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Development of a model to determine oxygen consumption when crawling

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Abstract

During a mine disaster or emergency, underground air can quickly become contaminated. In these circumstances, all underground mine workers are taught to don breathable air supply units at the first sign of an emergency. However, no contemporary oxygen consumption data is available for the purposes of designing breathing air supply equipment specifically for mine escape. Further, it would be useful to quantify the oxygen requirements of breathing air supply users for various escape scenarios. To address this need, 14 participants crawled a distance of 305 m each while their breath-by-breath oxygen consumption measurements were taken. Using these data, linear regression models were developed to determine peak and average oxygen consumption rates as well as total oxygen consumption. These models can be used by manufacturers of breathing air supply equipment to aid in the design of devices that would be capable of producing sufficient on-demand oxygen to allow miners to perform self-escape.

Keywords

Crawling; Oxygen consumption; Oxygen consumption rate; Four-point crawling; Self-escape

Introduction

Indirect calorimetry through metabolic measurement during work has been used for several decades by exercise physiologists aiming to estimate the energy expenditure requirements of occupational tasks (Astrand and Rodahl, 1970; Jørgensen, 1985; Toomingas, Mathiassen and Tornqvist, 2012). Typically, oxygen consumption rates, $\dot{V}O_2$ in L/min, have been used as criteria to design tasks such as lifting or lowering (Waters, Putz-Anderson and Garg, 1994). The goal of using $\dot{V}O_2$ is to design work tasks to accommodate the majority of the working population with respect to physiological capabilities.

Measuring oxygen consumption can also be used to define acute peak demands or total oxygen (O_2) requirements for tasks carried out while relying on a breathing air supply unit. In mining, workers are taught to don breathing air supply units at the first sign of an emergency as the mine air can quickly become contaminated with high levels of carbon

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monoxide (CO) and other toxic compounds as well as asphyxiants such as carbon dioxide (CO_2) and methane (CH_4), which can quickly displace O_2. To successfully escape, mine workers need to be provided with sufficient O_2 supply to allow the completion of all required self-escape tasks.

When developing breathing air supply equipment, two main factors related to the delivery of oxygen are important: the total volume of oxygen and the delivery rate of oxygen. The total volume of oxygen is an important consideration as it will determine how long a device can be expected to provide oxygen to the user, and this volume is affected by factors such as an individual's size, fitness and work output. Just as important is the rate of oxygen delivery. When users are performing an activity that requires a high $\dot{V}O_2$, it becomes possible for them to "overbreathe" the device, that is, they could be consuming oxygen at a rate higher than is being generated by their breathing air supply units. Although no scientific evidence has been found to document the cause or symptoms of overbreathing, several users have reported having difficulty breathing with their breathing air supply units (Vaught et al., 2000). Training packages created by the National Institute for Occupational Safety and Health (NIOSH) inform wearers of breathing air supply units that if they feel they are not being provided with sufficient on-demand oxygen they may need to slow their breathing rates (Kowalksi-Trakofler, Vaught and Brnich Jr., 2008). However, in emergency circumstances this sensation might be interpreted differently by different workers. What would be useful is a quantitative approach to determine the total volume of oxygen consumed and the rate of this oxygen consumption for representative mine self-escape tasks when mine workers would be expected to wear breathing air supply units.

Mine escape has received limited attention in the literature. Much of the research has been aimed at providing mine rescue personnel with adequate equipment and technologies to ensure their safety when entering hazardous environments. Studies on the metabolic cost of mine escape are limited. Kamon, Doyle and Kovac (1983) evaluated the oxygen consumption and heart rates of six mine workers as they maneuvered as quickly as they could through a course in an underground coal mine that consisted of multiple sections of differing terrain. Each section was considered a separate subtask, and the sequence for the subtasks was as follows: upright walk with the head bent for 940 m, duck walk for 150 m, crawl for 365 m, duck walk again for 465 m, walk with the head bent for 170 m, and walk upright for 300 m. The total length of the route was 2,390 m. While performing each subtask, the miner's oxygen consumption was measured. Heart rate (HR) and oxygen consumption measurements were recorded by emergency medical technicians after the mine workers completed each subtask. For the 365-m crawling portion of the study, the average crawling speed, average $\dot{V}O_2$, and HR were 24 ± 10 m/min, 1.53 ± 0.44 L/min, and 144 ± 17 bpm, respectively. Using the estimated average $\dot{V}O_2$ and the average crawling speed, approximately 23.3 L of O_2 were required for these mine workers to crawl 365 m during mine escape.

