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EVALUATION OF A NEWLY-DESIGNED, DYNAMIC KNEE EXTENSION DEVICE FOR THE STUDY OF MUSCLE FATIGUE IN HUMANS

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ENVIRONMENTAL MEDICINE
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Evaluation Of A Newly-Designed, Dynamic Knee-Extension Device For The Study Of Muscle Fatigue In Humans

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13. ABSTRACT (Maximum 200 words)

A device utilizing a simple pulley system was developed to study muscle fatigue during dynamic, submaximal exercise isolated to the knee-extensor muscles of one or both legs. The purposes of this study were to determine the following: (1) oxygen consumption requirements for various submaximal and maximal power outputs and to compare these data to values obtained from published reports using modified bicycle ergometers (criterion devices), (2) intra-individual test-retest variability, and (3) muscle fatigability during exercise. On each of 2 separate days, 8 male volunteers (mean age 18.6 $\pm$ 0.3 yr (SE), weight 79.5 $\pm$ 5.1 kg, and height 179.1 $\pm$ 2.0 cm) performed a graded, intermittent (4 min bouts) exercise test using the knee-extensor muscles of one leg to determine one-legged peak oxygen consumption. Maximal voluntary contractions (MVC) were obtained at the beginning, at 2 min, and at the end of each exercise bout as a means to monitor rate of muscle fatigue. The slope and intercept of the relationship of the increase in power output and oxygen consumption were 13.80 ml O_2/watt and 470 ml/min, respectively, with $r^2 = 0.96$. These values for slope and intercept are similar to those reported previously: slopes 13.10 and 14.70 ml O_2/watt; intercepts, 400 and 471 ml/min; and $r^2 = 0.99$. Also, there was minimal intra-individual variation ($r^2 = 0.90$) in oxygen consumption values for identical power outputs. Test-retest oxygen consumption values did not differ from a line of identity. Stepwise accelerations in muscle fatigability were discernable with small increments in exercise intensity and elapsed exercise time. Our device represents a low-cost, expanded capability alternative compared to previous units utilizing modified bicycle ergometers as a testing mode.

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Human Use

Human subjects participated in this study after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on "Use of Volunteers in Research."

Disclaimer

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FIGURE 3: Regression lines illustrating the relationship between oxygen consumption and power output are presented for two previous studies (1,18) and the present study. To be able to compare statistically the present data to previous data, it was necessary to calculate the regression in a similar manner to the previous studies. That is, the current data were collapsed into five-watt intervals (10-15, 15.1 to 20, etc), means of the intervals were calculated, and a regression line was drawn through the means. Note the similarity of the slopes, intercepts, and variance among studies.

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SUMMARY

A device utilizing a simple pulley system was developed to study muscle fatigue during dynamic, submaximal exercise isolated to the knee-extensor muscles of one or both legs. Structural components (wood) and all other materials such as bolts, pulleys, and rope were inexpensive and widely available. The purposes of this study were to determine the following: (1) oxygen consumption requirements for various submaximal and maximal power outputs and to compare these data to values obtained from published reports using modified bicycle ergometers (criterion devices), (2) intra-individual test-retest variability, and (3) muscle fatigability during exercise. On each of two separate days, eight male volunteers (mean age 18.6 ± 0.3 yr (SE), weight 79.5 ± 5.1 kg, and height 179.1 ± 2.0 cm) performed a graded, intermittent (4 min bouts) exercise test using the knee-extensor muscles of one leg to determine one-legged peak oxygen consumption. Maximal voluntary contractions (MVC) were obtained at the beginning, at 2 min, and at the end, of each exercise bout as a means to monitor rate of muscle fatigue. The slope and intercept of the relationship of the increase in power output and oxygen consumption were 13.80 ml O_2/watt and 470 ml/min, respectively, with $r^2 = 0.96$. These values for slope and intercept are similar to those reported previously: slopes 13.10 and 14.70 ml O_2/watt; intercepts, 400 and 471 ml/min; and $r^2 = 0.99$. Also, there was minimal intra-individual variation ($r^2 = 0.90$) in oxygen consumption values for identical power outputs. Test-retest oxygen consumption values did not differ from a line of identity. A prominent feature of our new device is the ability to measure force generating capacity of the knee-extensor muscles during brief 2-3 sec pauses in dynamic exercise. The device provides powerful resolution in detection of decrements in force generating capacity (i.e., muscle fatigue). Stepwise accelerations in muscle fatigability were discernable with small increments in exercise intensity and elapsed exercise time. The current knee-extension device therefore represents a viable, low-cost alternative with additional capabilities compared to previous units utilizing modified bicycle ergometers as a testing mode.

