Quantitative Model of Sustained Physical Task Duration at Varying Altitudes

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ABSTRACT

BEIDLEMAN, B. A., C. S. FULCO, M. J. BULLER, S. P. ANDREW, J. E. STAAB, and S. R. MUZA. Quantitative Model of Sustained Physical Task Duration at Varying Altitudes. *Med. Sci. Sports Exerc.*, Vol. 48, No. 2, pp. 323–330, 2016. **Purpose**: The objective of this study is to develop a quantitative model that can be used before ascent to altitude (ALT) to predict how much longer a sustained physical task would take for unacclimatized individuals in the early hours of exposure. **Methods**: Using multiple linear regression, we analyzed time-trial (TT) performance on 95 unacclimatized men (n = 83) and women (n = 12) at sea level (SL) and at an ALT ranging from 2500 to 4300 m. The TT was initiated within 4 h of ascent to ALT. The independent variables known before ascent were as follows: ALT, age, height, weight, sex, SL peak oxygen uptake, SL task duration time, and body mass index (BMI) classification (normal weight vs overweight). The dependent variable was the percent increase in TT duration from SL to ALT. **Results**: The most significant factor in the model was ALT (P = 0.0001), followed by BMI classification (P = 0.0009) and the interaction between BMI classification and ALT (P = 0.003). The model is as follows: percent increase in TT duration = $[100 + e^{(-1.517+1.323\ (\mathrm{ALT})+3.124\ (\mathrm{BMI\ class})-0.769\ (\mathrm{ALT})\ (\mathrm{BMI\ class}))}]$. The percent increase in TT duration in overweight individuals was 129% greater than for normal-weight individuals at 3000 m. However, as ALT increased beyond 3000 m, the disparity between groups decreased until 4050 m where the percent increase in TT duration became greater for normal-weight individuals. **Conclusions**: This model provides the first quantitative estimates of the percent increase in sustained physical task duration during initial exposure to a wide range of elevations. Because only two easily obtainable factors are required as inputs for the model (ALT and BMI classification), this model can be used by many unacclimatized individuals to better plan their activities at ALT. **Key Words:** HYPOXIA, HYPOBARIC HYPOXIA, ALGORITHM, ENDURANCE PERFORMANCE, SUBMAXIMAL EXERCISE, UNACCLIMATIZED LOWLANDERS

Physical tasks requiring sustained effort take longer to complete at altitudes (ALT) greater than approximately 600 m than they do at sea level (SL) (6–8,10,20). General factors such as increased elevation and less acclimatization increase the time it takes to complete a given physical task at ALT because of less oxygen transport to the working muscles (14). Previously published tables and graphs depict the relationship between increased elevation and increased physical task durations in *acclimatized athletes* after several days to weeks of ALT residence (14,17), but this information may not apply to *unacclimatized normal fitness-level individuals* during the early hours of ALT exposure.

It is well known that endurance performance improves dramatically with ALT acclimatization (15,21,26), and as such, previous estimates of the increase in physical task durations at ALT in *acclimatized* individuals may be underestimated in *unacclimatized* individuals after rapid ascent (17). Furthermore, these previous estimates did not take into account or control potentially important confounding factors such as age, fitness level, body mass index (BMI), ALT residence, gender, hydration status, environmental conditions, and medication use (14). Lastly, these estimates require interpolation and are not readily available in an easy-to-use or applicable format for the general population.

Given that more than 100 million *unacclimatized* normal fitness level individuals visit ALT on an annual basis (30) and the military is increasingly deployed to high ALT environments (33), there is a critical need for a universal prediction equation that accurately estimates increases in physical task durations after rapid ascent to a wide range of ALT. Such an equation would also provide military personnel, ALT workers, climbers, and search and rescue teams with a planning tool to coordinate missions, rest breaks, and personnel such that physical tasks can be completed safely and effectively at ALT. In addition, by developing an equation using easily obtainable demographics known *before ascent*,

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it can be universally applied to a large number of people that have little to no ALT experience or access to sophisticated equipment to measure individualized physiologic parameters.

