Development of a Lab Testing Protocol to Assess Ski Mountaineering Performance

Catherine Rack and Colin O'Gorman

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Dr. Melissa Thompson

Abstract

Ski mountaineering is a popular winter recreation sport that is quickly gaining importance and recognition in the competitive world. Competitive ski mountaineering is set to be included in the 2020 Youth Olympic Games and in the Olympics as a test sport. Ski mountaineering is a timed race done on an established track using light equipment designed specifically for the sport. Research is lacking on most aspects of the sport, especially the physiological variables that influence race performance. The purpose of this study was to develop an exercise testing protocol that simulates a ski mountaineering race. There were lab and field portions of this study. For the lab portion, subjects completed a ten stage graded exercise test on a large treadmill with roller skis that consisted of five-minute stages starting at 2 mph and 12% grade and increasing speed by 0.2 mph and grade by 2% each stage. The field test was a race simulation and involved two skinning and one bootpack intervals at race pace. Each interval consisted of 600 feet of vertical elevation gain with an average gradient of 20% for the two skinning intervals and 30% for the bootpack interval. VO2 and heart rate were taken continuously throughout both tests using a Cosmed K5 portable metabolic cart. Lactate and rate of perceived exertion were taken at the end of each stage during the laboratory test and at the end of each uphill interval during the race simulation. Pearson's R-Test was used to examine the relationship between the lab and field results. There were strong significant correlations between lab and field results in terms of VO2 and heart rate, indicating that the developed lab test accurately predicts performance in a ski mountaineering race. The lab test can be used to stratify ski mountaineers into skill levels, which will allow for the inclusion of varying skill levels and a higher volume of athletes in ski

mountaineering races and the development of athlete-specific training programs as a result of the specific physiological data the test provides.

Introduction

Ski mountaineering is a European winter sport that is gaining popularity around the world as evidenced by its inclusion in the 2020 Youth Olympic Games in Lausanne, Switzerland and as an Olympic Games test sport (Climbing the Olympic Summit, 2017). Ski mountaineering is a skiing discipline that involves climbing and descending on skis (Harper Collins, 1991). It is used as a winter recreation tool and is a competitive sport (Heil, 2019). Competitive ski mountaineering is a timed race done on an established track using light equipment designed specifically for ski mountaineering (About USSMA, 2017). With its growing popularity and the intricacy of ski mountaineering equipment, a number of studies have emerged detailing the basic physiological, performance, and biomechanical aspects of the sport. However, as precise as the sport is, scientific evidence is lacking to verify exactly what makes this sport different from other endurance sports. Research in the competitive ski mountaineering field centers on four topics: fatigue and performance, physiology, work efficiency and energy cost, and slope angle.

Skiing and ski mountaineering are demanding sports that require large muscle movements and great cardiovascular strength. Studies show that only one day of recreational downhill skiing produces a decrease in eccentric muscle strength (Haslinger et al., 2018; Koller, Leichtfried, & Schobersberger, 2015; Seifert, Kröll, & Müller, 2009). Muscle contraction levels can reach 100-150% of voluntary muscle contraction when making a turn on skis, meaning that the muscles of the legs must work very hard just to complete one turn (Seifert et al., 2009) and skiers make hundreds of turns in a single day. Fatigue is a prevalent part of downhill skiing, especially for novice and untrained skiers (Seifert et al., 2009). This is further evidenced by the fact that alpine skiers exhibit lactate levels that are indicative of fatigue after a half day of moderate skiing (Seifert et al., 2009). Additionally, recreational alpine skiers performing isokinetic muscle testing had a 10% decrease in eccentric hamstring and quadriceps peak torque 24 hours after one day of recreational skiing, which is indicative of muscle fatigue one day after skiing (Koller et al., 2015). Specifically in regard to the sport of ski mountaineering, a single day of ski mountaineering showed a 5% concentric decrease and an 8% eccentric decrease in peak thigh torque (Haslinger et al., 2018). This indicates that recreational ski mountaineering is more demanding on the muscles of the thigh than recreational alpine skiing (Haslinger et al., 2018; Koller et al, 2015). The effect of fatigue on competitive ski mountaineering performance is unknown, however, as indicated by the study above, most likely produces an even more significant decrease in peak thigh torque than recreational ski mountaineering (Haslinger et al., 2018).