INTRODUCTION

A variety of different experimental models utilizing animals and humans has been used to study muscle fatigue (1,10,14,16,17,25). One model often used on humans emphasizes the relationship between metabolite accumulation or substrate depletion and contractile ability at the end of exercise (15,24). In typical applications of this commonly used model, sustained static contractions are employed. If the static contractions are greater than approximately 20% of maximal voluntary contraction (MVC), there will be a large increase in intramuscular pressure and a decrease in effective perfusion pressure, which limits local blood flow and oxygen delivery, and causes fatigue to rapidly ensue (23). In this model, fatigue is defined as the point in time in which the active muscles are unable to maintain the required or expected force or power output (6). This concept implies that the fatigue process is not operative until force or power output declines below the required level. It is obvious, however, that maintaining a fixed, submaximal force or power output can become increasingly difficult over the course of an extended exercise bout. Experimental findings of gradual muscle weakening beginning shortly after the onset of submaximal exercise (9,14,17,25) support the view that fatigue is more appropriately defined as "any reduction in the force generating capacity of the entire neuromuscular system, regardless of the force expected (5,25)." In this construct, fatigue, beginning during maintained submaximal force or power output, can be measured as a gradual fall in the force generated in MVC that progresses until exhaustion, defined as the point at which MVC force falls to or below that needed to sustain a submaximal static contraction or dynamic power output (25).

The causes of a gradual reduction in force generating capacity, as measured by a reduction in MVC during exercise, are poorly understood. However, utilization of such a model that distinguishes between the gradual decrement in muscle performance and exhaustion during exercise provides a means of studying the temporal relationships between central motor drive, metabolic changes, and peripheral muscle contractile failure (12,25). For example, while using this model Vollestad et al. (25) found that quadriceps MVC fell during repeated submaximal static quadriceps contractions (30% MVC), and that fatigue and exhaustion occurred independently of metabolite accumulation or substrate depletion. Whether similar results and conclusions would be obtained using this model with other types, intensities, and durations of exercise is uncertain. In particular, there is a paucity of information about serial changes in force generating capacity during and after dynamic exercise of the same muscle group.

Unfortunately, local muscle fatigue during dynamic exercise has been little studied possibly because of the inherent difficulty of superimposing an indicator of fatigue such as a MVC during dynamic exercise. In previous attempts to determine the effect of dynamic exercise on muscle function, some studies (9,14,17) required subjects to dismount a 2-legged cycle ergometer after pedalling at various intensities (e.g., 20, 60, and 80% VO2max) and durations (e.g., 1, 3, 10, and 20 min), and then to sit in a leg dynamometer and perform a static quadriceps muscle contraction (40% of MVC at 90°) sustained until exhaustion. This approach provided important findings consistent with the notion that whole-body dynamic exercise over a large range of intensities and durations causes fatigue of the utilized muscles. There are, however, a number of limitations to this approach. These include differences in the equipment used to provide (2-legged cycle ergometer) and measure (dynamometer) fatigue, which resulted in differences in 1) the orientation and range of movement of the leg and 2) the number of leg muscles recruited. During cycling exercise, hip flexors, hip extensors, and hamstrings as well as the quadriceps muscles were utilized, while only the quadriceps muscles were used during the static knee-extension test. In addition, the length of time (15 sec) from the end of cycling to the beginning of the static knee-extension test allowed partial recovery of the exercised muscles, thereby limiting identification of possible factors relating to fatigue. Furthermore, fatigue was assessed only after, not during, dynamic exercise using an index of fatigue that independently causes marked fatigue (i.e., sustained static contraction) (9,14,17). Use of this model also does not permit assessment of gradual muscle weakening during exercise. This inability to monitor rate of fatigue makes it difficult to differentiate possible causes of altered performance from incidental by-products. For these reasons, this type of approach is considered not to be appropriate for study of the interactions of possible mechanisms of local muscle fatigue during dynamic exercise.

What is needed is an exercise model that permits virtually a complete overlap between the specific muscle actions used to produce and measure fatigue. The exercise and tested muscles should solely generate the force being measured; the involved muscles should not be augmented by synergists nor reduced by antagonists. Obviously, treadmill exercise, two-legged or even one-legged cycle ergometer exercise would not be appropriate because many different muscles are involved and each would be working at a different intensity relative to its maximal capacity. Another complication of using large, multi-muscle group dynamic exercise modes for the study of local muscle fatigue is that during heavy exercise there is likely to be vasoconstriction in active muscle to maintain systemic blood pressure as near peak levels of cardiac pumping capacity are approached (19,20). Under these conditions, it would be difficult to distinguish intrinsic intramuscular factors from the effects of reduced oxygen delivery secondary to a decrease in muscle blood flow (19,22,23).

