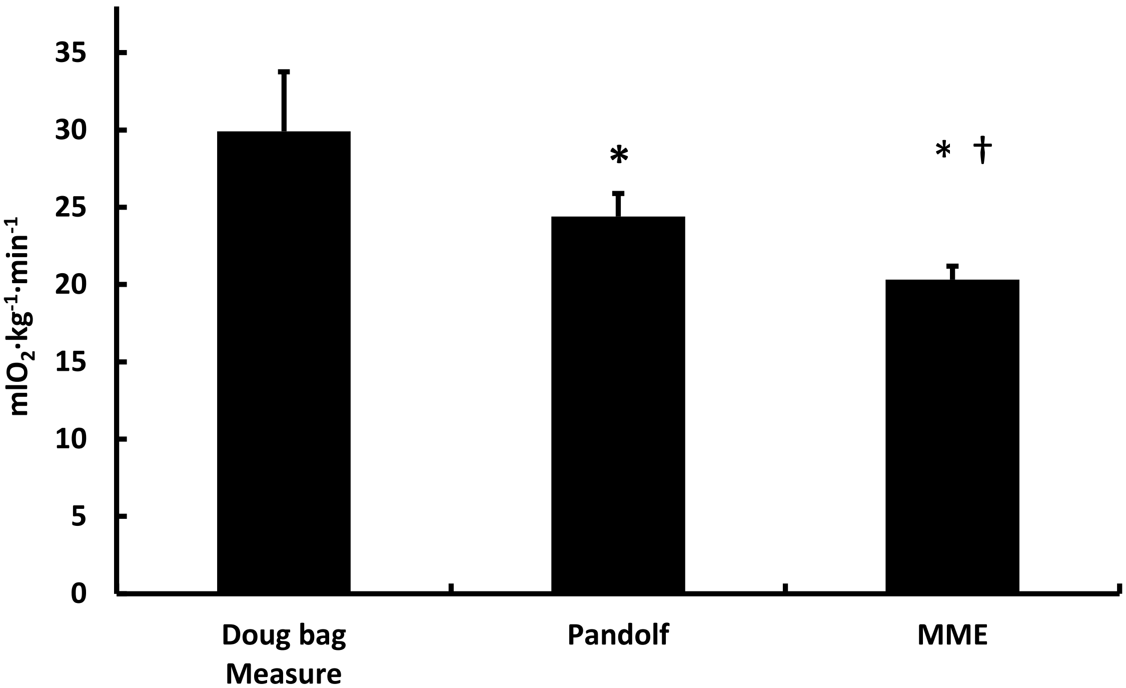

Figure 3: Mean VO_{2db} and estimated VO_2 during the simulated APT Douglas bag trial (n=10). *p<0.001; †p=0.003

Submaximal Treadmill Trials

Field-trial speed

The average number of days passed between the simulated APT and laboratory visit was 19 (study range was 3 to 42 days). There was a significant (p<0.001) positive correlation between field-trial speed walked on the treadmill and VO_{2lab} (figure 4). The Pandolf and MME equations consistently underestimated VO_{2lab} at the field-trial speed (figure 5).