The purpose of this study, therefore, was to develop the first quantitative predictive model of the increase in sustained physical task duration in unacclimatized lowlanders after rapid ascent to a wide range of ALT. Our approach was to use time-trial (TT) tests of various durations, in which men and women completed a given amount of work as fast as possible both at SL and within the first 4–8 h of exposure to various elevations, as a reliable measure of a sustained physical task duration (23). This goal was accomplished using the U.S. Army Research Institute of Environmental Medicine (USARIEM) Mountain Medicine database, which contained individual ascent profiles, easily obtainable demographics known before ascent, and TT duration data from six similarly designed and experimentally controlled studies.

METHODS

Combined studies overview. TT tests were completed at SL (50 m) at the USARIEM on 95 SL residents (83 men and 12 women) who also had no ALT exposure in at least the previous 3 months before testing. An additional TT test was completed by each individual at a given fixed ALT (2500–4300 m) after *rapid* ascent (<2 h). All individuals initiated the TT within the first 4 h of exposure to ALT and completed the TT test within the first 8 h of exposure. None of the test volunteers demonstrated acute mountain sickness (AMS) as defined as an AMS-C score ≥0.7 from the Environmental Symptoms Questionnaire (34) before beginning the TT. Ten of the volunteers (six at 4300 m, three at 4000 m, and one at 3000 m) demonstrated mild AMS when measured 60 min after the completion of the TT.

Three studies were conducted under natural terrestrial conditions in Colorado Springs, CO, at the USARIEM Pikes Peak facility (4300 m), and three were conducted in the USARIEM hypobaric chamber in Natick, MA, at various simulated ALT (2500–4300 m). Normobaric hypoxia studies were not used because of differences in physical performance between normobaric and hypobaric hypoxia (4). Recruiting practices were the same for all six research studies, and none of the volunteers participated in more than one study. Ascent times for the hypobaric chamber studies were more rapid (<15 min) than the ascent times for the terrestrial studies (<2 h). All TT testing was conducted on lowlanders under similar experimentally controlled conditions that included no medication use, adequate hydration, at least 24 h of no physical activity before the TT, and controlled ambient temperature and humidity.

Study population/independent variables. All 95 volunteers received medical examination before participation, and none had a preexisting medical condition that warranted their exclusion. Each participated in the study after giving their free and informed voluntary consent. The studies were approved by the Institutional Review Board of the USARIEM in Natick, MA, and conform to the Declaration of Helsinki. Investigators adhered to the policies for protection of human subjects as prescribed in DOD Instruction 3216.02, and the research was conducted in adherence to the provisions of 32 CFR Part 219.

Table 1 contains the mean, SD, and range of the independent variables from the overall study population used to develop the prediction model for the percent increase in physical task duration going from SL to ALT. Age (yr), ALT (km), height (ht), weight (wt), BMI, SL peak oxygen uptake ($\dot{V}O_{2peak}$), sex (men or women), SL task duration (min), smoking status (current smoker vs nonsmoker [>3 months]), race (white vs nonwhite), BMI classification (normal weight vs overweight), fitness classification (regular fit vs high fit), age classification (younger vs older), and SL task duration classification (shorter vs longer) were considered as potential predictor variables in the model.

Table 2 contains the breakdown of different classification variables at various ALT. Women represented 12.6% of the data set with a distribution of 10%–21% across ALT, and sex was considered in the development of the prediction equation. Smokers represented only 9.5% of the data set and demonstrated an unequal distribution across ALT with several ALT containing no smokers. Therefore, smoking status was not considered in the prediction equation. Nonwhites represented 20.0% of the data set with an empty cell at 4000 m, and the distribution of nonwhites was highly skewed with most exposed to the highest ALT (i.e., 4300 m). Therefore, race was not considered in the prediction equation. BMI classification, fitness classification, age classification, and SL task duration classification were equally distributed across the

TABLE 1. Characteristics of 95 unacclimatized men (n = 83) and women (n = 12) used to develop the prediction model of the percent increase in sustained physical task duration going from SL to ALT.

