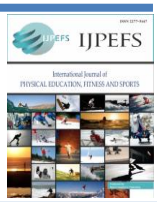
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Characterizing Steady-State Cardiovascular and Metabolic Responses of Recreational Climbers during Motorized Treadmill Climbing

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Abstract: Given that the popularity of indoor climbing exceeds that of outdoor climbing, health professionals need a better understanding of how these indoor climbing activities can be used to prescribe exercise. The primary goal of this study was to characterize both cardiovascular and metabolic responses of motorized treadmill climbing with respect to thresholds for heart rate as a percent of maximum (%HR) and metabolic equivalents (METs). Additionally, this study used these data to generate MET and energy expenditure (EE) prediction equations for prescription purposes. *Methods:* Twenty non-competitive recreational climbers (16 men; 4 women) were recruited to climb six combinations of "slow" and "fast" climbing speed (4.6-9.1 m/min) across three treadmill grades: vertical (90°), overhang or negative incline (85-80°), positive incline (95-100°). A portable metabolic system was worn by climbers during testing to measure HR and oxygen uptake (VO_2), the latter of which was converted to EE and METs using standard formulae. Mean HR% and MET values were compared to intensity thresholds (65%, or 3 and 6 METs) using one-sample t-tests, while standard multiple regression techniques were used to predict EE and METs from a pool of variables (climbing treadmill speed and grade, body mass, gender. *Results:* HR% (70.0-85.4%) was >65% at all test conditions ($P<0.01$) and mean MET values exceeded the 3-MET threshold and was ≥6-MET threshold at all conditions (6.0-8.5 METs; $P<0.01$). Multiple prediction equations for both EE ($R^2=0.81$; SEE=±0.83 kcals/min; $P<0.001$) and METs ($R^2=0.73$; SEE=±0.6 METs; $P<0.001$) included speed, grade, and gender. *Conclusions:* The vigorous metabolic intensity for motorized treadmill climbing (≥6 METs) in this study was clearly sufficient to promote positive health and metabolic fitness in healthy adults. In addition, health professionals can use the EE and MET prediction equations to prescribe specific motorized treadmill climbing intensities to clients, as well as generate climbing-specific testing protocols.

Key Words: Energy Expenditure, Metabolic Equivalent, Heart Rate, Exercise Prescription, Rock Climbing.

1. Introduction

Over the span of several decades, the sport of rock climbing has steadily evolved from a fringe activity with relatively few participants, to a mainstream physical activity (PA) and international sport. The evidence for mainstream popularity of rock climbing can be found in numerous locations, such as small climbing walls in children's playgrounds, bouldering features in public parks, as well as climbing walls and climbing treadmills in community fitness centers and physical therapy clinics. With sport climbing having been added to the 2020 Summer Olympics schedule, rock climbing is likely to continue its rise in popularity amongst those interested in novel and challenging forms of PA. Interestingly, the public's interest in rock climbing seems to heavily favor indoor over outdoor climbing activities [1] which includes artificial climbing walls, large artificial rocks for practice climbing ("bouldering"), as well as climbing-specific exercise equipment like motorized and non-motorized climbing treadmills. Thus, the growing popularity and preference for indoor climbing activities is a unique niche for promoting improved health, fitness, and health risk profiles in both children and adults through increased PA participation.

Despite climbing's rise in popularity, as well as the plethora of research focused on characterizing climbers' capacities, physical abilities, and injuries [2-6], not much is known about how recreational indoor climbing activities fit into the guidelines for promoting physical activities that contribute to improving markers of health and chronic disease risk. Both the World Health Organization (WHO) and the U.S. [7-8], for example, recommend that all adults accumulate ≥150 mins/week of moderate intensity PA or 75 mins/week of vigorous intensity PA. These PA standards are based upon common definitions of 3 and 6 metabolic equivalents (METs) as moderate (i.e., 3-5.9 METs) and vigorous (≥6 METs) intensity PA, respectively. In contrast, those studies characterizing the energy cost of climbing have done so with well trained and elite climbers who completed climbing routes or tasks that are too difficult for novice and recreational climbers [2, 5-6]. As such, the characterization of cardiovascular and metabolic responses specific to recreational climbers are not as well documented.

An exception to this trend is the study by Rodio et al [9] who characterized the physiological profiles of 13 non-competitive rock climbers which included cardiovascular and metabolic responses to outdoor rock climbing. Using a local rock face commonly used for "basic training" of beginner rock climbers, the authors reported mean relative heart rates (HR%) of 83% and 90% for their men and women climbers, respectively, both of which exceed the HR% threshold of 65% that has been recommended for improving cardiovascular fitness in healthy adults [10]. The metabolic responses for these same climbers was equivalent to 8.1 and 7.8 METs for men and women climbers, respectively, which also exceeds both the 3 and 6 MET thresholds promoted for minimizing chronic disease risk [7,8]. Collectively, the Rodio study [9] results suggest that outdoor climbing on a relatively easy route can easily stress both cardiovascular and metabolic systems at steady-state intensities consistent with traditional aerobic exercise. However, Rodio's results are also specific to a single outdoor route that was climbed at a self-selected pace (which was unreported) with only a single 2-min steady-state phase. Thus, while the results from Rodio et al [9] are generalizable to recreational climbers, the cardiovascular and metabolic responses are very specific to the study's measurement conditions and a single outdoor rock climbing route.