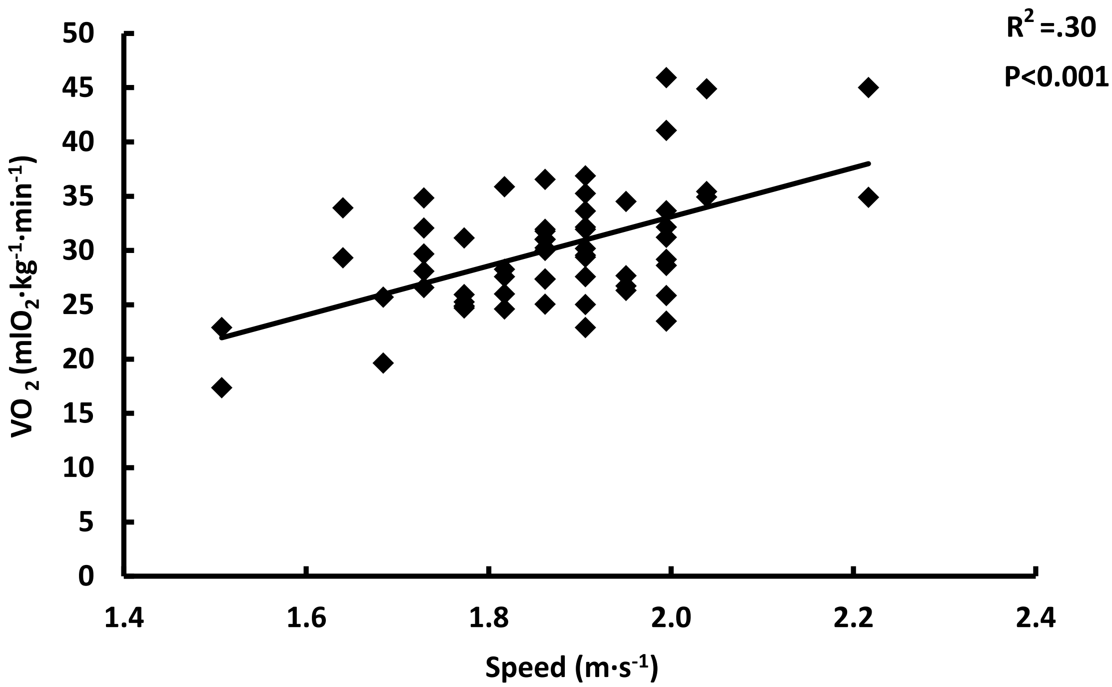

Figure 4: Pearson Correlation between mean speed walked during field-test and VO_{2lab} for all subjects (n=60).

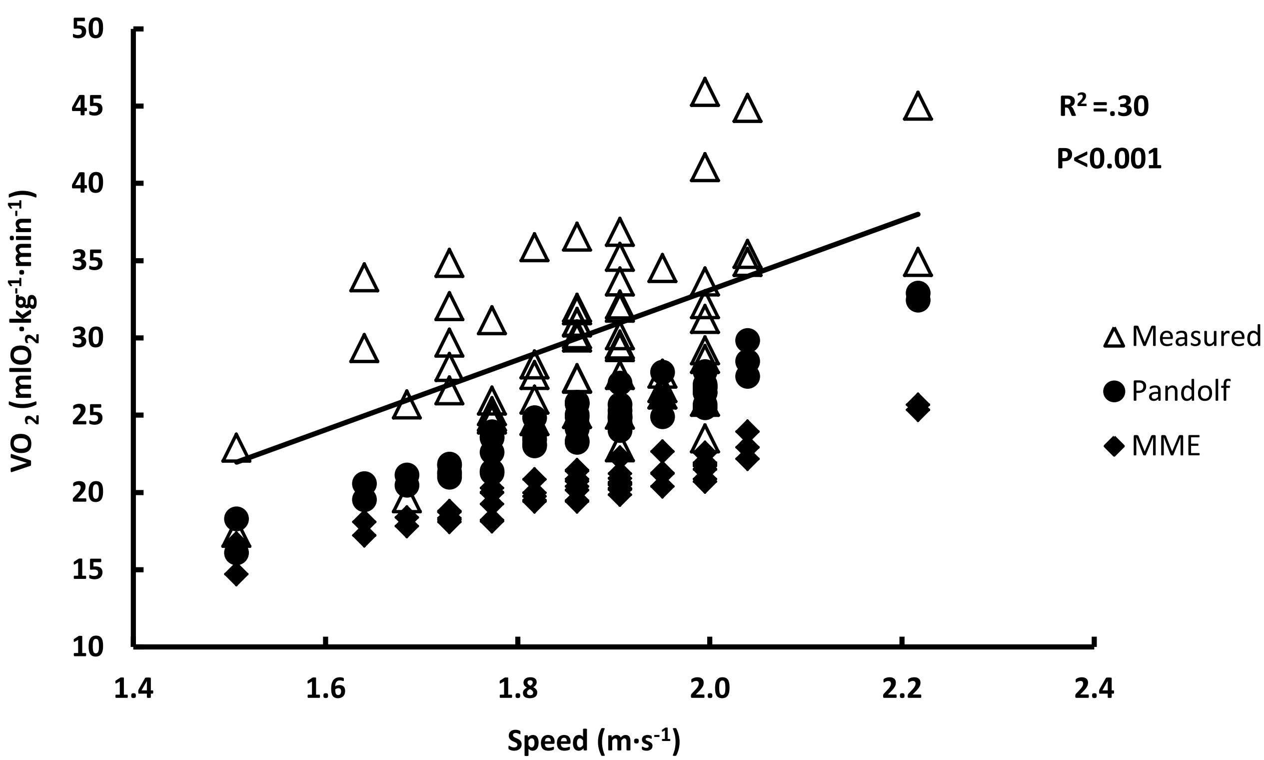

Figure 5: Correlation between measured and estimated VO_{2lab} and speed walked during field-trials. Trend-line fitted for measured energy expenditure (n=60).

Estimated vs. Measured Oxygen Consumption

The Pandolf and MME equations both underestimated oxygen consumption compared to measured values at all four speeds ($p<0.001$), and became less accurate at higher speeds (Table 2). Prediction error for Pandolf and MME ranged from -12.4 and -22.9% at the slowest predetermined speed (1.7 $m\cdot s^{-1}$) to -15.1 and -29.2% at the fastest predetermined speed (1.9 $m\cdot s^{-1}$), respectively. The prediction error for the MME estimates at 1.7 $m\cdot s^{-1}$ and 1.9 $m\cdot s^{-1}$ were significantly different ($p<0.01$), indicating that the MME equation became less accurate at higher speeds. Differences between Pandolf and MME estimations at all four speeds were also significant, with $p<0.001$ (figure 5).