In another study, computer simulation was used to estimate the probability of a successful mine escape, of which one component was having sufficient oxygen (Kovac, Vaught and Brnich, Jr., 1990). They estimated 0.7 mL of O_2/kg·m would be needed for crawling. Using this oxygen cost, a person weighing 78.6 kg (the average weight of the participants in the 1983 Kamon, Doyle and Kovac study) and crawling a distance of 365 m (the crawling distance of that study) would be expected to consume 20.1 L of O_2. However, it should be noted that the development of the equation for oxygen consumption was not justified in detail, and may not be as accurate as linear regression models developed using human data.

There is no contemporary oxygen consumption data available for the purposes of designing mine escape equipment and procedures to maximize successful escape. The existing data are three decades old and from limited samples that may not be representative of today's mining population. Furthermore, the working areas of mines have a variety of heights, based on the coal seam height, and can vary in distance from tenths of a mile to several miles if mechanical transportation is not viable post-disaster. In mines where the coal seams are thin, there will likely be a reduced ceiling height requiring mine workers to kneel or crawl to escape. In addition, the dust or smoke generated following an incident may obscure visibility to the point that even in high seam mines, escapees will need to crawl to follow cables or track. This will also affect oxygen consumption. Four-point crawling is the most physiologically taxing form of locomotion and would be considered the worst-case scenario for any mine escape situation.

Given the need for contemporary oxygen consumption data to inform breathing air supply design that would benefit miners during self-escape, the purpose of this study was to determine the volume and rate of oxygen consumption and CO_2 production during four-point crawls for a distance of 305 m at a self-selected pace. This data may be used to create a linear regression model to predict the oxygen consumption required for crawling 305 m based on body weight and crawling speed. A self-escape task of crawling a distance of 305 m (approximately 1,000 ft) was selected because this is the required distance from the working face to the nearest refuge location in underground coal mines (Code of Federal Regulations, 30 C.F.R. 75.1506 (c)(1)).

Methods

Sixteen participants were recruited (although two of these participants did not complete the study and were excluded) from the NIOSH Office of Mine Safety and Health Research (OMSHR) in Pittsburgh, PA. The demographics of these participants are presented in Table 1. After reading and signing an informed consent document approved by the NIOSH Institutional Review Board, each participant was fitted with a $K4b^2$ cardiopulmonary metabolic system from Cosmed (Rome, Italy), which included a face mask for the sampling of metabolic gases, a battery pack, a transmitter unit, and a telemetry strap to measure heart rate. This system measured and logged the participant's heart rate and respiration data breath by breath. The system was calibrated before each test using room air and a certified gas mixture with known concentrations. Participants spent several minutes becoming familiar with the device, then they were instructed to sit for 5 min during which baseline HR and O_2 measurements were obtained. Participants were then instructed to crawl around the test area. The test area consisted of a marked track located inside a simulated mine. Participants crawled approximately 5.5 laps around this area for a total distance of 305 m. All participants wore kneepads and gloves for their comfort.

Breath-by-breath O_2 consumption was calculated by multiplying the $\dot{V}O_2$ by the duration of each breath. First, all data were filtered by discarding any breaths outside of the normal physiological range, as identified by the cardiopulmonary metabolic system. This included any breaths where the breathing rate was less than 5 per minute or more than 80 per minute, the breath volume was less than 0.2 L or more than 10 L, the fraction content of expired O_2 was less than 10 percent or more than 20 percent, or the fraction content of expired CO_2 was less than 1 percent or more than 10 percent. Then, the data were smoothed by taking a three-breath moving average (Guidetti et al., 2008). Mean and maximal oxygen consumption and heart rates and total oxygen consumption were determined for each participant.

To determine the effect of body weight and crawling speed on oxygen consumption values, three linear regression models were developed using the dependent variables of peak oxygen consumption rate (Peak $\dot{V}O_2$), average oxygen consumption rate (Avg $\dot{V}O_2$), and total volume of oxygen consumed (VO_2), and the independent variables of body weight and crawling speed. Regression equations are reported for those cases where the parameter estimates had *p*-values less than 0.05. All intercepts, regardless of *p*-values, were included in the regression equations for those cases. The residuals were visually examined and studentized residual plots and Cooks D plots were examined. There was one observation (Subject 8, total VO_2) that had a large difference between observed and predicted, but the leverage statistic did not indicate significant influence on the regression. There was no reason to discard this data point as this participant took a longer amount of time to crawl.