Variable	Mean	SD	Min	Max
Age (yr)	22.6	4.3	18	37
Weight (kg)	78.9	11.9	48.5	113.3
Height (cm)	176.3	7.5	148	192
BMI (kg·m^{-2})	25.3	3.1	19.7	34.6
ALT (km)	3.627	0.697	2.503	4.276
SL peak oxygen uptake (mL·min^{-1}·kg^{-1})	46.7	7.7	30.0	65.9
Sex (%)				
Men	88.4			
Women	12.6			
Smoking status (%)				
Smokers	9.5			
Nonsmokers	91.5			
Race (%)				
Whites	80.0			
Nonwhites	20.0			
BMI classification (%)				
Normal weight (≤25 kg·m^{-2})	51.6			
Overweight (>25 kg·m^{-2})	48.4			
Fitness classification (%)				
Regular (≤45 mL·min^{-1}·kg^{-1})	43.2			
High (>45 mL·min^{-1}·kg^{-1})	66.8			
Age classification (%)				
Younger (≤30 yr)	75.8			
Older (>30 yr)	24.2			
SL task duration classification (%)				
Shorter (≤60 min)	40.0			
Longer (>60 min)	60.0			

MIN, minimum; MAX, maximum.

TABLE 2. Percentage breakdown of the classification variables for the 95 unacclimatized men (*n* = 83) and women (*n* = 12) exposed to the various ALT.

	ALT (m)				
Variable	**2500 (*n* = 16)**	**3000 (*n* = 19)**	**3500 (*n* = 10)**	**4000 (*n* = 10)**	**4300 (*n* = 40)**
Sex (%)					
Men	81.2	79.0	90.0	90.0	90.0
Women	18.8	21.0	10.0	10.0	10.0
Smoking status (%)					
Smokers	0	21.0	0	0	12.5
Nonsmokers	100	79.0	100	100	87.5
Race (%)					
Whites	75.0	89.4	80.0	100	75.0
Nonwhites	25.0	10.6	20.0	0	25.0
BMI classification (%)					
Normal weight ($\leq$25 kg·m^{-2})	62.5	31.6	60.0	50.0	55.0
Overweight (>25 kg·m^{-2})	37.5	68.4	40.0	50.0	45.0
Fitness classification (%)					
Regular fit ($\leq$45 mL·min^{-1}·kg^{-1})	62.5	52.7	40.0	20.0	39.0
High fit (>45 mL·min^{-1}·kg^{-1})	37.5	47.3	60.0	80.0	61.0
Age classification (%)					
Younger ($\leq$30 yr)	81.2	89.4	80.0	70.0	90.0
Older (>30 yr)	18.8	10.6	20.0	30.0	10.0
SL task duration classification (%)					
Shorter ($\leq$60 min)	5.3	52.6	20.0	50.0	50.0
Longer (>60 min)	88.2	47.4	80.0	50.0	50.0

ALT. Age, Ht, Wt, ALT, BMI, SL task duration, and SL $\dot{V}O_{2peak}$ met all the assumptions for a normal distribution and were considered in the development of the prediction model. Given that some of the variables contained redundant information (e.g., Ht, Wt, BMI, and BMI classification), correlational analyses were run to determine which variables had the highest correlation with the dependent variable before inclusion in the model. Out of the 14 original variables considered in model development, the independent variables included in the model development phase before regression analysis consisted of three continuous (ALT, age, and Ht) and four classification variables (sex, BMI classification, fitness classification, and SL task duration classification). Even though none of the volunteers exhibited AMS before beginning the TT, given that some developed AMS during the TT, the absence (AMS = 0) or presence of AMS (AMS = 1) after the TT was also included in the prediction model for a total of eight independent variables.

Peak oxygen uptake ($\dot{V}O_{2peak}$) was measured both at SL and ALT using an incremental progressive exercise bout to volitional exhaustion on an electromagnetically braked cycle ergometer. Volunteers pedaled at 70–100 rpm for 2 min at 50, 100, and 150 W, and then in 30-W increments thereafter until O_2 uptake failed to increase or they stopped the test despite strong encouragement. During the $\dot{V}O_{2peak}$ test, O_2 uptake via a metabolic cart (True Max 2400; ParvoMedics, Salt Lake City, UT) was continuously monitored. The results of the $\dot{V}O_{2peak}$ test were used to set the submaximal workloads before the TT test both at SL and ALT. Given that the purpose of the study was to develop an equation using easily obtainable demographics known *before ascent*, the ALT $\dot{V}O_{2peak}$ was not included in the development of the prediction model.