Given the growing popularity of indoor climbing activities, it would be useful to characterize the cardiovascular and metabolic responses for a type of indoor climbing that may be prescribed like traditional aerobic exercise. Motorized climbing treadmills, for example, which are now commonly found in many fitness centers, are designed to simulate outdoor rock climbing by using a motor-driven treadmill with climbing hand holds on a paneled surface that travels at a user-specified speed and grade. Unlike other forms of climbing, the climbing activity on motorized treadmills is usually performed at a steady submaximal pace, just like walking or jogging on a regular treadmill. In contrast, outdoor climbing and indoor climbing walls may be continuous for several climbing moves or a pitch, but these short high intensity bouts are typically separated by frequent rest bouts (i.e., no steady-state). Thus, use of a motorized climbing treadmill is the indoor climbing modality that best simulates the cardiovascular and metabolic demands commonly used for prescribing aerobic exercise.

The primary purpose of the present study was to characterize the cardiovascular and aerobic energy demands of indoor climbing on a motor-driven climbing treadmill at different combinations of speed and grade. Specifically, it was of interest to determine whether self-selected intensities of motorized treadmill climbing intensity exceeded either the HR% or MET cut points for exercise prescription and minimizing hypokinestic disease risk [10]. In doing so, it was also of interest to characterize the HR-VO_2 relationship for this type of exercise and to determine whether it changes as a function of treadmill grade (e.g., climbing a vertical grade versus either negative or positive grades). A secondary goal of this study was to use these same data to generate generalized energy expenditure and MET prediction equations that were specific to steady-state motorized treadmill climbing exercise. Such equations would be useful for developing exercise prescription plans by health professionals,

as well as the development of testing protocols that were specific to motorized treadmill climbing.

2. Methods

2.1 Participants

Local climbers with at least one year of self-reported indoor and/or outdoor climbing experience were recruited as volunteers for this study. Written informed consent was provided by all subjects in accordance with Montana State University's (MSU) Internal Review Board (IRB). All study volunteers, hereafter referred to as subjects, were screened for contraindications to high intensity climbing exercise prior to testing using a PA readiness questionnaire (PAR-Q) and the procedures recommended by the American College of Sports Medicine [10].

2.2 Procedures

The test subjects were required to make three visits to the testing lab within a four-week period, while all testing was completed over the course of three consecutive months. The first lab visit was used to familiarize the subjects with the climbing treadmill, as well as establish the climbing speeds and grades that each subject would climb during subsequent lab visits. The goal was to determine combinations of speed and grade that could be climbed for five consecutive minutes while maintaining a steady-state cardiovascular response. As such, subjects were directed to self-selected three different treadmill grades at both "slow" and "fast" treadmill speeds that would result in a total of six testing conditions per subject. The three treadmill inclines corresponded to the following: 1) A vertical incline, which was defined as 90°; 2) A "negative", or less than vertical incline, at either 80° or 85°; 3) A "positive", or greater than vertical incline, at either 95° or 100°. The purpose for having the incline options above and below vertical was to better customize the test conditions to abilities of each subject – i.e., the 100º incline was easier climbing than the 95 º at any speed, as was 85 º easier than 80 º. For demographic purposes, subjects also completed a brief questionnaire to determine self-assessed climbing experience and climbing skill level at the time of testing. After completing this first test visit, subjects were randomly assigned a counterbalanced order of the six conditions that were evenly spread across the next two lab visits.

Upon arrival for the second lab visit, subjects were weighed (with clothes but without shoes) and allowed to warm up on the climbing treadmill at any combination of self-selected speeds and grades for 10-15 mins. Next, subjects were fitted with a portable metabolic measurement system and telemetry heart rate (HR) monitoring device for measuring oxygen consumption (VO_2) and HR, respectively. Once data collection was initiated, the subject was instructed to begin climbing the first assigned condition. Each condition was climbed for five consecutive minutes, which was followed immediately by two minutes of standing rest, and then followed again by five minutes of climbing at the next condition, and then again with two mins of standing rest and another five mins of climbing to complete the three assigned test conditions. The remaining three test conditions were then tested in the same manner during each subject's last lab visit. During the three-month period of testing, the location of the climbing treadmill handholds never changed, but the subjects could choose their own climbing route along the treadmill surface. If a climbing fall occurred while testing, subjects were instructed to remount the treadmill immediately. If successive falls occurred, or if it was apparent that the condition being tested was not going to be maintained at a steady-state for five minutes, testing was immediately halted. In such an instance, the test condition would be redefined to an easier incline (e.g., 85° incline instead of 80°) and retested during the same lab visit after a two-minute standing rest period.

2.3 Instrumentation

Energy expenditure during treadmill climbing was determined from measures of submaximal VO_2 and carbon dioxide production (VCO_2) as determined through standard indirect calorimetry procedures using the KB1-C Ambulatory Metabolic Measurement System (Aerosport, Inc., Ann Arbor, MI USA) (Figure 1). The KB1-C was a portable

system utilizing similar gas analyzer and pneumotach technology validated in Aerosport's TEEM 100 portable metabolic system [11]. Using a single 2-hr Nicad battery, the KB1-C system was light enough to wear on a vest while climbing (2.1 kg, which included the telemetry HR system) which truly allowed subjects to move freely over the treadmill surface. Based upon feedback from subjects after testing, the equipment worn during testing did not pose a limitation to climbing freely on the treadmill. A calibrated three-liter syringe (Model D, Sensor Medics Corporation, Yorba Linda, CA USA) was used to calibrate the KB1-C pneumotach for ventilation measurement, and the oxygen and carbon dioxide analyzers were calibrated using certified gases of known concentrations. Calibration of the KB1-C system immediately preceded each test session for every subject. Measurements by the KB1-C include that of HR via telemetry from a strap worn around the chest and a receiver connected to the body of the KB1-C. All measures were recorded over one-minute sample intervals and downloaded at the end of each test. Calibration and maintenance of the KB1-C system followed the guidelines established by the manufacturer.