Results

Due to issues with the data collection instrument and subject discomfort, the data from two participants (Participants 6 and 9) were not in the expected range and were discarded. Participant 9 developed a muscle cramp and had to stop crawling in order to stretch, and Participant 6's data were drastically outside of the expected range. Therefore, the data presented are from the remaining 14 participants. Table 2 presents the results from the 305-m crawl. To show a typical time series, the oxygen consumption rates for each breath are presented in Fig. 1 for one participant in the study: Participant 8.

In order to quantify the effect of body weight and average crawling speed on oxygen consumption parameters (total, average and peak) during the crawling phase, multiple linear regression models were developed using SAS 9.3 software. Initially, body weight and average crawling speed were entered into the models. For average and peak oxygen consumption, body weight and average crawling speed were significant. For total oxygen consumption, average crawling speed was not significant, so a model with only weight as a predictor variable was run. Body weight and crawling speed together were found to account for over 82 percent of the variability in the Avg $\dot{V}O_2$ and over 51 percent of the variability in the Peak $\dot{V}O_2$ (Figs. 2 and 3). Weight alone was found to account for nearly 50 percent of the variability in VO_2 during the crawling stage (see Fig. 4).

Discussion

In this study, regression models were developed to estimate average and peak oxygen consumption rates and total oxygen consumption for crawling 305 m. To our knowledge, this is the first study to publish a model to determine peak and average consumption rates for crawling. These models can be used to determine what levels of oxygen consumption may be expected when crawling based on a person's speed and body weight. Two participants in this study were found to have peak oxygen consumption rates exceeding 3 L/min for three or more consecutive breaths. At this rate of oxygen utilization, it may be difficult for some types of current breathing air supply technologies to generate sufficient on-demand oxygen, and wearers may feel their oxygen is insufficient or they may experience difficulty breathing. When there is a disparity between oxygen utilization and oxygen production rates, users may need to slow their breathing rates. This may be counterintuitive as the user may feel their device is no longer capable of producing oxygen and not that their breathing rate is too high.

Research is available to allow some comparisons with the total oxygen consumption values published previously. The model developed by Kovac, Vaught and Brnich, Jr., (1990) to determine oxygen consumption by multiplying the oxygen costs for the mode of travel by the escape distance by body weight, overestimated the total oxygen consumption for most of the participants in this study by nearly 20 percent. It is not clear whether the Kovac model was developed using participant data or simulated data, or if that model was meant to determine oxygen costs for a population older than those who participated in this study. When compared against the Kovac model, the present model accounted for nearly half of the variations in the data and showed that body weight accounts for the variability in the total volume of oxygen consumption during crawling. Using the values from Kovac, Vaught and Brnich, Jr., (1990) to determine the amount of oxygen necessary to escape while crawling 305 m will likely result in an overestimation of oxygen usage for the population in this study, which should allow a margin of safety to control for differing personal factors such as body weight and fitness level. Additionally, the VO_2 measured in this study was lower than what would have been expected using the crawling speed and oxygen consumption rates for a group of mine workers crawling 305 m (Kamon, Doyle and Kovac, 1983). On average, Kamon, Doyle and Kovac (1983) overestimated the total oxygen consumption by 4 L. This overestimation may be due to several factors, including participant population and research methodologies. Kamon, Doyle and Kovac (1983) conducted their research on six underground coal miners with an average age of 45 years and weight of 78.6 kg. That participant pool was older but not much heavier than the participants in this study. A number of differences in the study protocols, including the fact that Kamon, Doyle and Kovac (1983) conducted their experiment underground with irregular floor conditions, make comparisons difficult. Additionally, in the Kamon, Doyle and Kovac (1983) study the crawling routine was conducted after participants had already walked upright and walked in a stooped posture for a distance of over 1,000 m. Therefore, it is likely that fatigue was already a factor in the increase in $\dot{V}O_2$ when the participants began crawling. In the present study, the participants started crawling after a rest period and were not already fatigued from previous efforts. A main limitation of this study is that no low-seam coal mine workers were recruited to participate. All participants were current employees of NIOSH and not representative of all underground coal mine workers. Previous research has indicated that the aerobic capacity of the mining population does not differ from the non-miner population (Ayoub and Selan, 1981). Thus, it is expected that the results obtained from the subjects in this study will be applicable to miners with similar body weights and ages to the participants in this study traversing relatively level grounds from a resting position. Moreover, only 14 participants were used to develop this model, which limits its generalizability. In the future, a wider age range than investigated in this study should be investigated to determine what effect age has on oxygen consumption rates and volumes when crawling.