TT duration among the six studies was assessed using a bicycle ergometer (Excalibur; Lode BV, Groningen). Each TT was initiated within the first 4 h of exposure and preceded by steady-state exercise for 15 min at ~40% of ALT-specific $\dot{V}O_{2peak}$ followed by 15 min at ~60% of ALT-specific $\dot{V}O_{2peak}$. Each individual was then given a 5- to 10-min rest break before completing the TT, which consisted of 180 to 760 kJ of work as fast as possible depending on the study design. All volunteers underwent at least two familiarization sessions at SL to become accustomed to the TT. During the TT, the volunteers were free to manually increase or decrease the work rate or speed at any time and by any amount. Volunteers were continually informed of the work or distance completed but not the time elapsed during the TT. The volunteer's HR, arterial oxygen saturation (SaO_2), and RPE (5) was obtained every 5 min during the TT, and the mean was calculated.

Our laboratory coefficient of variation (CV) for this type of cycle TT from the second familiarization test at SL to the first experimental test at SL is 4.6% to 5.2% depending on the study (15). This CV is similar to the 3.4% CV previously reported for trained cyclists completing TT of similar durations (23).

BMI was calculated as weight (kg)/height (m^2). If an individual's BMI was $\leq$25 kg·m^{-2}, then he or she was classified as normal weight (BMI classification = 0). If the BMI was >25 kg·m^{-2}, then he or she was classified as overweight (BMI classification = 1), according to the current American College of Sports Medicine guidelines (2). If an individual's $\dot{V}O_{2peak}$ was $\leq$45 mL·min^{-1}·kg^{-1}, then he or she was classified as regular fit (fit = 0), and if >45 mL·min^{-1}·kg^{-1}, he or she was classified as high fit (fit = 1). If the SL task duration was $\leq$60 min, the physical task was considered shorter (task duration = 0), and if >60 min, the physical task was considered longer (task duration = 1). All classification variables were coded as dummy variables (either 0 or 1) in the multiple regression analysis.

Dependent variable. The percent increase in TT duration (presented as percent increase in task duration) for the same amount of work performed (bicycle ergometer) at ALT compared with SL was chosen as the dependent variable.

Statistical analysis. The percent increase in task duration from SL to ALT was log-transformed for data analysis to conform to normality assumptions *before* using multiple linear regression and PROC REG (SAS 9.2, Cary, NC). All subset regression as well as stepwise, forward, and backward regression models using entry and exit at the 0.10 level were developed with the data set and compared using subject matter expertise (29). Many different statistics were used to evaluate competing models including the coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), Mallows' C_p statistic, Akaike's information criteria, and Schwarz's Bayesian criteria (1,27,35). Most of these criteria are based on the assumption that you want to create a model that minimizes the unexplained variability (e.g., root mean square error (RMSE)) with the fewest number of variables possible. In choosing the final model, all four regression methods resulted in the same selection of independent variables. Pearson product–moment correlations (r), point biserial correlation coefficients (r_{pb}), and biserial correlation coefficients (r_b) were computed between continuous and dichotomous variables as appropriate. Statistical significance was set at $P < 0.05$. Data are presented as mean ± SD.

Model diagnostics for general linear models were performed to compare the data with the fitted model to highlight any discrepancies (29,36). Regression diagnostics included evaluating the model assumptions of normality with the Kolmogorov–Smirnov test, homoscedasticity with residual versus predicted plots, independence with the Durbin Watson statistic, and constant variance with the Spearman rank correlation coefficient. In addition, the model fit was evaluated using model-fitting statistics such as R^2, Akaike's information criteria, and Schwarz's Bayesian criteria. The presence of multicollinearity was examined using a variance inflation factor <10. Influential observations were evaluated with Studentized residuals <3 and Cook's D statistic $>4/n$, where n is the sample size. There were no systematic trends in the residuals that indicated a misspecified model.

Cross-validation of the model was conducted using Efron bootstrap resampling (9). The procedure is conducted as follows: 1) Given an observed set of data of size n, fit the model and obtain parameter estimates; 2) take a sample of size n from the observed data (with replacement) and call this the bootstrap sample; 3) using the bootstrap sample, fit the model developed in step 1 and obtain the parameter estimates; 4) go to step 2 and repeat 1000 times; 5) take the mean and SD of the 1000 estimates of the parameters, coefficient of determination, and RMSE. This SD is an estimate of the SE of these parameters (12).