Studies conducted by Duc, Cassirame, & Durand (2011) and Fornasiero et al. (2017) give insight to the physiological demands of a ski mountaineering race, such as changes in heart rate (HR), power output, and oxygen uptake. Heart rate and power output data obtained during this race were used to quantify the intensity of the competition by understanding how hard a given athlete was working at any period of time (Duc, Cassirame, & Durand 2011; Fornasiero et al. 2017). Heart rate and power output data are commonly used by coaches, trainers and athletes to create and control workouts (Duc, Cassirame, & Durand 2011). The knowledge of time spent in different intensity zones during training and competition is important so that the athlete can effectively train in the zones that he spends the most time competing in. This knowledge increases the effectiveness of a ski mountaineering training program (Duc, Cassirame, & Durand 2011). The previous studies have shown that more than 40% of the race time in an individual race is spent at or near maximal heart rate intensities (Fornasiero et al. 2017). Therefore, training for skimo races at higher intensities is vital to performing well in competition.

The amount of energy that is spent during a ski mountaineering race is greatly impacted by the slope angle and speed. Less energy is expended to climb one vertical meter at steeper slope gradients, up to an optimum slope gradient between 25 and 30% (Praz et al. 2016; Tosi et al., 2010). In both a field and laboratory study done by Praz et al. (2016), the main finding was that a combination of a steep slope gradient and a high speed resulted in a lower energy cost of locomotion and a higher mechanical efficiency, suggesting that it was more energy cost efficient to choose a steeper route while going uphill. Further, this study found that slope gradient had significant effect on energy expenditure, while the effect of speed on energy expenditure was significant only when the slope angle was steep (Praz et al. 2016). Both of these studies found that slope gradient had a significant effect on stride frequency and length, both of which decreased significantly with increasing slope gradient (Praz et al. 2016).

A lower energy cost means more efficient ski mountaineering. Since energy expenditure is a function of the energy cost of locomotion, the latter is of interest for optimizing a ski mountaineering athlete's performance (Praz, Léger, & Kayser, 2014). Studies have found that the majority of energy cost in ski mountaineering is a result of the locomotion of walking that changes the bodies center of mass (Tosi et al. 2010, Praz, Léger, & Kayser, 2014). This shifting center of mass is related to the overall energy cost (EC) of locomotion (Praz, Léger, & Kayser, 2014). In the two studies done by Tosi et al. (2010) and Praz, Léger, & Kayser (2014), the EC was examined with varying slope steepness up to a 21% incline on a treadmill. Tosi et al. (2010) observed that less energy is spent at an optimal speed of 4.5 kilometers per hour, while more energy was spent and lower and higher speeds. Ski mountaineering races can last multiple hours, so the more time spent traveling at this optimal speed, the less overall EC, which has a direct correlation with performance (Praz, Léger, & Kayser 2014).

The literature on ski mountaineering is lacking and undeveloped. More research is needed to understand the results found in the above studies and to learn more about the biomechanics of ski mountaineering. In particular, there is not a lab study that produces comparable results to a field study. With its growing popularity a replicable and accurate laboratory protocol that is valid in-field is needed to better understand the sport so athletes can have a valid training and testing program for competitive ski mountaineering.

The purpose of this research is to develop a laboratory test that simulates ski mountaineering field conditions. With the rising popularity of this sport a laboratory test that accurately mimics field conditions is needed to advance the way athletes train for the sport, as well as to understand the physiological and biomechanical intricacies that differentiate ski mountaineering from other ski disciplines.

Methods

Subjects

Ten experienced ski mountaineers were recruited through word of mouth in the local backcountry skiing community. For the purposes of this study, experienced was defined as having two or more years of ski mountaineering experience with no less than ten days spent ski mountaineering each year. Athletes were screened for previous medical conditions and were excluded from the study if they exhibited symptomatic musculoskeletal injuries or had a preexisting cardiac condition. Three female subjects and seven male subjects were selected with a mean age of 34 (11) years, mean weight of 66 (7.9) kg, and mean height of 171.8 (8.33) cm. All subjects gave their voluntary informed consent to a protocol approved by the Institutional Review Board of Fort Lewis College in Durango, Colorado.

Procedures

Lab Testing

Subjects performed a graded exercise test on a Large Research Treadmill (VacuMed, Ventura, CA) with roller skis, ski mountaineering bindings, and the subject's own ski boots. The protocol begins at a low speed (2.4mph) and a gentle incline (12%). Every five minutes, the speed increases by 0.2mph and the incline increases by 2%. This continues until the subject reaches lactate threshold, at which point the stage time decreases to one minute. The protocol is shown in Figure I. VO_2 and heart rate were measured constantly using the K5 metabolic cart (COSMED, Italy). Lactate was measured using a Lactate Plus Meter (Nova Biomedical, U.S.) by taking a blood sample from the earlobe during the last minute of each stage.