The regression modeling had several limitations. One results from using average crawling speeds in the calculations. This eliminated the ability to relate peak in energy expenditure to changes or peaks in crawling speed. The second limitation is that speed was self-selected and body weight was a random variable, thus the ranges of both were limited. However, the regression parameter estimates in Fig. 3 provide quantitative estimates of how these two variables affect mean oxygen consumption. The body weights may not be representative of the underground mining population. In spite of these limitations, body weight and crawling speed accounted for 82 percent of the variation in average oxygen consumption. Overall, these results suggest that the body weight of representative mining populations should be considered for future designs of breathing air supply units to ensure that they provide sufficient oxygen. The peak value predictions can also assist with determining the likelihood that breathing air supply units provide sufficient on-demand oxygen. Manufacturers can use these peak values to determine minimum rates of oxygen generation for their breathing air supplies. Although a distance of 305 m was used, we believe it is reasonable to extrapolate the results to longer distances until additional data can be collected.

The Mine Safety and Health Administration (MSHA) requires that mines with entry heights less than 1.02 m provide breathing air supply caches every 671 m when grades are less than 5 percent (Code of Federal Regulations, 30 C.F.R. 75.1714-4 (c)(2)(ii)). This means that a miner may have to crawl 671 m before reaching another cache, unless breathing air supply units are provided at the refuge location, and may be expected to consume more than double the oxygen reported in this study. In addition to employee-specific factors, underground coal mines have varying conditions and environmental factors that may also need to be considered when estimating oxygen requirements.

While this work provided meaningful results, more information is needed to help guide the design of future breathing air supply units for underground coal mine workers. Longer crawling distances should be examined as it is possible that a mine worker would crawl further than just 305 m before reaching a cache. Miners may have difficulty navigating or choosing the shortest route due to smoke and stress. The breathing rates for mine escape tasks should be measured while mine workers of various ages, job types and fitness levels simulate these specific escape tasks at their current mine of employment. Moreover, these tasks could be simulated after the workers have been working for some period and not after a period of rest. Those breathing rates should then be applied to actual breathing air supply units to determine if the breathing air supply units will be able to provide sufficient on-demand oxygen. This would also allow researchers to determine if overbreathing actually occurs and what are the likely causes of this issue. This information would be used to determine potential improvements for existing oxygen delivery devices. This may allow for the development of improved training to help mine workers have more realistic expectations for the wearing of breathing air supply units.

Conclusion

Underground mine escape has received some attention in the literature. However, the oxygen delivered by a breathing air supply unit required for a mine worker to escape has not been evaluated. In this study, we quantified the oxygen required for relatively young test subjects to crawl 305 m and developed models to predict the volume and rate of oxygen consumption based on participant body weight and crawling speed. This new information can be used by manufacturers of breathing air supply units to aid in the design of devices that would be capable of producing sufficient on-demand oxygen to allow miners to perform self-escape. If oxygen cannot be generated at a rate equal to that at which it is consumed, users may need to slow their escape efforts or may feel that their breathing air supply device is no longer working, with detrimental consequences. It is always recommended that users continue wearing their breathing air supply units until they are outside of the mine even if they feel the breathing air supply units are reducing their breathing rates.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