The sample size was based on achieving good predictive ability with seven to eight predictor variables (25) and a 50% or greater coefficient of determination. Based on these values, a sample size of 85 subjects was needed for good predictive ability, and a sample size of 320 subjects was needed for excellent predictive ability. Although our coefficient of determination fell slightly below the 50% level, the number of subjects (n = 95) in our study still provides appropriate power for good predictions.

RESULTS

No difference in percent increase in task duration existed between those individuals who were tested either under natural terrestrial or hypobaric chamber environments. ALT (P = 0.0001), BMI classification (P = 0.0009), and the interaction between BMI classification and ALT (P = 0.003) were significant predictors of the percent increase in task duration from SL to ALT. There was no difference in the mean HR (bpm), SaO_2 (%), and RPE during the TT at SL between the normal-weight (165.3 ± 11.0, 96.4 ± 1.1, and 14.0 ± 2.8) and overweight (162.0 ± 17.3, 97.1 ± 1.1, and 14.5 ± 2.5) groups. There was also no difference in these variables during the TT at ALT between the normal-weight (153.1 ± 15.2, 79.8 ± 6.5, and 15.1 ± 2.4) and overweight (149.0 ± 17.7, 79.9 ± 6.7, and 15.4 ± 2.1) groups. Age, ht, sex, AMS classification, fitness classification, and SL task duration classification were not significant predictors in the model. Table 3 contains the parameter estimates, SE, parameter standardized estimates, R^2, adjusted R^2, and RMSE for the quantitative model of physical task duration at varying ALT. The current model accounted for 47.0% of the explained variability of the percent increase in sustained physical task duration at ALT.

Figure 1 shows that the sustained physical task duration was increased to a greater degree in normal-weight (threefold) compared with overweight (onefold) individuals per every 1-km increase in ALT. Calculations for threefold (e.g., 291%) increases in normal-weight individuals and onefold (e.g., 81%) increases in overweight individuals per 1-km increase in ALT are based on the following example: the

TABLE 3. Parameter estimates from the multiple regression model predicting the percent increase in sustained physical task duration at various ALT.

Variable	Parameter Estimate	Standardized Parameter Estimate	SE	Lower 95% Confidence Interval	Upper 95% Confidence Interval	P
Intercept	−1.632	0	0.618	−2.861	−0.0404	0.0098
ALT (km)	1.364	0.844	0.166	1.033	1.695	0.0001
BMI classification	3.144	1.403	0.916	1.325	4.963	0.0009
BMI classification * ALT	−0.773	−1.283	0.248	−1.266	−0.279	0.0025
R^2	0.470					
Adjusted R^2	0.452					
RMSE	0.833					

BMI classification, $<25\ \mathrm{kg \cdot m^{-2}}$ = normal weight and $\geq 25\ \mathrm{kg \cdot m^{-2}}$ = overweight. R^2, coefficient of determination; adjusted R^2, adjusted coefficient of determination. Example computation at 4000 m in an overweight (BMI classification = 1) individual is as follows: percent increase in sustained physical task duration = $100 + e^{[-1.632+(1.364*\ 4)+(3.144*1)-(0.773*4*1)]}$ = 148%. The parameter estimates are per 1-km (1000-m) increase in ALT. The RMSE when log-transformed is $e^{0.833}$, which equals 2.30%.