All Subjects

Speed $m\cdot s^{-1}$	Measured ($ml\cdot kg^{-1}\cdot min^{-1}$)	Pandolf ($ml\cdot kg^{-1}\cdot min^{-1}$)	MME ($ml\cdot kg^{-1}\cdot min^{-1}$)
1.7	23.3 ± 3.8	**19.9 ± 0.7***	**17.5 ± 0.6*†**
1.8	26.3 ± 3.9	**22.5 ± 0.8***	**19.1 ± 0.7*†**
1.9	29.2 ± 4.1	**24.3 ± 0.9***	**20.2 ± 0.7*†**
Field-Trial speed (1.88±0.14)	30.1 ± 5.6	**24.5 ± 3.0***	**20.4 ± 1.9*†**

Table 2: Measured and estimated VO_{2lab} across all submaximal speeds (n=60). *$p < 0.001$: measured vs estimates; †$p < 0.001$: Pandolf vs MME

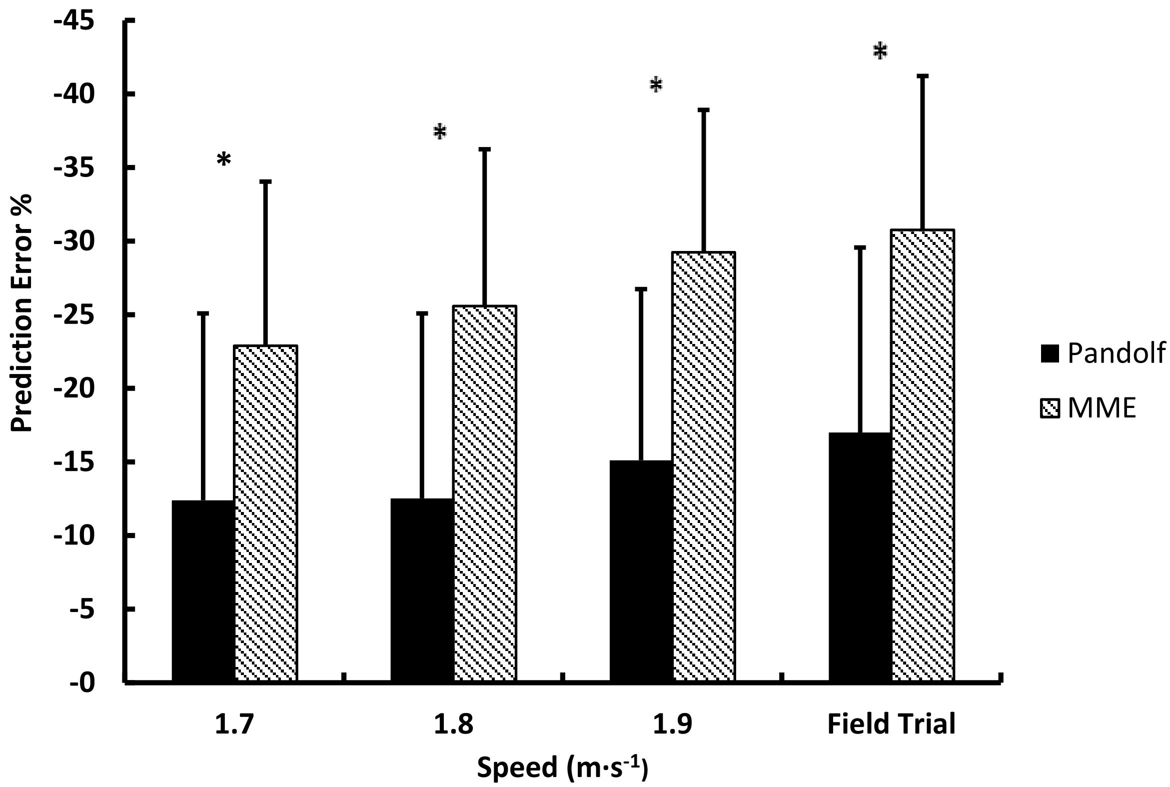

Figure 5: Prediction error (%) for both estimation equations at all four treadmill speeds. *****$p<0.001$ (n=60)

Prediction Errors for Males and Females

Pandolf and MME prediction error for males ranged from -10.9 and -21.5% at the slowest predetermined speed (1.7 $m \cdot s^{-1}$) to -14.5 and -28.7% at the fastest predetermined speed (1.9 $m \cdot s^{-1}$), respectively (table 3). Both estimation equations significantly ($p<0.001$) underestimated VO_{2lab} for males in all four treadmill trials. Values from both estimation equations were also found to be significantly different ($p<0.001$). Measured mean VO_{2lab} was also significantly different between males and females at 1.7 and 1.8 $m \cdot s^{-1}$ ($p \leq 0.05$), but not at 1.9 $m \cdot s^{-1}$ or the field-trial speed (table 3).