Stage	Speed (mph)	Grade (%)
1	2.4	12
2	2.6	14
3	2.8	16
4	3.0	18
5	3.2	20
6	3.4	22
7	3.6	24
8	3.8	26
9	4.0	28
10	4.2	30

Figure I: Ski mountaineering graded exercise test

Field Testing

Subjects were tested on outside courses that simulated the uphill segments of ski mountaineering race courses. Subjects used their personal ski mountaineering equipment. Three different routes were completed, two routes were climbed using the skins and skis while a third route was done as a boot pack. Heart rate and VO_2 were monitored continuously using the K5 metabolic cart. Lactate was taken using the Lactate Plus Meter at the top of each section using a blood sample from the earlobe.

Statistical Analysis

The primary statistical comparison was between the laboratory data and the field data. The data was analyzed using a Pearson-R Test. This test is done on Microsoft Excel. This test measures the linear relationship between two variables, which produces an R value. Mean heart rate, blood lactate, and VO2 values for each subject were taken from each stage of the lab test. These values were then averaged to create aggregate data. These values were compared to the routes completed in the field. Numbers close to negative one and one indicate a strong correlation. The further away from zero an R-value is, the more correlated the results are. For this analysis, a P-value of 0.001 was used to determine whether the results were statistically significant or not.

Results

Participants completed field testing using personal gear, with mean ski weight 3.4 (1.37) kg, ski width 89.3 mm (16.5), ski length 169.85 (7.9) cm, boot weight 2.44 (0.832) kg, skin weight 0.47 (0.19) kg, and pole weight 0.475 (0.946) kg. Outdoor temperature was an average of 31.6 (9.01) degrees Fahrenheit and conditions ranged from hard packed and icy to soft and punchy. Laboratory testing was completed with a pair of roller skis weighing 2.8 kilograms and the subject's own boots and poles.

Table I:

	Average	Maximum
VO2 (mL/kg/min)	35.1210 (4.077)	54.0458 (8.67)
Heart Rate (bpm)	155 (16.363)	189.7 (12.789)
Lactate (Mmol/L)	2.57 (.815)	6.51 (2.473)
RPE	5.21 (.361)	8.2 (.918)

Average and maximum VO2, heart rate, lacate, and RPE values for lab testing

Table I details the average , standard deviation, and maximum values (data are reported as mean (SD)) for heart rate, VO2, lactate levels, and rate of perceived exertion (RPE) for each individual subject during the laboratory test. Average VO2 max across all of the subjects was 54.0458 mL/kg/min. Average VO2 was 35.1210 mL/kg/min (4.077). Average maximum heart rate was 189.7 bpm. Average heart rate was 155 bpm (16.36). Average maximum lactate was 6.51 (2.473) Mmol/L. Average lactate among was 2.57 Mmol/L (0.81). Average maximum RPE was 8.21 (.918) and average RPE throughout the test was 5.21 (.361).

Table II:

	Average	Maximum
VO2 (mL/kg/min)	35.2999 (4.45)	55.7138 (9.04)
Heart Rate (bpm)	158.14 (18.38)	181.14 (14.33)
Lactate (Mmol/L)	4.96 (.640)	5.56 (.869)
RPE	7.47 (.753)	8.11 (.893)

Average and maximum VO2, heart rate, lacate, and RPE values for field testing

Table II above shows the average , standard deviation, and maximum values (data are reported as mean (SD)) for heart rate, VO2, lactate levels, and RPE during for each subject. The data is from the field test. The average maximum VO2 was 55.7138 (9.04) mL/kg/min. Average VO2 is 35.299 mL/kg/min (4.45). Average maximum heart rate was 181.14 (14.33) bpm. Average heart rate measurement is 158.14 bpm (18.38). Average maximum lactate was 5.56 (.869) Mmol/L. Throughout the race simulation, average lactate was 4.96 Mmol/L (0.640). Average RPE was reported at 7.47 (.753) and maximum average RPE was 8.11 (.893).

Figure I represents average laboratory VO2 plotted against average field VO2 for 8 subjects. Average VO2 for the lab and field tests were highly correlated, r =A two-tailed T-Test revealed an R-Value of 0.8326, $p < 0.01$.