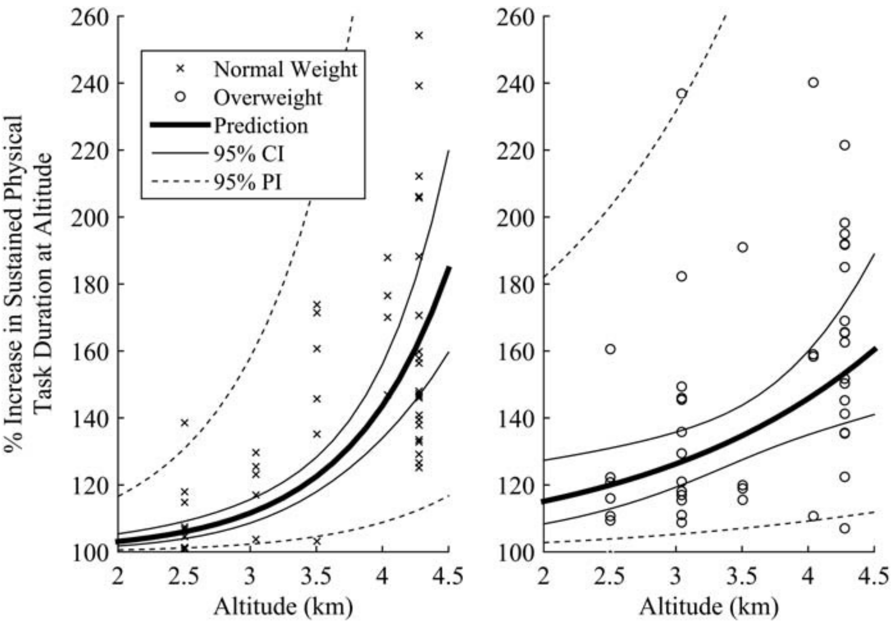

FIGURE 1—This figure demonstrates individual data and population predictions of the percent increase in sustained physical task duration from SL to a wide range of ALT after rapid ascent and a stay at a fixed ALT ranging from 2500 to 4500 m in unacclimatized male and female lowlanders possessing a wide range of fitness levels. The TT test, which was used to measure task duration, was initiated within 4 h of arrival to ALT and completed within 8 h of arrival to ALT. Normal-weight individuals ($\leq$25 kg·m^{-2}) demonstrated less percent increase in task duration at ALT than overweight individuals (>25 kg·m^{-2}) up to 4050 m ALT. However, above 4050 m, the percent increase in task duration became greater in normal-weight individuals. Age, ht, sex (male vs females), fitness classification (normal fit vs high fit), AMS classification (sick or not sick), and SL task duration time classification (shorter vs longer) were not significant predictors in the model.

percent increase in task duration in normal-weight individuals at 2000 m is 3.0% and at 3000 m is 12%, which amounts to an approximately threefold (291%) increase in the percent task duration per 1-km increase in ALT (3.0% + (3.0% × 2.91) = 12%). Conversely, for every 1-km decrease in ALT, task duration was decreased by 74% in normal-weight individuals and by 45% in overweight individuals. The percent increase in task duration in overweight individuals was 128% longer ($P = 0.0009$) than normal-weight individuals at 3000 m. However, as ALT increased beyond 3000 m, the disparity between groups decreased until 4050 m where the percent increase in task duration became greater for normal-weight individuals. There tended to be a significant negative relationship between BMI classification and fitness level classification ($r_b = -0.18$, $P = 0.08$). Internal (cross) validation of the model was conducted using Efron bootstrap resampling with replacement on 1000 bootstrap samples (9) (Table 4). The RMSE for the model (2.30%) and RMSE for the 1000 bootstrap samples (2.23%) were similar, indicating no evidence of model overfitting. The RMSE was also within the measurement error of a TT test (23).

DISCUSSION

This article presents the first quantitative predictive model that accurately determines the percent increase in sustained physical task duration that occurs within the first 8 h of exposure to a wide range of commonly ascended ALT in unacclimatized lowlanders. The strength of this model is that it requires knowledge of only two factors that can easily be obtained at SL before the actual ascent to any ALT. Once these factors (i.e., destination ALT and BMI classification) are inputted into the model, the percent increase in sustained task duration during subsequent exposure to any ALT can be easily calculated. Determining the actual duration of the task

TABLE 4. Parameter estimates from the Efron bootstrap multiple regression model using 1000 samples with replacement to predict the percent increase in sustained physical task duration at various ALT.

Variable	Bootstrap Parameter Estimate	Bootstrap Estimate of SE	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Intercept	−1.532	0.811	−3.122	0.058
ALT (km)	1.327	0.202	0.931	1.723
BMI classification	3.124	1.001	1.162	5.086
BMI classification * ALT	−0.770	0.256	−1.272	−0.268
R^2 ± SE	0.486 ± 0.078			
Adjusted R^2 ± SE	0.469 ± 0.066			
RMSE ± SE	0.806 ± 0.015			

BMI classification, <25 kg·m^{-2} = normal weight and $\geq$25 kg·m^{-2} = overweight. R^2, coefficient of determination; adjusted R^2, adjusted coefficient of determination. The parameter estimates are per 1-km (1000-m) increase in ALT. The RMSE when log-transformed equals $e^{0.846}$ = 2.23%. The bootstrap estimates of the SE for each parameter are based on running 1000 samples with replacement.

at ALT simply requires the time it takes to perform the task at SL be multiplied by the calculated percentage from the prediction model.