Males	**(n=35)**				
Speed m·s⁻¹	**Measured (ml·kg⁻¹·min⁻¹)**	**Pandolf (ml·kg⁻¹·min⁻¹)**	**MME (ml·kg⁻¹·min⁻¹)**	**Pandolf Error (%)**	**MME Error (%)**
1.7	**22.4 ± 3.3₽**	**19.6 ± 0.4***	**17.3 ± 0.4*†**	-10.9	-21.5
1.8	**25.5 ± 3.7₽**	**22.1 ± 0.5***	**18.8 ± 0.4*†**	-11.6	-24.8
1.9	28.5 ± 4.0	**23.8 ± 0.5***	**19.9 ± 0.4*†**	-14.5	-28.7
Field-Trial (1.88±0.14)	31.1 ± 5.4	**25.0 ± 2.6***	**20.6 ± 1.7*†**	-17.8	-32.2
Females	**(n=25)**				
1.7	24.6 ± 4.1	**20.4 ± 0.8***	**18.0 ± 0.6*‡**	-14.5	-24.9
1.8	27.4 ± 3.8	**23.0 ± 0.9***	**19.6 ± 0.7*‡**	-13.9	-26.8
1.9	30.4 ± 4.0	**24.9 ± 0.9***	**20.7 ± 0.7*‡**	-16.1	-30.2
Field-Trial (1.88±0.14)	28.8 ± 5.8	**23.7 ± 3.3***	**20.0 ± 2.1*‡**	-15.8	-28.7

Table 3: Measured and estimated VO_{2lab} across all speeds for males and females (n=60). *****p < 0.001: measured vs estimates; **†**p < 0.001: Pandolf vs MME; **‡**p < 0.01: Pandolf vs MME; **₽**p≤0.05: males vs females

Similar results were found with the female subjects; prediction error ranged from -14.5 and -24.9% at 1.7 m·s^{-1}, to -16.1 and -30.2% at 1.9 m·s^{-1} for Pandolf and MME estimations, respectively (table 3). Oxygen consumption was significantly (p<0.001) underestimated at all speeds by both estimation equations. Difference between estimated VO_2's was also significant for females (p<0.01).

Prediction Errors for Subjects by Weight

Subjects were divided by body mass into three groups for analysis; 55—69 kg (n=20), 69—77.3 kg (n=20), 77.3—120 kg (n=20). Mean load-carried to body-mass ratio was 33.3±2.4, 27.8±1.0 and 23.7±2.4% for the light, intermediate and heavy groups, respectively. Measured VO_{2lab} between the three weight ranges at all four speeds was insignificant (table 4). However, in all four treadmill trials, the lightest group of subjects (55—69 kg) yielded a trend of higher mean VO_{2lab} than the heaviest group of subjects (77.3—120 kg).

All Subjects Separated by Weight

Speed $m \cdot s^{-1}$	Weight Range (kg)	Measured ($ml \cdot kg^{-1} \cdot min^{-1}$)	Pandolf	MME	Pandolf Error (%)	MME Error (%)
1.7	55-69	24.1 ± 3.7	20.8 ± 0.4	18.2 ± 0.3	-12.1	-22.8
	69-77.3	22.9 ± 4.1	19.8 ± 0.2	17.5 ± 0.1	-10.9	-21.5
	77.3-120	22.8 ± 3.5	19.2 ± 0.4	16.9 ± 0.3	-14.0	-24.2
1.8	55-69	26.9 ± 3.9	23.4 ± 0.5	19.9 ± 0.4	-11.3	-24.7
	69-77.3	26.3 ± 4.0	22.4 ± 0.2	19.0 ± 0.2	-12.5	-25.5
	77.3-120	25.7 ± 3.8	21.7 ± 0.4	18.4 ± 0.4	-13.7	-26.5
1.9	55-69	29.9 ± 4.0	25.3 ± 0.5	21.0 ± 0.4	-14.1	-28.6
	69-77.3	28.9 ± 4.1	24.2 ± 0.2	20.2 ± 0.2	-14.4	-28.6
	77.3-120	28.8 ± 4.3	23.4 ± 0.4	19.5 ± 0.4	-16.8	-30.6
Field-Trial speed (1.88±0.14)	55-69	30.5 ± 6.3	25.3 ± 3.3	21.1 ± 2.0	-15.3	-29.3
	69-77.3	30.3 ± 5.7	24.6 ± 2.7	20.4 ± 1.6	-16.8	-30.7
	77.3-120	29.6 ± 5.1	23.6 ± 2.8	19.6 ± 1.8	-18.8	-32.2

Table 4: Measured and estimated mean VO_{2lab} ($mlO_2 \cdot kg^{-1} \cdot min^{-1}$) separated by body mass (n=60). Columns five and six show prediction errors of respective estimation equations relative to measured values.