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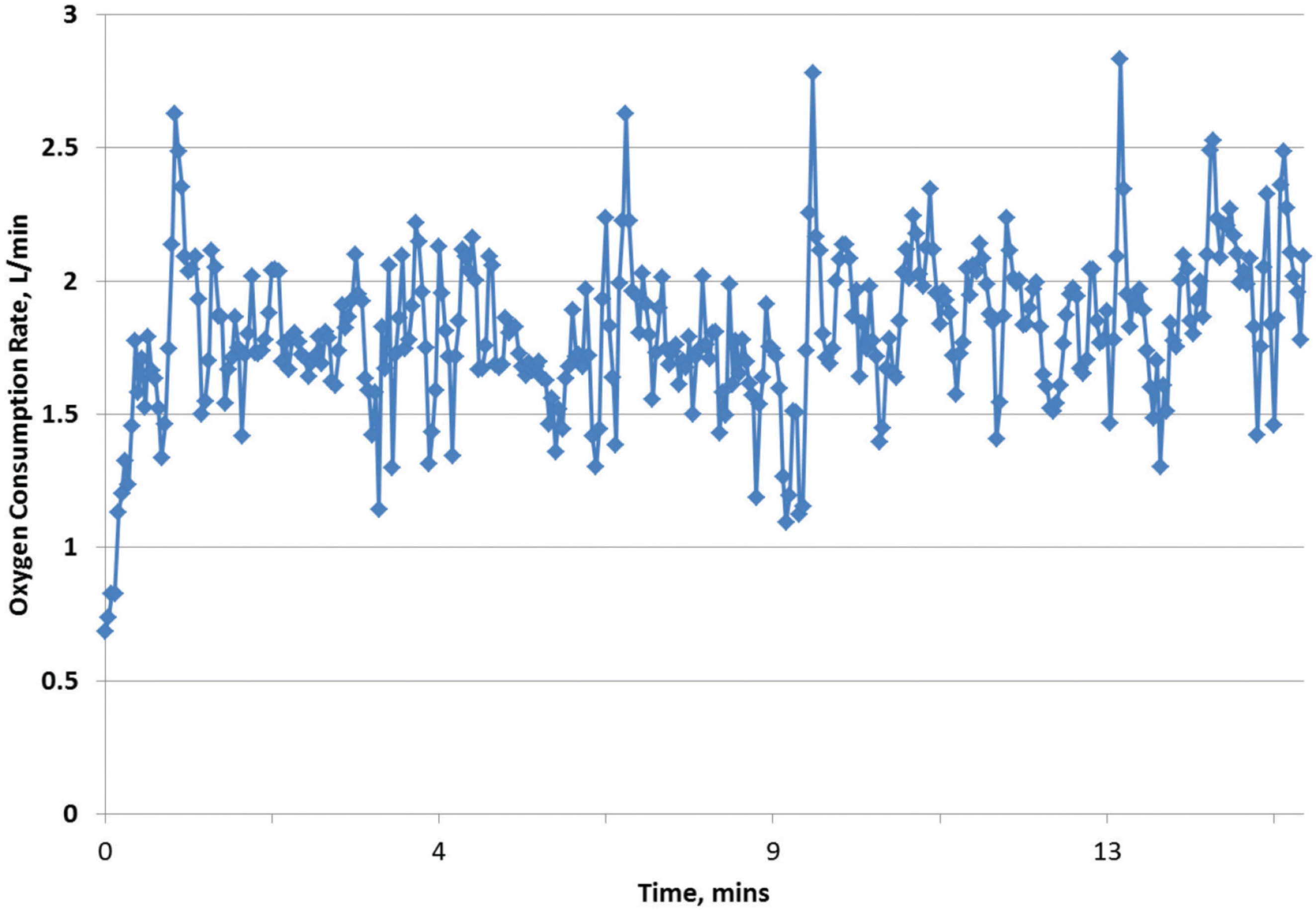

Figure 1.

Typical filtered time series of the breath-by-breath oxygen consumption rates for Participant 8.