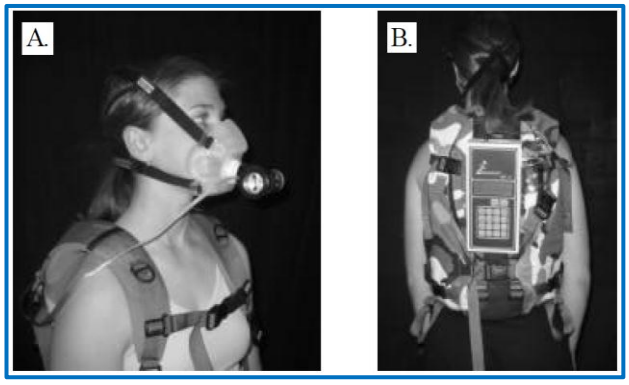


Figure1. Portable metabolic measurement system used to assess cardiovascular and metabolic responses to motorized treadmill climbing. First image (A) shows the face mask and attached pneumotach for the measurement of minute ventilation and expired gas sampling, while the second image (B) shows the system attached to the outside of a hydration backpack.

2.4 Data Processing

The last three mins of VO_2, VCO_2, and HR data for each climbing condition for each subject were averaged for subsequent calculations and data summarization. Measures of absolute VO_2 (L/min), for instance, were converted to relative VO_2 (ml/kg/min) using total mass (M_T, kg) for each subject (i.e., MB + climbing shoes + data collection equipment), as well as metabolic equivalents (METs = Relative VO_2 / 3.5). Measures of VO_2 and VCO_2 were converted to energy expenditure (EE) using Weir's equation [12]: EE (kcals/min) = $3.9xVO_2 + 1.1xVCO_2$, where measures of VO_2 and VCO_2 were in L/min. Finally, HR% for each subject during each climbing condition was computed as HR% = (HR/APMHR)x 100, where HR was the mean HR for that condition and APMHR was the age-predicted maximum HR calculated as 220-Age.

3. Statistical Analyses

Summary statistics were computed as means and standard deviations for all measured (HR, VO_2, VCO_2) and computed (relative VO_2, METs, HR%, EE) variables of interest. In addition, simple linear regression and correlations were used to describe relationships between HR and VO_2. One-sample t-tests were used to compare mean HR% and MET values at each test condition to the published intensity thresholds – i.e., 65% of HR%, as well as 3 and 6 METs for moderate and vigorous intensity.

Reliability. Intraclass reliability (ICC) for internal consistency was computed for measures of VO_2, VCO_2, and HR over the last three minutes of each five-minute bout of climbing using a two-factor repeated measures ANOVA [13]. In addition, intraclass reliability for stability (i.e., test-retest on separate days) was assessed using a subsample of subjects (n = 3) who returned for a second visit to repeat all aspects of data collection for either the second or third visit. Stability reliability was then assessed using a two-factor repeated measures ANOVA [13].

Regression Analyses. Computed values of EE (kcals/min) for each of the six conditions from each subject were treated as independent observations using standard step-forward multiple regression analysis procedures [14]. Prediction equations were

derived from a pool of possible independent variables that included treadmill speed ($m \cdot min^{-1}$), treadmill inclination (degrees), and total mass of the subjects (M_T, kg), and gender (coded "0" for women and "1" for men). The significance of each potential independent variable, as well as potential interaction variables, were verified with partial F-tests at the 0.15 alpha level [14] while the overall model significance was evaluated at the 0.05 alpha level.

The determination of a final regression model for predicting EE was a three-step process. The first step involved using 80% of the available observations to develop a *validation model*, while the second step used the remaining 20% of available observations to *cross-validate* the validation model. Observations from the cross-validation sample were used to create predicted EE values that were then compared to the computed EE values using paired t-tests, Pearson product moment correlations, the standard error of the estimate (SEE), as well as a total error term. A comparison of the SEE and the total error terms, which are used to evaluate prediction bias, were performed as described previously [15]. The third and last step involved pooling the observations from both the validation and cross-validation groups to create a *final regression model.*

The final regression model was evaluated further using the PRESS cross-validation technique described in detail by Holiday et al. [16]. The PRESS technique was used by the present study to compliment the cross-validation procedures described above by providing cross-validation statistics on the final regression model without data-splitting. The PRESS technique results in the familiar multiple correlation (R) and standard error of the estimate (SEE) statistics, but the PRESS equivalents (hereafter referred to as R_P and SEE_P, respectively) tend to be more conservative (i.e., less optimistic) than their non-PRESS counterparts. Thus, the PRESS statistics (R_P and SEE_P) are generally considered to provide a better reflection of the expected accuracy of the final regression model when applied to data samples with which it was not originally derived. All statistical analyses were performed using the software package Statistica Version 7.1 (Statsoft, Inc., Tulsa, OK, USA) and the 0.05 alpha level unless otherwise stated.