Loaded Maximal Trial

Estimated vs. Measured Oxygen Consumption during inclined walking

Mean VO_2 from stages one and two (10% grade and 0.76 $m \cdot s^{-1}$; 12% grade and 1.12 $m \cdot s^{-1}$, respectively) was analyzed for 58 subjects. Mean measured VO_2 was 21.1±3.5 and 30.8±5.0 $ml \cdot kg^{-1} \cdot min^{-1}$ for stages one and two, respectively. The Pandolf equation estimated VO_2's of 17.8±0.6 ($p<0.001$) and 29.0±1.0 $ml \cdot kg^{-1} \cdot min^{-1}$ ($p=0.008$), while the MME equation estimated 18.0±0.6 ($p<0.001$) and 27.1±0.9 $ml \cdot kg^{-1} \cdot min^{-1}$ ($p<0.001$) for stages one and two, respectively. Pandolf and MME VO_2 estimates for both stages were also significantly different

($p<0.001$). Mean prediction errors by both equations were -13.4 and -12.5% (stage 1), and -3.8 and -10.0% (stage 2) for the Pandolf and MME equations, respectively.

Prediction Errors for Males and Females

Measured VO_2 between males and females for stages one and two did not differ ($p>0.05$). Estimated values for males and females from both equations at both stages were significantly ($p<0.05$) different from measured VO_2 except for the Pandolf estimate for females at stage two ($p>0.05$).

Mean VO_2peak for all subjects, males, and females is shown in table 5. Males had a significantly higher peak than females ($p=0.004$). Males worked at a significantly ($p<0.01$) lower percentage of their VO_2peak at speeds of 1.7 and 1.8 $m \cdot s^{-1}$ (table 5).

	VO_2peak ($ml \cdot kg^{-1} \cdot min^{-1}$)	**% VO_2 at 1.7**	**% VO_2 at 1.8**	**% VO_2 at 1.9**	**%VO_2 Field Trial Speed**
All Subjects	46.5 ± 8.4	52.4 ± 15.0	58.7 ± 15.2	62.7 ± 13.6	65.3 ± 11.0
Male	**49.4 ± 7.2***	**46.9 ± 12.6**†	**52.7 ± 12.8**†	58.2 ± 12.7	63.1 ± 11.4
Female	42.4 ± 8.3	59.9 ± 14.8	66.7 ± 14.8	69.7 ± 12.2	68.4 ± 9.7

Table 5: Mean VO_2peak for males, females and all subjects in column one; Mean %VO2peak shown for males, females and all subjects across all speeds ($m \cdot s^{-1}$). *$p<0.05$; †$p<0.01$

Body Mass and Height

There was a non-significant ($p>0.05$) correlation between body mass and oxygen consumption during the field-trial speed (figure 6). Correlation between subject height and energy expenditure at field-trial speed, as well as correlation between height and walking speed during the field trial was also non-significant (figure 7 & 8).

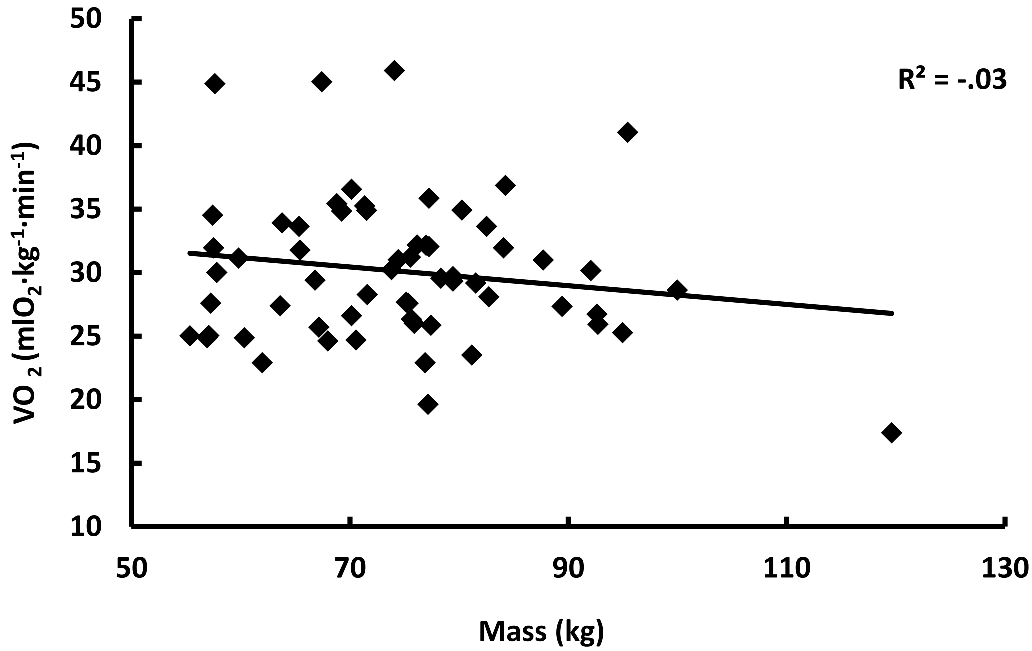

Figure 6: Correlation between subject body mass and steady state VO_{2lab} during field-trial speed on treadmill (n=60).