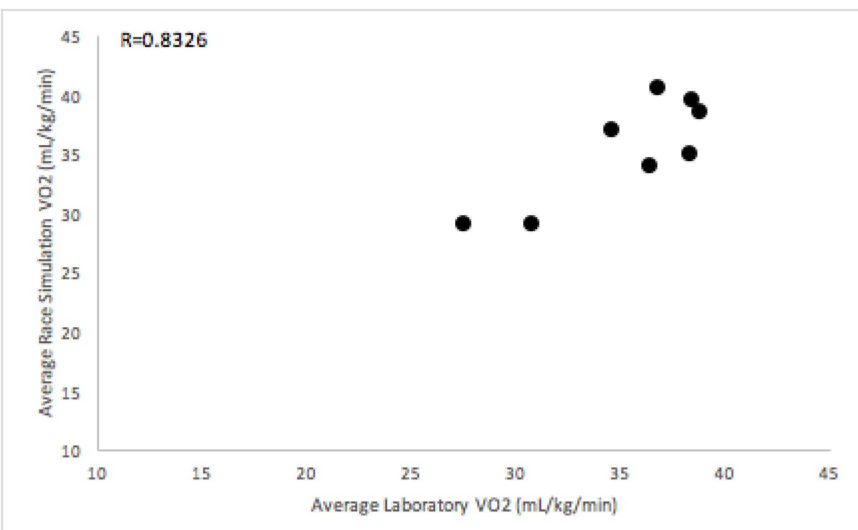

Figure I: : Average laboratory VO2 plotted against average field VO2 across 8 subjects

Figure II represents shows average laboratory heart rate plotted against average field heart rate for 7 subjects. The average heart rate for the lab and field tests were highly correlated, r =A two-tailed T-Test revealed an R-Value of 0.9713, $p < 0.01$.

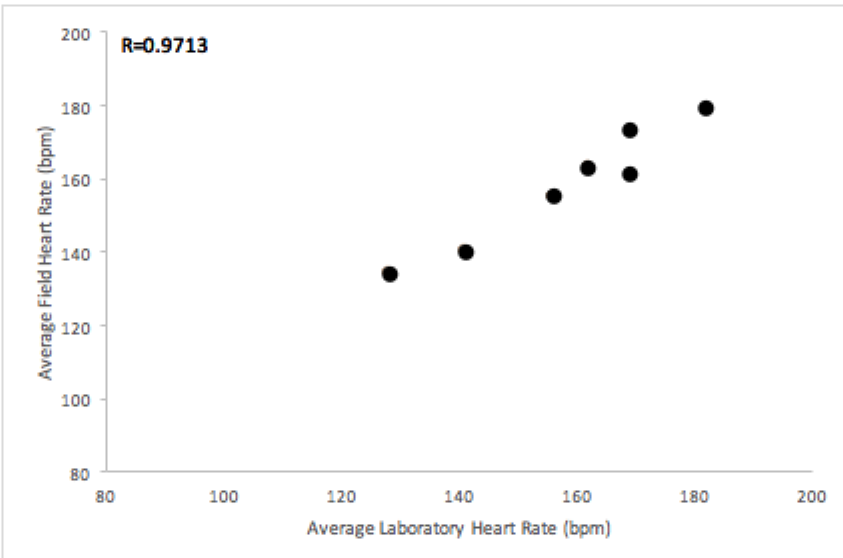

Figure II: Average laboratory heart rate plotted against average field heart rate across 7 subjects

Figure III, shown below, shows VO2 max plotted against average race simulation time. Subjects who had, on average, a higher VO2 max, also had a faster race simulation completion time. Average race simulation time and VO2 max were highly correlated, r =A two-tailed T-Test revealed an R-Value of 0.7541, $p < 0.01$.

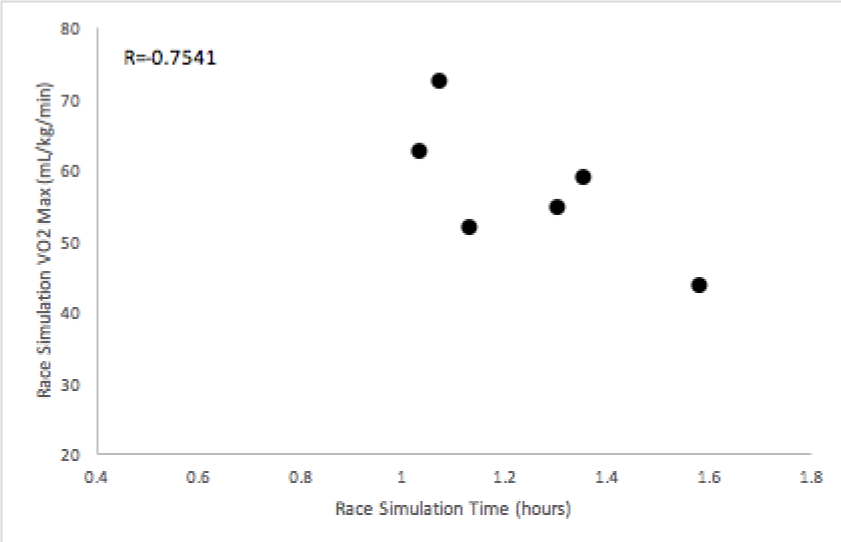

Figure III: Race simulation VO2 (mL/kg/min) plotted against race simulation time (hours)