4. Results

4.1 Descriptive summary

Twenty-one subjects were originally recruited for this study, but one subject became sick after the first testing visit and was not able to complete the second test session. A summary of demographic measures for the remaining 20 subjects (16 men, 4 women) is provided in Table 1. In general, the subjects were relatively young (20-34 years of age) and all were classified as "normal" according to their BMI [10]. The climbing questionnaire data for these subjects revealed that 53% (n=10) considered their outdoor climbing skill level to be "Advanced", 32% (n=6) considered their skill level to be "Intermediate", while "Beginner" best described the skill level of the remaining subjects. Using a seven-point Likert-scale (1 = inexperienced, 7 = extremely experienced), subjects self-rated their climbing experience as (Mean±SD) 4.8±1.5 with a range of 1 to 7. Lastly, subjects reported that 73.2±24.6% of their climbing time (training and actual climbing) was performed outdoors, while the remaining time (26.7±24.6%) was spent indoors on climbing walls. Six subjects reported using a climbing treadmill on a regular basis.

The intraclass reliability (ICC values) for VO_2, VCO_2, and HR across mins 3-5 ranged from 0.883 (for the fastest speed and steepest grade) to 0.964 (for the slowest speed and easiest grade), while the test-retest reliability was 0.901. Thus, all reliability values were considered sufficiently high to justify the averaging of VO_2, VCO_2, and HR values for subsequent summarization and regression analyses. However, despite the high reliability for these pooled data, a preliminary residual analysis during regression modeling identified four outlier observations, all of which corresponded to the most difficult climbing condition (fastest speed and steepest incline) for four different subjects. Further inspection of these four data points revealed that the subjects were, in fact, not at a steady-state (i.e., progressive increase in VO_2 and HR from minutes 3 to 5). As a result, these four

observations were removed from the data pool which dropped the total number of observations from 120 to 116 for all subsequent analyses.

Table 2 provides a descriptive summary of variables for this final data set (n=116 observations) by treadmill speed and grade for HR, VO_2, and EE for each of the six climbing conditions.

Interestingly, mean HR% at each condition (70.0-85.4%) was statistically higher (P<0.001) than the 65% threshold value for each testing condition. Similarly, mean MET values across testing conditions (6.0-8.5 METs) were all statistically greater than or equal to the 6 MET threshold value.

Table 1: Summary of demographic measures for local sample of recreational climbers. All values expressed as Mean±SD.

Subjects	Age (years)	Body Mass (kg)	Body Height (cms)	BMI (kg/m^2)
Women (n=4)	24±3	61.4±5.8	162.0±7.5	23.4±1.9
Men (n=16)	25±5	72.7±6.4	179.7±5.9	22.5±1.4
All Subjects (n=20)	25±4	70.5±7.6	176.3±9.3	22.7±1.5

4.2 HR-VO_2 relationship

A scatterplot of all mean HR and relative VO_2 values from all six test conditions is shown in Figure 2. After categorizing the data according to grade (i.e., negative, vertical, or positive), there was no statistical difference between slopes for the regression lines between HR and VO_2. As a result, a single regression line was fit to collectively describe the HR-VO_2 relationship for all test conditions: HR (BPM) = 59.0 + 3.70xVO_2 (R^2=0.75, SEE= ±13.5 BPM).

4.3 Regression analyses

After randomly selecting 80% of the 116 observations (n=93), the best fitting equation for predicting absolute EE was given as follows (R^2 = 0.80; SEE = ±0.867; Model P-value<0.001):

(1) EE (kcals/min) = 0.7514×SPD + 0.1174×GRD + 0.1308xM_T + 0.8503xG – 16.45

where SPD is treadmill climbing speed (m/min), GRD is treadmill grade (degrees), M_T is total mass (kg), and G is a gender term coded "0" for women and "1" for men. All variables entered the model independently (i.e., no interactions), significantly (P<0.001), and without covariance with other variables in the model. Using the remaining observations (n=23) to cross-validate the validation model (Equation 1), the mean predicted EE (9.10±1.9 kcals/min) did not differ significantly (P=0.28) from the actual EE (9.2±2.7 kcals/min), as well as there being a high correlation between these two variables (r=0.93; P<0.001). In addition, the difference between the SEE of ±0.867 kcals/min and the total error term of ±0.871 kcals/min was almost zero which indicates a lack of EE prediction bias in the cross-validation group. Collectively, these cross-validation results indicate that the validation model was stabile within a sample of observations not originally used to develop the validation model. Thus, the entire sample of available observations (n=116) was then used to derive the final regression model as shown in Table 3. The computational form of the final EE prediction model is given as Equation 2 (R^2 = 0.81; SEE = ±0.827 kcals/min; P<0.001):

(2) EE (kcals/min) = 0.7177×SPD + 0.1149×GRD + 0.1344xM_T + 0.775xG – 16.173

Again, all variables entered the above model independently (i.e., no interactions), significantly (P<0.001), and without covariance with other variables in the model. A scatterplot of measured versus predicted EE values (Figure 1) shows an even scatter about the line-of-identity for both men and women which indicates good overall prediction by Equation 2. Finally, the PRESS residuals were computed as R_P^2 = 0.78 and SEE_P = ±0.840 kcals/min for Equation 2. The PRESS statistics for the final model shows less accuracy (i.e., lower R and higher SEE), as expected, since these statistics are supposed to represent realistic values of accuracy to expect for use of the full prediction models (Equation 2) in a field setting.