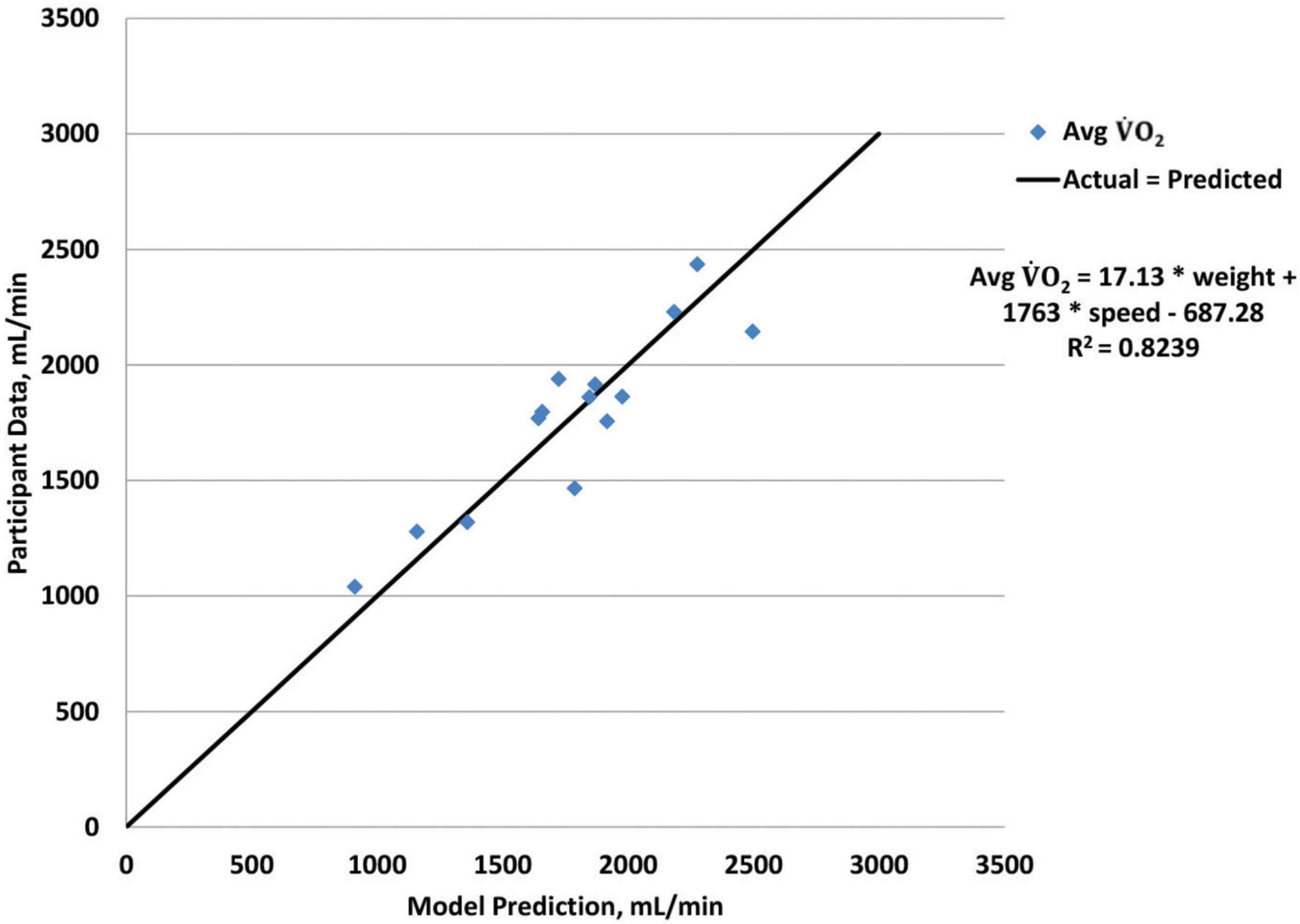

Figure 2.

Comparison of actual average $\dot{V}O_2$ values against the regression model predicted average $\dot{V}O_2$ values. The regression equations and associated R^2 values are shown for the predicted equation based on participant weight (measured in kg) and crawling speed (measured in m/sec). An Actual = Predicted line is included to show a "perfect" prediction line.