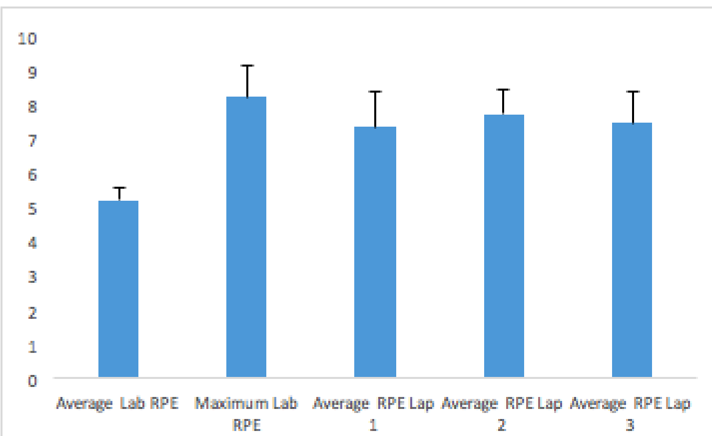

Figure IV: Average and maximum RPE values during the lab and field tests

Subjects, on average, had a higher RPE during the individual laps of the field test than during the lab test. Maximum RPE in the lab is similar to average RPE in the field, most likely due to the field test being race pace and the lab test increasing in intensity. The end of the lab test and the whole of the field test were completed at similar intensities. At the top of each field lab, subjects were working at 91% of their maximum RPE measured in the lab test.

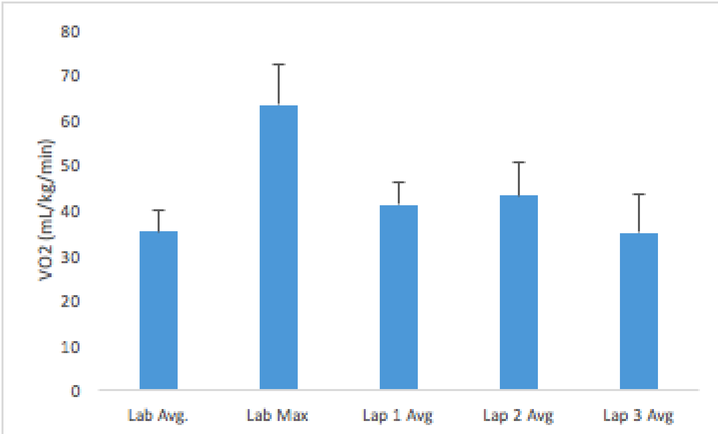

Figure V: Average and maximum VO2 (mL/kg/min) values for the lab and field test

Subject's average VO2 in in the lab and their average VO2's for each field lap are very similar. Subjects were working at an average of 63% of their VO2 max throughout the lab test and the field test laps.

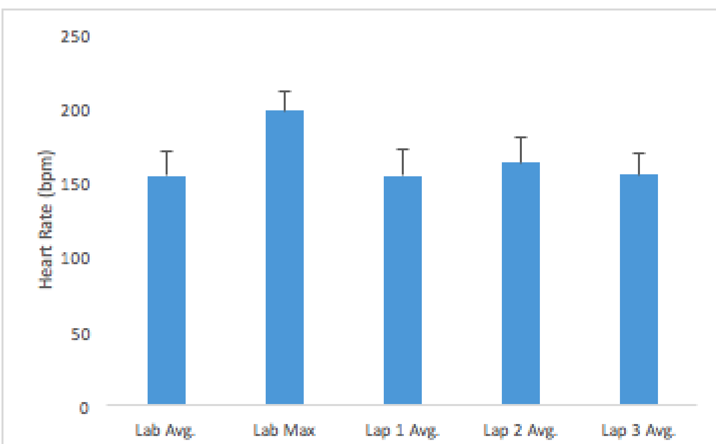

Figure IV: Average and maximum heart rate (bpm) values for the lab and field test

Subjects had similar average and maximum heart rates across all tests. The sustained difficult efforts of both tests ensured high heart rate measurements throughout the whole protocol. Measured average heart rate in the field is 84% of measured heart rate max in the lab.

Subjects were working, on average, at 84% of their heart rate max in the field and at 82% of their maximum heart rate in the lab.