The standardized regression coefficients for the final model, or β-weights (Table 3), are used to indicate the importance of that variable in determining differences in EE between observations. The β-weights in Table 3 indicate that both treadmill speed (β-weight = 0.641) and total mass (β-weight = +0.523) were more significant predictors of energy expenditure during treadmill climbing than was either treadmill grade (β-weight = +0.428) or gender (β-weight = +0.169). Lastly, to test the assumption of independence on repeated measurements, the final regression model was reevaluated with an additional independent variable that treated repeated measures (those derived from the same subjects) as a cluster of nominal scale variables [17]. In the presence of the other independent variables (treadmill speed and incline, total mass, and gender), this cluster of variables did not explain a significant proportion of additional variability (change in R^2 < +0.01) and was thus dropped from the analyses.

The same analytical procedures described above were then applied to predicting METs using the same collection of independent variables, the same validation and cross-validation analyses, as well as generation of a final METs regression model and PRESS statistics. While the results for the final regression model are given in Table 4, the computational form of the final regression model for predicting METs given as Equation 3 (R^2 = 0.73; SEE = ±0.616; P<0.001):

(2) METs = 0.5659×SPD + 0.08878×GRD + 0.716xG – 5.038

where variables SPD, GRD, and G are defined the same as that for Equations 1 and 2. Applying the PRESS technique again resulted in more conservative estimates of both R^2 (R_P^2 = 0.70) and SEE (SEE_P = ±0.638), all of which are summarized in Table 4.

Table 2. Descriptive statistics for cardiovascular and energy expenditure variables from six treadmill climbing conditions: Three treadmill grades at each of two treadmill speeds. All values expressed as Mean±SD (Range).

	"Negative" Inclines of 80º or 85º		**Vertical Incline of 90º**		**"Positive" Inclines of 95º or 100º**	
Variable	**"Slow" Speed**	**"Fast" Speed**	**"Slow" Speed**	**"Fast" Speed**	**"Slow" Speed**	**"Fast" Speed**
Treadmill Speed (m/min)	6.0	9.1	4.6	7.6	4.6	7.6
HR (BPM)	137±21 (99-182)	158±13 (126-174)	136±17 (109 –175)	163±17 (135-197)	156±15 (127-192)	167±14 (138-195)
HR%	70.2±10.2	81.0±5.9	70.0±8.2	83.2±8.4	80.0±7.1	85.4±6.0

(%)	(52.5-92.0)	(67.0-87.7)	(58-87.7)	(70.4-100)	(67.6-97.3)	(73.6-97.5)
VO_2 (L/min)	1.60±0.26 (1.1-2.2)	2.05±0.35 (1.4-2.5)	1.58±0.32 (1.0-2.0)	2.04±0.33 (1.3-2.5)	1.80±0.37 (1.1-2.3)	2.18±0.33 (1.5-2.9)
VO_2 (ml/kg/min)	21.7±2.2 (18.2-26.0)	27.8±2.3 (24.4-31.3)	21.1±2.6 (17.5-7.4)	27.8±2.5 (23.6-31.9)	24.0±2.4 (19.1-27.4)	29.8±2.7 (24.1-34.4)
METs	6.2±0.6 (5.2-7.4)	8.0±0.6 (7.0-9.0)	6.0±0.7 (5.0-7.4)	7.9±0.7 (6.7-9.1)	6.9±0.7 (5.5-11.5)	8.5±0.8 (6.9-9.8)
EE (kcals/min)	10.9±1.6 (7.7-14.3)	8.0±1.3 (5.4-10.8)	10.0±1.4 (7.3-12.4)	10.2±1.7 (6.7-12.7)	8.8±1.5 (5.4-11.4)	10.9±1.6 (7.7-14.3)

NOTES: HR is heart rate; HR% is HR expressed as a percent of age-predicted maximal HR; VO_2 is oxygen consumption; METs is metabolic equivalents (dimensionless); EE is absolute energy expenditure. Calculations of both relative VO_2 (ml/kg/min) and METs used the total mass (M_T, kg) for each subject, which included body mass and equipment mass.