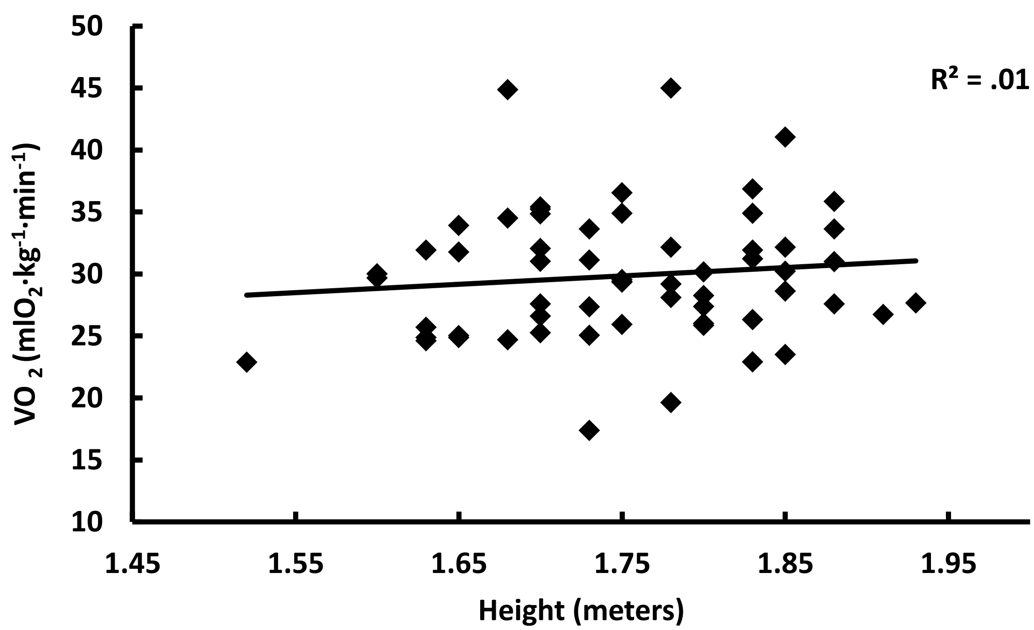

Figure 7: Correlation between subject height and steady state VO_{2lab} during field-trial speed on treadmill (n=60).

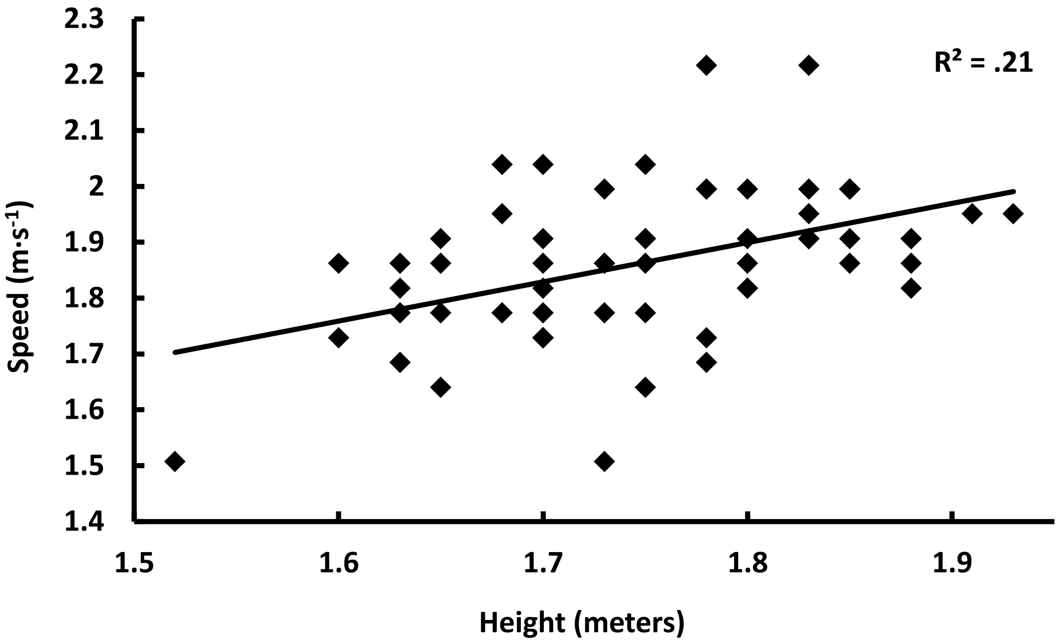

Figure 8: Relationship between subject height and mean speed walked during simulated APT (n=60).