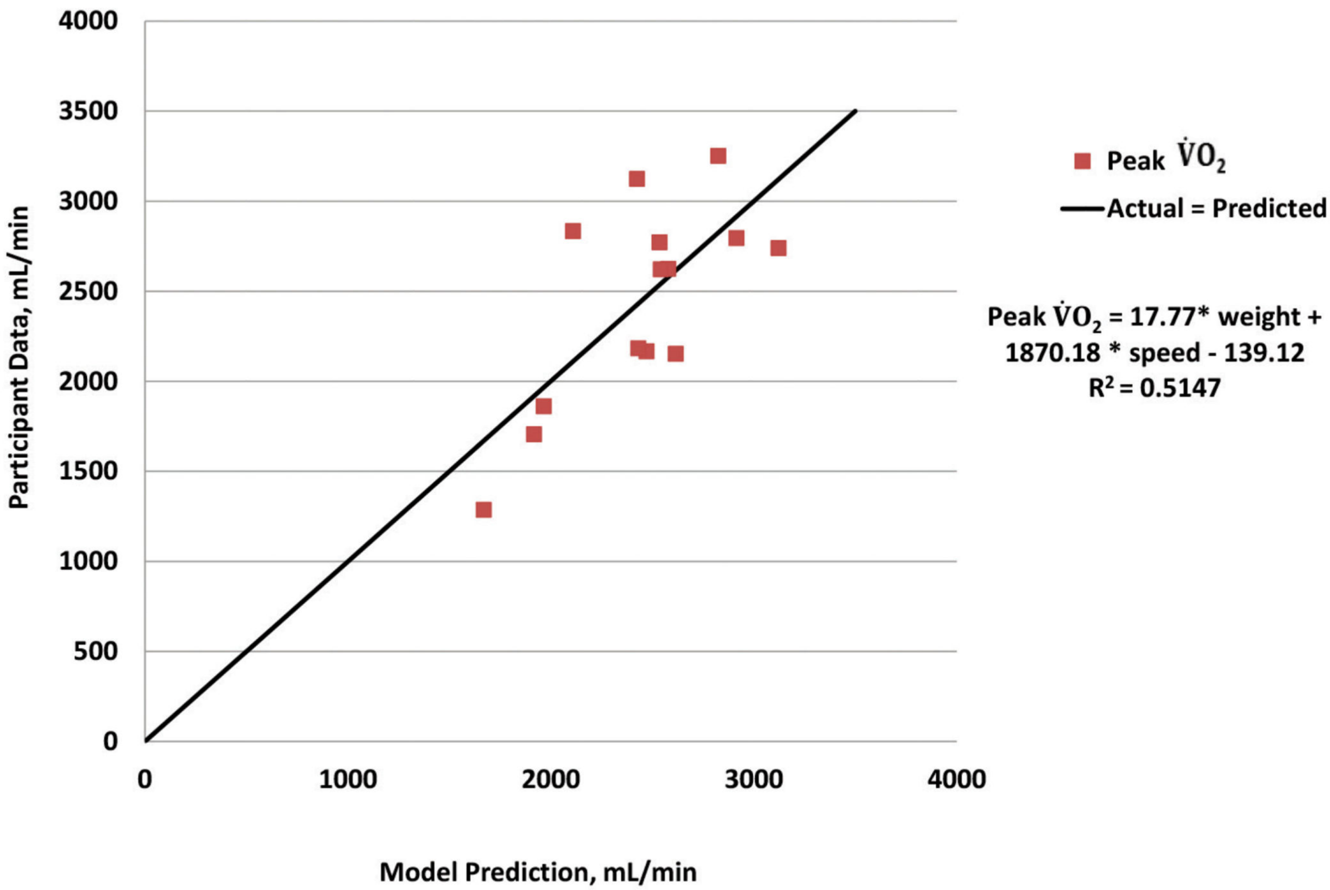

Figure 3.

Comparison of actual peak $\dot{V}\,O_2$ values against the regression model predicted peak $\dot{V}\,O_2$ values. The regression equations and associated R^2 values are shown for the predicted equation based on participant weight (measured in kg) and crawling speed (measured in m/sec). An Actual = Predicted line is included to show a “perfect” prediction line.