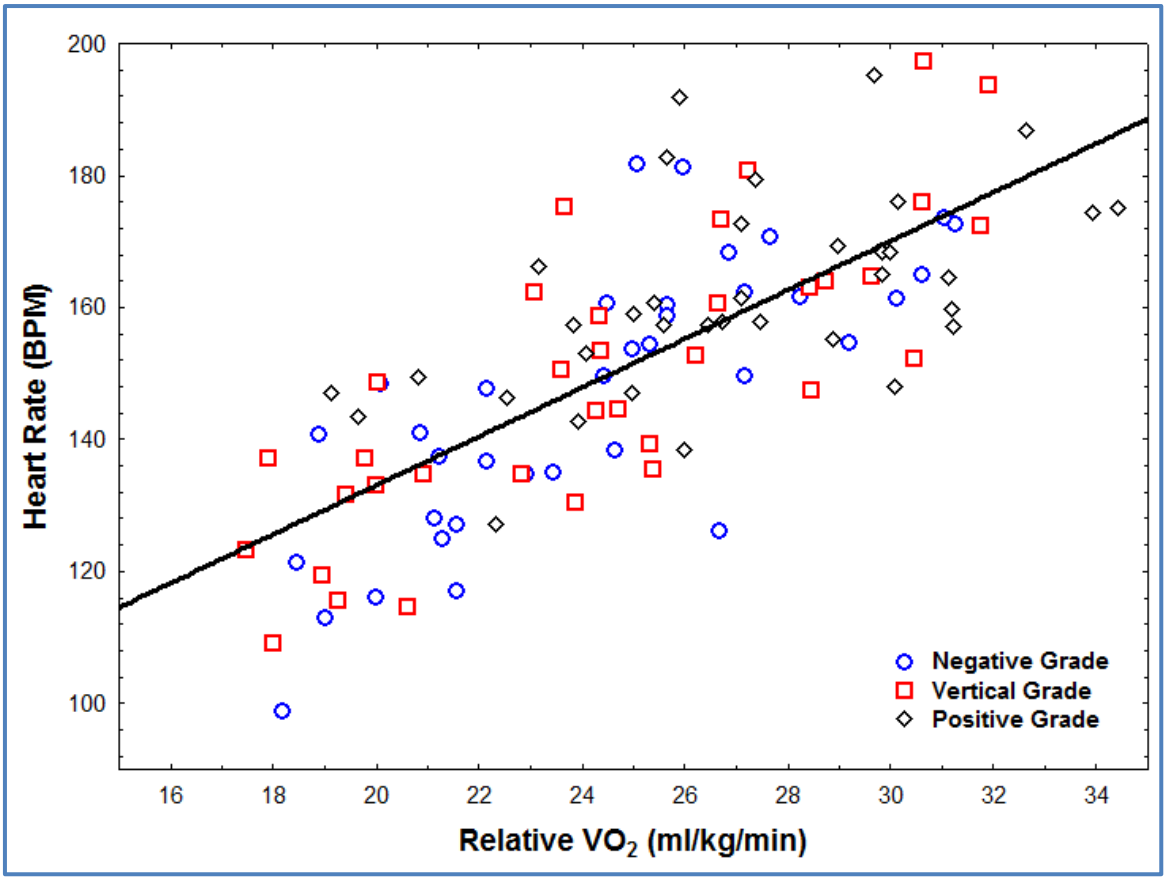


Figure 2. Observed relationship between steady-state heart rate and relative oxygen uptake across three categories of motorized treadmill grade – i.e., Negative, vertical, and positive – where each grade was tested at "slow" and "fast" treadmill speeds. The solid line is that of best fit for all observation pairs (n=116).

Table 3: Final regression model that predicts steady-state energy expenditure (kcals/min) from four variables: Climbing treadmill speed and grade, as well as total mass (body mass plus that of any equipment) and gender ("0" for women and "1" for men) of the climber. Other statistics provided include the 95% confidence interval for each model coefficient, the standardized regression coefficient (i.e., β Weight) for each independent variable, the significance for each predictor variable (P-values), as well as the summary statistics (R^2, SEE, R_P^2, SEE_P, and P-value) for the model itself.

Prediction Model Variable	**Model Coefficient (β)**	**β Weights**	**P-Value**
Intercept	-16.173		P<0.001
Climbing Treadmill Speed (m/min)	+0.718	*+0.641*	P<0.001
Climbing Treadmill Grade (degrees)	+0.115	*+0.428*	P<0.001
Total Mass (kg)	0.134	*+0.523*	P<0.001
Gender	0.775	*+0.169*	P=0.001
R^2 = 0.81	**R_P^2** = 0.78		
SEE = ±0.827	**SEE_P** = ±0.840		
Model P-Value = <0.001			

Table 4: Final regression model that predicts steady-state metabolic equivalents (METs) from three variables: Climbing treadmill speed and grade, as well as gender ("0" for women and "1" for men) of the climber. Other statistics provided include the 95% confidence interval for each model coefficient, the standardized regression coefficient (i.e., β Weight) for each independent variable, the significance for each predictor variable (P-values), as well as the summary statistics (R^2, SEE, R_P^2, SEE_P, and P-value) for the model itself.

Prediction Model Variable	**Model Coefficient (β)**	**β Weights**	**P-Value**
Intercept	-5.0378		P<0.001
Climbing Treadmill Speed (m/min)	+0.566	*+0.808*	P<0.001
Climbing Treadmill Grade (degrees)	+0.0888	*+0.528*	P<0.001
Gender	0.716	*+0.250*	P<0.001
R^2 = 0.73	**R_P^2** = 0.70		
SEE = ±0.616	**SEE_P** = ±0.638		
Model P-Value < 0.001			