Chapter 5: Discussion

The purpose of this study was to examine the accuracy of two prevailing energy expenditure estimation equations in addition to measuring oxygen consumption of subjects walking with load carriage on flat surfaces at pack test speeds. Specifically, we wanted to identify which equation could better predict metabolic output during load-carriage while walking at speeds at and surrounding the 1.8 $m \cdot s^{-1}$ minimum speed necessary to pass the USFS Arduous Pack Test in 45 minutes or less. We found that both the Pandolf *et al*., (1976) equation and the Ludlow & Weyand, (2017) Minimum Mechanics equation under-predicted oxygen consumption during load-carriage (20.5 kg) on level grade at all speeds administered in the study. In contrast with the findings by Ludlow & Weyand, (2017), the MME consistently produced a greater prediction error than the Pandolf equation when applied to flat walking conditions at relatively fast speeds (table 2).

Our measures of VO_{2db} during the simulated APT provided a second measure of metabolic output with which comparisons between level treadmill and track walking could be made. Our results indicate that the metabolic requirements of treadmill walking at the individualized field-trail speed were no different than the metabolic requirement of walking on the track surface when measured with Douglas bags ($p>0.05$). Regarding APT field-trials, oxygen consumption was underestimated by the Pandolf and MME equations by 5.5±3.5 and 9.6±3.6 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ respectively, compared to the measured values.

It is important to note the changes in speed observed throughout the simulated APT field-trial. Although statistical significance was not detected, there was a general trend among the Douglas bag subjects (n=10) to increase their mean speed across miles one, two and three (figure 2). It is unclear whether fluctuations in speed observed among subjects was influenced by knowledge of their own pace which was vocalized to them every 200 meters. Specifically, it is likely that some subjects altered their walking speed when informed that they were behind or ahead of pace for successfully completing the APT in 45 minutes. Fluctuations in individual walking speed for the Douglas bag subjects for any given lap ranged from 0.07 to 0.33 $m \cdot s^{-1}$. It is therefore not unreasonable to assume that metabolic output varies considerably within subjects throughout the duration of the APT. Moreover, previous Pandolf-equation estimations of VO_2 during the APT by De-Lorenzo-Green & Sharkey, (1995) approximating 22.2 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ are questionable when considering speed variability, and thus metabolic output variability, within individual subjects throughout the duration of the APT.

The Pandolf and MME underestimated oxygen consumption at treadmill field-trial speeds by 6.0±4.9 and 10.4±4.9 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for males and 5.0±4.4 and 8.8±4.7 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for females, respectively. Interestingly, differences in predicted VO_2 values between males and females at field-trial speeds did not reach significance. The reasons for the tendency of males having larger under-predictions in oxygen consumption than females are unclear; however, it could be a reflection of their faster walking speeds (1.91±0.12 vs 1.80±0.14 $m \cdot s^{-1}$). The accuracy of the estimation equations were negatively correlated with walking speed for both males and females, while a significantly ($p<0.001$) lower load-carried to body-mass ratio was observed in males (26.1±2.8%) vs females (31.2±4.7%).

Subject height was a stronger predictor for passing the simulated APT than body mass (passers: 1.77±0.08 m vs. non-passers 1.69±0.08 m [$p<0.01$]), and was positively correlated to walking speed (Figure 8), suggesting that a shorter stature may result in less economic load carriage, possibly due to shorter leg length and thus smaller strides. Moreover, the mean height for women was significantly less than males (1.68±0.06 vs 1.8±0.07m [$p<0.001$]), as was body mass (67.5±13.5 vs 79.5±8.8 kg [$p<0.001$]), exemplifying the higher failure rate for females than males (36% vs 8%, respectively).

The mean %VO_2peak that the 1.8 $m \cdot s^{-1}$ trial elicited across all subjects was 58.7±15.2%, which is greater than the previously demonstrated long-term sustainable work intensity of approximately 50% VO_2max (Astrand & Rodhal, 1977; Epstein *et al.*, 1988; Hughes & Goldman, 1970; Dumke *et al.*, 2006). Our findings of a mean VO_2 of 26.3±3.9 $ml \cdot kg^{-1} \cdot min^{-1}$ at 1.8 $m \cdot s^{-1}$ suggest that WLFF's require a maximal metabolic capacity of at least 52 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ to maintain long-term the level of intensity required to pass the APT.

Male subjects worked at a significantly lower relative percentage of their VO_2peak at 1.7 and 1.8 $m \cdot s^{-1}$ (table 5). All speeds induced a higher mean %VO_2peak for females, although statistical significance wasn't obtained in 1.9 $m \cdot s^{-1}$ and field-trial speed. These findings suggest that females worked at a higher relative intensity than males during fixed load-carriage at certain speeds, which may be explained by a combination of the 20.5 kg pack comprising a higher percentage of their body mass and having a shorter stature on average relative to their male counterparts.