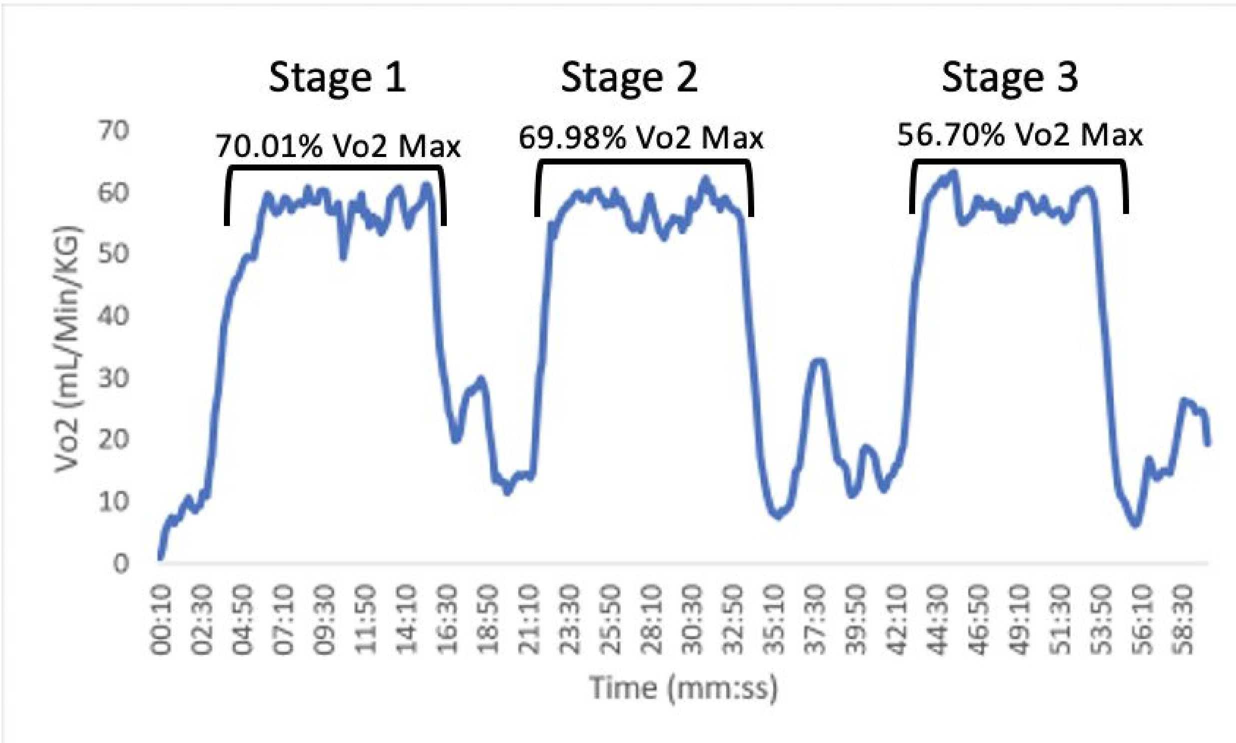

Figure VII: Subject five's individual VO2 profile for the field test

Above is an individual VO2 and heart rate profile of Subject 5's field test. Subject five's VO2max for his field test is 62.6775mL/kg/min and his average VO2 throughout the test is 40.693 (19.772) mL/kg/min. The field test consisted of three uphill intervals, as represented by the three plateaus shown in the figure. Subject five's maximum laboratory VO2 was 58.3296 mL/kg/min. The subject had a higher maximum VO2 in the field. The subject's average VO2 in the laboratory 36.7156 mL/kg/min. Subject five's average VO2 was also higher in the field than it was in the lab. During lap 1 of the field test, subject five was working at 70.01% of their VO2 max, during lap 2, they were working at 69.98%, and during lap 3 they were working at 56.7% of their VO2 max. The first two laps the subject had a sustained effort, dropping off a little during the 3rd lap. From this, it is assumed that subjects were working, on average, at 65.5% of their VO2 max during the race simulation.

Discussion

The purpose of this study was to develop a ski mountaineering laboratory protocol that simulated ski mountaineering under race conditions. Through analysis and comparison of VO2, heart rate, lactate, and rate of perceived exertion (RPE) it was determined that our laboratory protocol has been developed accurately simulates ski mountaineering under race conditions. Average VO2 and heart rate in the lab were strongly correlated with field testing results, average VO2 and heart rate suggesting that the subjects sustained a comparable work level during the laboratory protocol to their work level during a race simulation ski mountaineering course. The average RPE was higher during the race simulation than in the lab, however, because subjects were asked to maintain a race pace during the entire field test and gradually increased workload to race pace in the lab. The maximum RPE in the laboratory was strongly correlated with average RPE during the race simulation.