The predictive model can be used to determine task durations of varying length at many ALT for most unacclimatized men or women of any BMI who are either fit or unfit, and young or older (i.e., 18 to 37 yr). Additionally, the sustained physical task duration estimates for which the model has been internally validated range from 15 to 109 min, which is inclusive of many types of endurance tasks. This model therefore provides medical personnel, athletes, occupational workers, and military planners an effective means to accurately and safely plan for events, competitions, jobs, and mission-related activities requiring performance of sustained physical tasks of varying durations before ascent.

The most significant independent variable for predicting the percent increase in task duration was ALT. As individuals ascend to ALT, the inspired oxygen is reduced in direct proportion to the reduction in atmospheric barometric pressure resulting in a diminished rate of oxygen transport from the atmosphere to the cell (13). The result is a decline in $\dot{V}O_{2peak}$ and inability to maintain sustained efforts at the same absolute pace at ALT as at SL (13). To ensure that the sustained task can be completed during early ALT exposure, the reduced pace is most commonly compensated for by an increase in duration. Although a generalized quantitative prediction equation had been developed for the relationship between *maximal* exercise performance and ALT (31), there has not been an equation developed to estimate the increase in *sustained physical task duration* at varying ALT for unacclimatized individuals after rapid ascent. It is important to note that although ALT acclimatization resulting from several days or more of living at ALT has little or no effect on $\dot{V}O_{2peak}$, it greatly improves endurance performance (16,21,26). The implication being that the use of previously published reports to estimate the percent increase in sustained task duration going from SL to ALT using semi- to fully *acclimatized* individuals is not appropriate for predicting the percent increase in sustained task duration in *unacclimatized* lowlanders during the early hours of ALT exposure.

When we compared our predicted increases in physical task duration in unacclimatized lowlanders with the increases estimated by Fulco et al. (17) in acclimatized athletes, we found as anticipated that our model predicts a greater percent increase in physical task duration at the higher ALT. For instance, when data are extrapolated from the graph supplied by Fulco et al. (17) in acclimatized athletes for a task that takes 30 min at SL, the percent increase in task duration going from SL to ALT is estimated to be 103%, 108%, and 115% at 2000, 3000, and 4000 m, respectively. In contrast, our estimated percent increase in task duration in unacclimatized normal-weight lowlanders is 103%, 112%, and 144% at 2000, 3000 and 4000 m, respectively. In overweight individuals, the difference between acclimatized and unacclimatized individuals is even larger. It is difficult to compare predictions from our equation to the published literature on endurance performance at ALT because most have used normobaric hypoxia to simulate ALT (3,22,24,32). Our previously published work demonstrated a 65% increase in sustained task duration in hypobaric hypoxia compared with a 35% increase in normobaric hypoxia (4). These findings and comparisons highlight the importance of this model because it can be applied to the more general population of unacclimatized normal-fitness level individuals visiting natural terrestrial elevations.

The second most significant factor in the model was BMI classification. Our model predicts at 3000 m that overweight individuals will have ~128% longer task duration than normal-weight individuals. However, there was an interaction with BMI classification and ALT such that above 4050 m, normal-weight individuals demonstrated larger increases in task duration at ALT than overweight individuals. This finding suggests that lower BMI values are beneficial when ascending to most ALT. At the higher ALT, caution should be exercised with the conclusion that normal-weight individuals will do poorly. If the normal-weight individual completes the physical task faster at SL than the overweight individual, then the normal-weight individual may still perform the task faster above 4050 m despite a greater predicted percent increase in task duration. For instance, if both a normal and overweight individual complete the same task at SL, but it takes the normal individual 60 min to complete the task and the overweight individual 80 min to complete the task, then even though the normal has a greater predicted percent increase in task duration at 4500-m ALT than the overweight (e.g., 190% vs 165%), the normal individual will still complete the task faster at 4500-m ALT than the overweight individual (60 min × 190% = 114 min for normal vs 80 min × 165% = 132 min for overweight).