There appear to be several possible explanations for the greater prediction errors observed for the MME in our study. First, our load-carriage procedure was a fixed absolute weight across all subjects (20.5 kg) regardless of their body mass. The methodology used by Ludlow and Weyand involved fixing the load carried as a relative percentage of the subjects body mass, which resulted in mean values of 18 and 31% of their subject's body mass for the two load-carriage conditions tested. Second, placement of external load carried in Ludlow & Weyand's protocol was symmetrically distributed around the torso of the subject, which included military-style backpacks (posteriorly) and vests (anteriorly). The USFS APT frequently utilizes backpacks in which the 20.5 kg is supported by the shoulders and hips, and hangs posteriorly, although weighted vests are allowed. Third, the speeds used by Ludlow & Weyand were slower (0.4, 0.7, 1.0, 1.3, and 1.6 $m \cdot s^{-1}$ in protocol part 1, and 0.6, 1.0, and 1.4 $m \cdot s^{-1}$ in protocol part 2) than the speeds that are necessary to pass the APT in 45 minutes or less. These discrepancies between methodologies could account for the large differences in predictive ability of the MME.

The estimation equations evaluated in this study were designed to predict metabolic output for both flat and graded walking conditions. Although the Pandolf and MME equations significantly underestimated VO_2 during flat APT and submaximal treadmill walking trials, they reported a smaller under-prediction for stages one (3.2±3.5 and 3.0±3.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ [$p<0.001$]) and two (1.8±5.0 and 3.7±5.0 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$[$p<0.001$]) of the graded maximal test, respectively. The more accurate predictions by both equations during inclined conditions and slower speeds are consistent with the previous findings of Ludlow & Weyand (2017).

Conclusion

In conclusion, reports from De-Lorenzo-Green & Sharkey (1995) showing that the APT induced a mean metabolic cost of 22.2 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ should be reconsidered in light of our findings of 26.3±3.9 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ at 1.8 $m \cdot s^{-1}$, which is the minimum speed necessary for passing the APT. Other literature showing the metabolic cost during typical fireline duties approximating 22.5 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ (Budd *et al.*, 1997; Sharkey & Rothwell, 1996) suggests that successfully passing the current APT is more energy demanding than common job tasks on the fireline. Moreover, reports by Sol *et al.* (2018; in press) of 26.7±11.4 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ during ingress hikes more closely resembles the average energy demands observed from our subjects during load carriage (20.5 kg) at 1.8 $m \cdot s^{-1}$. Sol and colleagues indeed derived their estimates of oxygen consumption using the Pandolf equation, which we have just shown to underestimate VO2; however, they applied the Pandolf equation to inclined hiking that varied from 0 to 25%, which may have produced more accurate predictions because of the incorporation of grade.

The findings in this experiment support previous literature which demonstrated that the application of the Pandolf equation in estimating oxygen consumption during load carriage on a flat surface should be used with caution, especially at higher speeds (Drain *et al.*, 2017; Pimental *et al.*, 1982). Furthermore, our analysis of the recently published Minimum Mechanics equation (Ludlow & Weyand, 2017) produced findings that were in direct contrast to their reports of achieving roughly half the SEE of the Pandolf equation when compared to measured oxygen consumption (R^2= 0.99; SEE= 1.06 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$). Our findings of SEE= 8.7 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ for the MME equation over all four submaximal speeds without grade warrants reconsideration of applying this equation to scenarios of level walking with fixed absolute load-carriage at relatively high speeds until further investigation resolves the ambivalence regarding which scenarios are most appropriate for the application of the MME equation.

Appendix 1: Supplemental Equations

Pandolf Equation **(Pandolf *et al.*, 1976):**

$M = 1.5 \cdot W + 2.0(W + L)(L/W)^2 + \eta(W + L)(1.5V^2 + 0.35VG)$

M = metabolic rate, watts; W = subject weight, kg; L = external load, kg; η = terrain factor (η = 1.0 for treadmill); V = velocity, $m \bullet s^{-1}$; G = grade (slope), %

Minimum Mechanics Equation **(Ludlow & Weyand, 2017):**

$VO_{2\text{-gross}} = [VO_{2\text{-rest}} + ((C_1 \cdot G) + VO_{2\text{-walk-min}}) + (1 + (C_2 \cdot G)) \cdot (C_3 \cdot V^2))]$

$VO_{2\text{-}}$gross = the body's gross, or total metabolic rate; $VO_{2\text{-}}$rest = supine, resting metabolic rate*; $VO_{2\text{-}}$walk-min is a constant; G = grade, %; C_1 is a coefficient describing the minimum walking metabolic rate in conjunction with grade; C_2 is a coefficient describing the influence of grade on speed-dependent walking metabolism; and C_3 is a coefficient that describes the influence of velocity on speed-dependent walking metabolism regardless of grade. *$VO_{2\text{-}}$rest values determined using (Schofield *et al*., 1985) equation.

- *Metabolic rate (watts)* = $(VO_2 \times 5.0)/0.0143$ (Drain *et al.*, 2017)

- *Prediction error (%)* = ((MRM− MRP)/MRM) × 100 (Drain *et al.*, 2017)

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