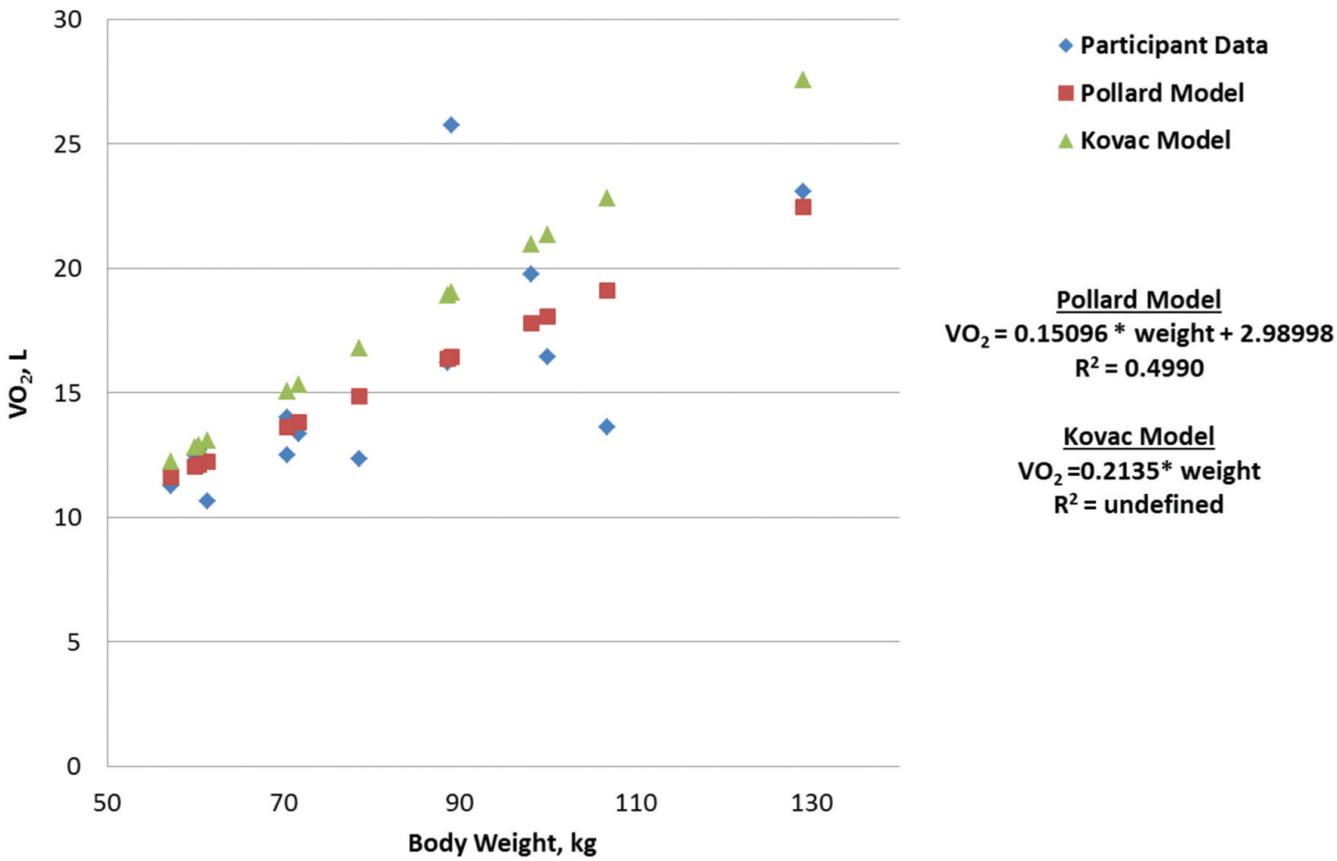

Figure 4.

Comparison of actual VO_2 values against the models proposed by Pollard (current study) and the 1990 model of Kovac, Vaught and Brnich, Jr., versus body weight (measured in kg). The regression equation and associated R^2 value are presented for the Pollard model and only the equation is presented for the Kovac model. The Kovac model was converted from its published form of 0.7 mL of O_2/kg·m to 0.2135 L of O_2/kg to use the same units as the Pollard model and to account for a crawling distance of 305 m. The Kovac model was listed as having an undefined R^2 value because the sum of the deviations using the body weights in this dataset was higher than the sum of the residuals.

Table 1

Demographics of the 14 participants who completed the study. Data for Participants 6 and 9 were excluded.

Participant	Gender	Age (yr)	Height (m)	Weight (kg)	Body mass index	Resting heart rate (bpm)	Resting $\dot{V}O_2$ (L/min)
1	F	25	1.7	61	23	63	0.31
2	M	25	1.8	79	23	73	0.40
3	F	33	1.7	57	21	64	0.29
4	M	29	1.8	107	31	73	0.47
5	M	18	1.8	70	21	73	0.40
7	F	35	1.7	72	26	91	0.25
8	M	29	1.8	89	26	54	0.41
10	M	27	1.8	98	32	68	0.60
11	M	32	1.9	129	37	86	0.53
12	F	21	1.5	60	28	84	0.26
13	M	26	1.7	70	25	72	0.34
14	M	24	1.7	100	35	72	0.54
15	F	32	1.8	89	28	90	0.44
16	F	28	1.8	60	20	75	0.43
Mean	–	28	1.74	82	27	74	0.41
Standard deviation	–	5	0.11	21.26	5.23	11	0.11

Table 2

Test measurements when crawling 305 m.

Participant	Duration (min:sec)	Avg speed (m/sec)	VO_2 (L)	Avg $\dot{V}O_2$ (mL/min)	Peak $\dot{V}O_2$ (mL/min)	VCO_2 (L)	Avg $\dot{V}CO_2$ (mL/min)	Peak $\dot{V}CO_2$ (mL/min)	Avg heart rate (bpm)	Peak heart rate (bpm)
1	6:50	0.81	10.65	1,658	2,166	10.06	1,574	2,041	132	150
2	7:39	0.73	12.37	1,724	2,153	11.86	1,659	2,111	140	170
3	13:08	0.42	11.28	911	1,286	10.69	867	1,105	116	146
4	12:40	0.44	13.64	1,868	2,624	12.03	1,663	3,121	114	138
5	7:55	0.70	14.00	1,916	3,124	13.72	1,897	2,994	138	162
7	13:19	0.42	13.35	1,158	1,706	13.61	1,185	1,760	152	175
8	15:36	0.36	25.74	1,787	2,833	22.75	1,583	2,451	122	156
10	8:31	0.65	19.78	2,497	3,251	17.93	2,311	3,141	130	149
11	10:44	0.52	23.08	2,276	2,740	24.00	2,382	2,894	164	180
12	10:05	0.55	12.71	1,359	1,860	13.05	1,406	1,802	74	110
13	7:18	0.76	12.52	1,846	2,772	13.27	1,988	2,951	147	164
14	8:08	0.68	16.44	2,184	2,795	16.39	2,200	2,855	165	183
15	10:26	0.53	16.22	1,643	2,182	8.88	1,714	2,082	162	181
16	6:26	0.86	12.52	1,977	2,621	10.69	1,703	2,159	152	170
Mean	9:55	0.60	15.31	1,772	2,437	14.21	1,724	2,390	136	160
Standard deviation	2:51	0.16	4.54	425	562	4.56	419	620	25	20