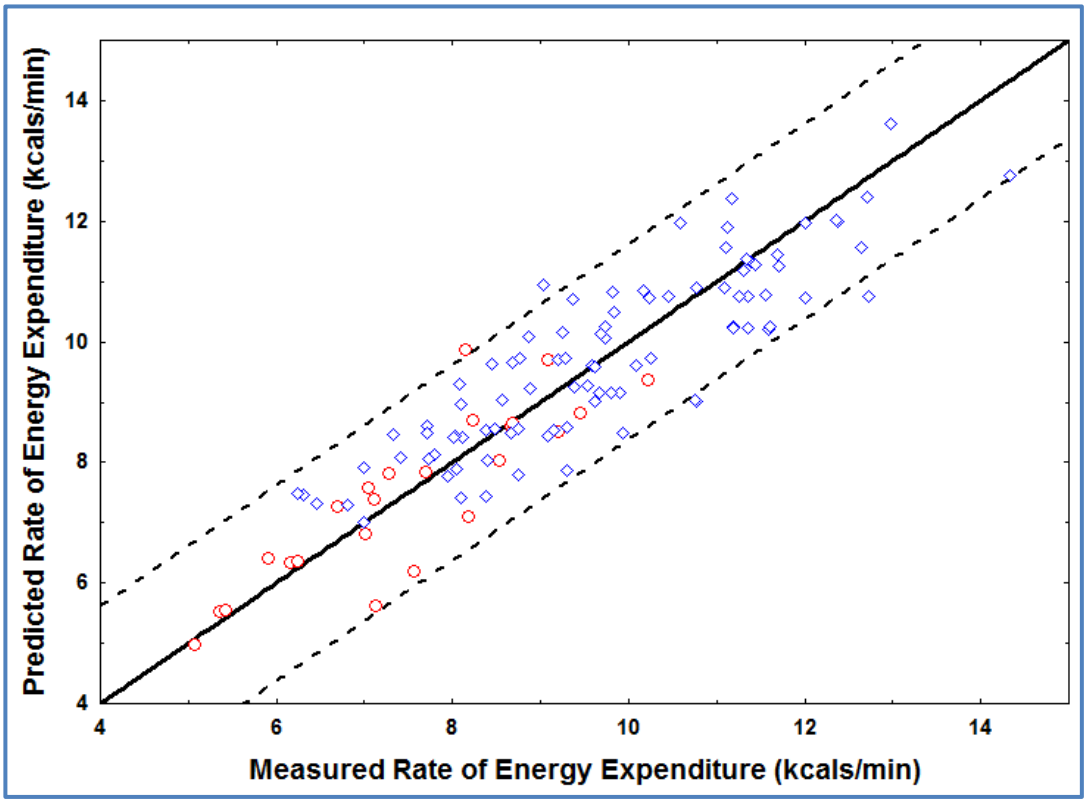


Figure 3. Relationship between measured and predicted rates of steady-state energy expenditure whilst using a climbing treadmill (n=116). The solid line is the line-of-identity and best-fit-regression line, while the upper and lower bounds of the 95% prediction interval around the regression line are shown as dashed lines. Finally, open diamonds (blue in color)) represent observed values for men and open circles (red in color) are those for women.

5. Discussion

The present study sought to characterize the cardiovascular and metabolic responses of a relatively unique form of indoor rock climbing – i.e., motorized treadmill climbing - within a group of local recreational climbers. Using treadmill inclines between 80º and 100º (where 90º was vertical; <90º was considered a "negative" incline; >90º was considered a "positive" incline), as well as treadmill speeds between 4.6 and 9.1 m/min, mean HR% responses for each of the six test conditions (70.0-83.2%; Table 2) easily exceeded the 65% threshold used to promote improved cardiovascular fitness for healthy adults [10]. Further, the aerobic metabolic demands of steady-state climbing at these test conditions was unexpectedly high: All mean MET values (6.0-8.5 METs; Table 2) were ≥6 METs, which means that nearly all test conditions were classified as "vigorous" intensity for nearly all subjects. Given that an underlying goal for the treadmill's speed and grade assignments was to elicit a range of both moderate and vigorous metabolic responses, the metabolic responses for this study were collectively higher than expected. These results suggest that proscribing the use of a motorized climbing treadmill for lower MET intensities will require easier combination of treadmill speed and grade than that tested in the current study. For example, using the easiest grade (115º, or +20º past vertical) and slowest speed (0.5 m/min) for the climbing treadmill used in this study as MET prediction inputs, Equation 3 predicts an average MET intensity at 5.8 METs, which is the high end of what is considered moderate intensity. While these results support the proscribed use of motorized treadmill climbing to promote both cardiovascular and metabolic fitness, the activity itself may be too intense for those at the lowest end of the aerobic fitness spectrum (i.e., those needing

PAs proscribed at <6 METs). As such, motorized treadmill climbing may be best suited for those people who are already capable of sustained vigorous intensity (≥6.0 METs) aerobic exercise.

There were several unique methodological characteristics about this study worth noting. First, in contrast to several other reports [18-20], the present study was able to use a relatively diverse group of climbers with respect to climbing experience. Though four observations were removed from the final analysis due to lack of a steady-state responses, the remaining observations did not appear to adversely influence the accuracy of the assessment or prediction of energy expenditure. Second, unlike many studies that have used fixed routes for climbers to follow on indoor climbing walls or outdoor rock faces [18-20], the present study allowed climbers to roam freely over the entire available climbing surface. Collectively, these methodological characteristics should support the generalizability of the final regression equations' ability to predict energy expenditure (Equation 2) or METs (Equation 3) in a diverse group of recreational and sport climbers that is not climbing route specific.