Heart rate and VO2 data taken throughout the laboratory protocol and the race simulation provided information about how hard a given athlete is working during any stage of the tests. Similarly, previous studies obtained heart rate and power data during real ski mountaineering races to quantify the intensity of that particular race and understand how hard the athletes are working at certain points of the race (Duc, Cassirame, & Durand 2011; Fornasiero et al. 2017). Studies also found that ski mountaineering athletes spend more than 40% of total race time at or near maximal heart rate intensities (Fornasiero et al. 2017). In the present study, the average maximal laboratory heart rate was 189 (12.7) beats per minute (bpm) and average laboratory heart rate was 155 (16.4) bpm. During the race simulation, average maximal heart rate was 181 (14.3) bpm and average heart rate was 157 (16.6) bpm. This indicates that subjects, on average, were working at 82.0% of their maximal heart rate in the lab and at 84% of their maximal heart rate during the race simulation. Additionally, the correlation between average heart rate during the laboratory protocol and during the race simulation is statistically significant, showing that a subject's average heart rate during the lab protocol is similar to their average heart rate during the race simulation. The designed laboratory protocol pushed subjects to reach intensities greater than those achieved in the field, but is a good predictor of what a subject will achieve in the field. Continuous VO2 data taken during the laboratory protocol and the race simulation quantified how hard individual subjects were working throughout the tests, but also during different stages of each test. The laboratory protocol increased slope angle and speed by 2% and 0.2 mph respectively, with each stage lasting 5 minutes, up until subject exhaustion. Previous research found that less energy is expended to climb one vertical meter at steeper slope gradients, up to an optimum slope gradient between 25 and 30%.(Praz et al. 2016; Tosi et al., 2010) This is why the developed protocol increases all the way to 30% grade. This requires that the athlete self-selects speed in order to avoid exhaustion (Tosi et al., 2010). The laboratory protocol increases speed, therefore leading to a greater workload for the athlete. This study quantified workload by measuring VO2 throughout the lab test. The lab test was designed to push participants to max effort, while the race simulation was completed at a sustained effort to achieve fastest possible time. Max VO2max during the race simulation was 55.7 (9.04) mL/kg/min while average VO2 was 35.39 (4.46) mL/kg/min. Participants on average used 63.75% of their VO2 max during the race simulation compared to the lab test. Average VO2 across both tests has a statistically significant correlation, showing that on average subjects expended the same amount of work in both tests. There is a clear correlation that subjects used a larger percent of their VO2 during the lab test, performed better in the simulation race (Praz et al. 2016; Tosi et al., 2010). In summary, the developed laboratory protocol that increases with intensity via increasing speed and slope angle accurately predicts how a subject will perform in a ski mountaineering race simulation. In order to be a successful ski mountaineering athlete, individuals need to be aware of the workload that they can sustain throughout a race, which can last for hours (Praz, Léger, & Kayser 2014). This enables athletes to train at the right intensity so that they can perform better throughout the entire race (Praz, et al., 2016). Efficient performance is done through looking at the lactate threshold and anaerobic threshold. In the present study, the average lactate was significantly higher during the race simulation than the lab test. Specifically, the average lactate during the race simulation was 4.96 Mmol/L, whereas it was only 2.57 Mmol/L in the laboratory. Lactate in the laboratory was only taken up until the data showed that the subject had reached lactate threshold, while lactate was taken throughout the whole race simulation, which was a sustained hard effort. Lactate measurements enable athletes to gain a better understanding of their training and their body's response to different workloads.

Weather will always have an effect on testing done in the field. Weather conditions presented limitations while trying to conduct the field test section of the study. The variable weather that comes with spring presented challenges with the snow conditions. One of the testing days was started at 8am when the sun was barely rising and the slope that the test was being conducted on was still in the shade. This made for very hard, icy snow, which when accompanied by steep slopes is not the easiest conditions to skin up in. The following day of testing was significantly warmer than the previous making the snow very soft and wet. This also proved to be difficult conditions because the skis were not sliding on the snow as easily as they were the previous day. On the final day of testing, the snow was too soft to do the bootpack section of the test for the participants testing in the afternoon. In a real race scenario, all subjects complete the same course at the same time, so conditions would not be an issue.

Another limitation that could not be avoided during the field testing is the altitude at which the race simulation was completed at. The elevation that the laboratory testing was completed approximately 6,500ft above sea level. The elevation at Hesperus Ski Area is just over 8,000ft above sea level. Although 1,500 feet is not a significant change in elevation, it is potentially large enough to increase the demand placed on the body to provide sufficient oxygen during the race simulation. In an ideal world, both the lab and field sections of the test would be conducted at more of a similar elevation.

Since ski mountaineering is still an up and coming sport, it was difficult to find a large number of subjects with ski mountaineering experience that were willing to volunteer for this study. For the lab portion of the study, ten subjects were tested. However, for the field portion, due to scheduling conflicts, only nine subjects were tested. This does not have a huge impact on the data, because that subject was not included in any of the race simulation results. However, conducting this study with more individuals will further validate the lab protocol.