Given the negative association between BMI classification and fitness-level classification in this data set ($r_b = -0.18$), the significant interaction between BMI classification and ALT may point to the well-known fact that more highly conditioned athletes demonstrate greater desaturation and bigger decrements in maximal performance at ALT than less well-conditioned individuals (11,19,38). Oxygen diffusion limitations are more likely to occur in individuals with a high cardiac output (i.e., higher fitness level) at the higher ALT (37). Although there are certainly many examples of individuals that demonstrate a high BMI as well as a high fitness level because of body type and composition, in general, there is a negative relationship between the two variables as demonstrated in this data set. Fitness-level classification did not reach statistical significance in this model, and as such, there is something unique about BMI classification that captures more of the variance in sustained task performance at ALT than just the fitness level. Those with a higher BMI may not have exerted themselves as much during the TT, which would result in a greater increase in the task duration at high ALT. Motivation is difficult to measure but similar RPE during the TT in both the normal and overweight groups suggests that both groups were working hard during the TT.

Previous reports also indicate that heavier individuals are more likely to develop AMS at ALT (18) and therefore not likely to perform as well. However, all TT in the present study were initiated and completed before significant development of AMS symptoms. Individuals that did develop AMS during the TT were limited, and the presence or absence of AMS postexercise did not explain significant variability for the percent increase in task duration at ALT. Although our laboratory has found a significant association between the presence of AMS and percent increase in sustained task duration measured after a night of sleep at ALT (e.g., 18–24 postascent), we are confident that the TT data represented in this model reflect the effects of hypobaric hypoxia on muscular performance rather than sickness.

The accuracy of our predictions for the percent increase in TT duration going from SL to ALT for a population of individuals is quite good as reflected by our tight confidence intervals in Figure 1. However, because of the variability of our measurements, the prediction intervals for this model are quite large. Prediction intervals are always larger than confidence intervals because they reflect both the uncertainty in knowing the population mean as well as the individual scatter. In determining what we can expect to see if we randomly sample one more individual from the population, there is considerable overlap in the prediction intervals between both the normal and overweight individuals. Therefore, the model should be used as a planning tool for population predictions in physical task durations as originally intended.

Limitations of this study should be acknowledged. First, the number of women in the database was limited (~12.6%) even though the distribution was equally spread across ALT and age groups. Second, race and smoking status were not evaluated because of unequal distributions and empty cell sizes across the various ALT. Third, this physical performance model was developed using a bicycle ergometer and therefore may not be applicable to weight-bearing endurance exercise. Preliminary model development from treadmill data collected in our laboratory at limited ALT, however, suggests that BMI remains a factor in predicting increases in task duration at ALT. Fourth, although this model represents a significant advancement in the field, the total explained outcome variation in task performance was 47.0%. This finding was expected, however, given that the intent of developing the model was to use easily obtainable demographics known before ascent. As such, the equation can be applied to a large population of normal individuals with little or no access to equipment required for measuring basic blood parameters (e.g., hemoglobin and hematocrit); individual physiologic variables (e.g., arterial oxygen saturation and HR); and genomic, proteomic, and metabolomic markers of hypoxic stress. Although the measurement of $\dot{V}O_{2peak}$ requires specialized equipment, a simple 2-mile run time can be converted to an approximate $\dot{V}O_{2peak}$ value (28). Future model development should focus on adding these individualized markers of hypoxic stress as well as weight-bearing exercise to enhance the predictive ability of the model.

CONCLUSIONS

In conclusion, this model provides the first quantifiable estimates of the increase in sustained physical task duration after rapid ascent to a wide range of ALT in unacclimatized lowlanders. Although predictions from these models are limited to a homogeneous population who are relatively young and fit, this model is unique in that it can predict the percentage increase in task duration *before exposure* over a wide range of ALT in *unacclimatized lowlanders* just by knowing the destination ALT and BMI classification. Clinicians, health-care providers, athletes, employers, and military commanders can use these estimates to effectively plan for the increased time to complete a given task at ALT compared with SL when exposed to high-mountainous terrain. This type of prediction model can be used to implement more rest breaks, allow more time to complete tasks, or involve more personnel to mitigate risks to the individual engaging in sustained physical activity soon after arriving at ALT.

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