The most unique characteristic of this study, however, was the use of a motorized climbing treadmill. As with treadmills used for walking and running, a motorized climbing treadmill can control changes in both speed and grade such that a climber's pace, as well as cardiovascular and metabolic intensities, can be precisely controlled. The ability to control the climbing treadmill in this manner was thought to facilitate the subjects' ability to reach a steady-state, but these same characteristics also make it difficult to directly compare energy expenditure (EE, kcal·min^{-1}) values from the present study to those reported in the literature. For example, Watts and Drobish [20] assessed both VO_2 and EE for climbers using a non-motorized climbing treadmill. These types of treadmills allow for the precise control of grade but not speed because the weight of the climber is used to advance the treadmill surface. As such, the actual climbing speed is controlled by each climber. Thus, Watts and Drobish report mean relative VO_2 and EE values of 29.5-31.7 ml·kg^{-1}·min^{-1} and 10.4-11.2 kcal·min^{-1}, respectively, for grades of 80-102°, but the speed of ascent was described simply as self-selected. These values are similar to the mean relative VO_2 of 29.78 ml·kg^{-1}·min^{-1} and 10.90 kcal·min^{-1} reported for the present study (Table 1) during the most difficult combination of speed and grade. Relative VO_2 has also been reported for experienced rock climbers using fixed routes on three inclines (90°, 106°, 151°) on an indoor climbing wall [19]. For the 90° incline the climbers averaged 20.7 ml·kg^{-1}·min^{-1} which is similar to the 21.67 ml·kg^{-1}·min^{-1} mean VO_2 value reported in Table 1 for slow-paced climbing (4.6 m/min) at 90°, but is much lower than the 27.78 ml·kg^{-1}·min^{-1} value reported for fast-paced climbing (7.6 m/min) at the same grade. Thus, without knowing the *climbing speed* associated with each test condition in these studies, a direct comparison of metabolic intensity values with those in the present study are impossible. However, the development of prediction equations by the present investigation provides a basis for comparing levels of steady-state energy expenditure for various forms of climbing (i.e., outdoor, indoor, and climbing treadmills) given that total mass, grade of pitch, and speed of ascent are known.

One comparison that is possible with other studies is the apparent disassociation of VO_2 and heart rate (HR) responses as compared with traditional large muscle group dynamic activities – e.g., walking, running, and bicycling. Using the fitted line in Figure 2, for example, a mean change in VO_2 from 20 to 30 ml/kg/min corresponded to a large change in mean HR of +37 BPM (133 to 170 BPM). Additional support for this observation is found in Table 2. Specifically, the mean change (Δ) in relative VO_2 between slow and fast "positive" and "negative" grade conditions were nearly identical (ΔVO_2 = 5.8 and 6.1 ml/kg/min, respectively), yet the mean change in HR for the "negative" incline (ΔHR = 21 BPM) was nearly double that of the "positive" incline (ΔHR = 11 BPM). Assuming the negative incline grades caused much stronger static muscular contractions for musculature of the hands and upper body [19-23], these observations were expected because of the additive demand on the cardiovascular system from both high intensity statically contracting muscles (upper body) and

lower intensity dynamically contracting muscles (lower body). Indeed, previous researchers [19,20,23] have pointed out the disproportionately higher values of HR relative to observed VO_2 for climbers under every type of experimental setting (i.e., outdoor rock climbing; indoor climbing walls and bouldering; non-motorized climbing treadmills). What these observations also suggest is that the high %HR values reported in Table 2 are actually a result of the classic combined pressor response [22] rather than that of traditional aerobic exercise. Therefore, the traditional use of HR for prescribing intensities of aerobic exercise should not be used with motorized treadmill climbing since the HR-VO_2 relationship is not the same as that upon which the principles of prescription were originally based [10]. The alternative, of course, could be to use Equations 2 or 3 from the present investigation to prescribe motorized treadmill climbing intensity according to desired rates of energy expenditure or MET levels.

The present study findings may be used in exercise prescription applications where use of motorized treadmill climbing is an available form of physical activity. It has been suggested previously that rock climbing is probably not the best choice of exercise for those interested in the development of cardiovascular fitness [20]. The rationale, however, was that extreme localized fatigue of the finger and wrist flexor muscles often associated with outdoor and indoor forms of rock climbing often limits single bouts of climbing to <5-10 minutes. To counter this limitation, motorized climbing treadmill can adjust both speed and grade to the needs and the abilities of the climber. For example, the better climbers in our subject pool could easily maintain the 80-90° inclines (i.e., "negative grades) at slower speeds for 10-20 mins, but the least fit subjects would need 95-100° inclines (i.e., "positive" inclines) to achieve the same climbing time. Lastly, it should be noted that the ability of any form of simulated rock climbing to actually *change* cardiovascular fitness has never been documented in the research literature and is certainly worth investigating in the future.

6. Conclusions

This study appears to be the first study to characterize both cardiovascular and metabolic responses to motorized treadmill climbing. Specifically, these data were used to generate predictions equations for both the absolute rate of energy expenditure (kcals/min), as well as METs, using a collection of independent variables that included both treadmill speed and grade. These equations, in turn, can be used for developing exercise prescription plans, develop testing protocols for future studies, or possibly predicting the energy cost or metabolic intensity of specific indoor or outdoor rock climbing routes. This study also found that measured heart rate tended to be higher than would be expected for the range of metabolic intensities observed because of the combined static and dynamic pressor response. This latter observation also suggests that traditional methods of prescribing aerobic exercise by heart rate should not be used with motorized treadmill climbing for any skill level of climbers. Future studies may want to focus on increasing the range of treadmill grades evaluated by the current study (80-100º), as well as using motorized treadmill climbing to test climbing-specific maximal VO_2 (VO_{2MAX}) or as a training modality to improve climbing economy.

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Competing Interests:

The authors declare that they have no competing interests.

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