The findings and limitations of the present study indicated areas that would be beneficial for further research. The first is to have a larger participant pool to help improve statistical power. By having a larger number of participants, there would be more data to analyze and any findings would be more significant. In addition, to the larger testing pool, more females should be included. For this study only three females completed the testing. If there were more females, the results could be further analyzed by gender. Using more participants would also allow the lab protocol to be an even better predictor of ski mountaineering skill.

The second recommendation for future research is to use a real ski mountaineering race course for the field test section of the study. For the race simulation that was conducted at Hesperus Ski Area, the subjects had to take three different laps with different routes on each to try and simulate an entire race. In a real skimo race, the participants have one long course to follow as opposed to the multiple laps. During the transitions between laps, subjects took their skins off their skis, skied down, and put the skins back on. During this time subjects were able to catch their breath, almost like a break, which during a real race typically does not happen.

The developed laboratory protocol has been shows to be a valid test for accurately predicting ski mountaineering performance. VO2 and heart rate exhibited strong significant correlations between the lab and field indicating the validity of the lab test. The ramped VO2max ski test designed in this study can reliably predict a subject's VO2 and heart rate during an hour long ski mountaineering race-simulation, even with subjects of varying ability and experience. This research indicates that the developed lab protocol is a valuable fitness indicator for all ski mountaineering athletes, regardless of competition level or experience.

References

About USSMA. (2017). Retrieved October 29, 2019, from https://ussma.org/about/.

Climbing the Olympic summit: Everything you need to know about ski mountaineering. (2017, October 10). Retrieved October 29, 2019, from https://www.olympic.org/news/climbing-the-olympic-summit-everything-you-need-to-know-about-ski-mountaineering.

Duc, S., Cassirame, J., & Durand, F. (2011). Physiology of ski mountaineering racing. *International journal of sports medicine*, *32*(11), 856-863.

Fornasiero, A., Savoldelli, A., Boccia, G., Zignoli, A., Bortolan, L., Schena, F., & Pellegrini, B. (2017). Physiological factors associated with ski-mountaineering vertical race performance. *Sport Sciences for Health*, *14*(1), 97–104. doi: 10.1007/s11332-017-0407-0

Harper Collins. (1991). *Collins English dictionary*. Glasgow.

Haslinger, S., Blank, C., Morawetz, D., Koller, A., Dünnwald, T., Berger, S., Schlickum-Wolfgang, S., Schobersberger, W. (2018). Effects of Recreational Ski Mountaineering on Cumulative Muscle Fatigue – A Longitudinal Trial. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.01687

Heil, N. (2019, July 31). Up Is the New Down. Retrieved from https://www.outsideonline.com/2045806/new-down-rise-skimo.

Gellaerts, J., Bogdanov, E., Dadashi, F., & Mariani, B. (2018). In-field validation of an inertial sensor-based system for movement analysis and classification in ski mountaineering. *Sensors (Switzerland)*, *18*(3). https://doi.org/10.3390/s18030885

Ioc. "Climbing the Olympic Summit: Everything You Need to Know about Ski Mountaineering." *International Olympic Committee*, IOC, 10 Oct. 2017, www.olympic.org/news/climbing-the-olympic-summit-everything-you-need-to-know-about-ski-mountaineering.

Koller, A., Fuchs, B., Leichtfried, V., & Schobersberger, W. (2015). Decrease in eccentric quadriceps and hamstring strength in recreational alpine skiers after prolonged skiing. *BMJ Open Sport and Exercise Medicine*, *1*(1). https://doi.org/10.1136/bmjsem-2015-000028

Praz, C., Léger, B., & Kayser, B. (2014). Energy expenditure of extreme competitive mountaineering skiing. *European Journal of Applied Physiology*, *114*(10), 2201–2211. https://doi.org/10.1007/s00421-014-2939-1

Praz, C., Fasel, B., Vuistiner, P., Aminian, K., & Kayser, B. (2016). Optimal slopes and speeds in

uphill ski mountaineering: a field study. *European Journal of Applied Physiology*, *116*(10), 2017–2024. https://doi.org/10.1007/s00421-016-3455-2

Praz, C., Fasel, B., Vuistiner, P., Aminian, K., & Kayser, B. (2016). Optimal slopes and speeds in uphill ski mountaineering: a laboratory study. *European journal of applied physiology*, *116*(5), 1011-1019.

Seifert, J., Kröll, J., & Müller, E. (2009). The Relationship of Heart Rate and Lactate to Cumulative Muscle Fatigue During Recreational Alpine Skiing. *Journal of Strength and Conditioning Research*, *23*(3), 698–704. doi: 10.1519/jsc.0b013e3181a2b55e

Tosi, P., Leonardi, A., Zerbini, L., Rosponi, A., & Schena, F. (2010). Energy cost and efficiency of ski mountaineering. A laboratory study. *Journal of Sports Medicine and Physical Fitness*, *50*(4), 400–406