The muscle mass utilized should also be large enough to permit adequate resolution of different exercise intensities, yet not so large that muscle perfusion is limited by eliciting near maximal cardiac output. One means of satisfying these requirements is by performing rhythmic knee-extension exercise limited to the quadriceps femoris muscles of one leg. Surface electromyogram (EMG) findings indicate that during dynamic knee-extension exercise, activity is primarily confined to the quadriceps femoris, the largest muscle synergy in the human body (1), and that the four heads of the quadriceps muscle group contribute almost equally to the extension of the knee up to about 10-15° of full extension (4,13). Since the quadriceps femoris muscles represent less than 10% of total muscle mass, their perfusion is not likely to be limited by cardiac output. Rather, peak muscle blood flow and oxygen delivery will be determined in large part by local muscle oxygen demand and the relationship between local intramuscular pressure and blood pressure (19,20,22,23).

Knee-extension devices using modified friction-braked Krogh (1,2,4,20) or Monark (18) cycle ergometers have been developed in other laboratories, but their use is limited to performing one-legged dynamic knee-extension exercise. None have reported a capability of performing periodic MVCs with the same leg as a means to monitor rate of fatigue. It has also not been possible to perform knee extensions using two legs (either with both legs extending alternately or together) without having two modified ergometers side by side. Having the capability to perform exercise with one or two legs at *varying* intensities with *each* leg would allow, for example, the ability to determine the effect on local muscle fatigue of a systematic increase in central circulatory demand. Furthermore, modifying a cycle ergometer to perform dynamic knee extensions would be costly and require sophisticated engineering skills and materials that may not be readily available. Therefore, the Altitude Physiology and Medicine Division of the USARIEM in collaboration with Sargent College of Allied Health Professions at Boston University designed a knee-extension device that uses a simple pulley system to provide 1) a means of allowing the quadriceps femoris muscle to exercise dynamically over a wide range of exercise intensities, 2) the ability to precisely quantify power output during submaximal exercise, 3) a means of quickly transferring between dynamic exercise and a static exercise test mode which utilize the same muscle group, and 4) precise measurement of the reduction in force generating capacity (i.e., an index of the rate of muscle fatigue) resulting from dynamic exercise. The device also has the flexibility to allow exercise to be performed with either leg, or with both legs extending alternately or together, in a seated or recumbent position.

GENERAL DESIGN FEATURES (FIGURES 1a to 1d)

The structural component of the device is made of easily obtainable, inexpensive wooden materials (2" X 4"s, 3/4" plywood) and measures 39.66" wide X 44.62" long X 47.10" high. The relatively large dimensions are necessary to 1) allow two weight-stack platforms (during two-legged exercise) to be placed and moving next to each other without contact, 2) provide the required height for the weight platforms to travel vertically, 3) enable supine studies to be conducted, and 4) provide stability. The legs, made of 2" X 4" pine boards, are bolted to the top frame (also 2" X 4" boards) of the structure and can be easily disconnected to facilitate storage, shipping to field studies, etc. The seat deck and seat back unit, made of 3/4" plywood, are padded with 1/4" foam and covered with vinyl. The angle of the back of the seat is adjustable in 5° increments in the range of 95° to 170°. The seat and seat back are connected with a piano hinge and can be moved forward or backward to properly accommodate any size individual such that the lower legs relative to the upper legs can be fixed at any angle in the range of 80° to 100°. Boards of varying width, also padded and covered in vinyl, are used to fill any voids between the seat deck and the well-padded front edge of the structure that are created when accommodating different-sized individuals. Individuals are secured with padded straps at the waist and upper leg to minimize extraneous body movement.

The exercise device utilizes a simple pulley system during dynamic exercise (**FIGURES 1c and 1d**). Three, 2", high-quality, stainless steel bullet-block pulleys with ball bearings, available in any marine supply outlet, are used. For each leg, an exit bullet block (Harken Co., model 114355) is mounted between the horizontal hardwood crossmembers and two upright bullet blocks (Harken Co., model 114421) are attached underneath the seating platform. The ankle(s) of the subject, via a harness, is(are) attached to nonelastic rope (1/4"), which is threaded through the pulleys to a 8" diameter, 1/2" plywood weight stack platform designed to hold up to 10 kg of small, calibrated weights. A load cell force transducer (Interface, Inc., Scottsdale AZ., model c12015 SM-250) is placed between the back of the ankle harness and one end of the rope to measure force throughout the knee extension motion. Force output can be recorded onto computer and/or physiological recorder. The other end of the rope is connected to the top center of the plywood platform. When a leg is extended, the platform rises up on two vertical columns of smooth PVC tubing (0.625" diameter) abundantly-greased to minimize resistance. The guide holes in the platform in loose contact with the columns contain smooth, fiberglass washers.

Power output (watts) can be estimated by multiplying mean force output, distance of leg extension (e.g., from 90° to 150°), and the rate of leg extension (e.g., 60 extensions/min). Since power output can be accurately determined, the moment of exhaustion can be precisely defined: failure to maintain power output (e.g., by reducing leg distance traveled and/or the rate of knee extensions).

The rate of muscle fatigue can be determined by periodically measuring maximal muscle force generating capacity (i.e., MVC) during brief pauses in dynamic exercise using another load cell force transducer (Interface, Inc., Scottsdale AZ., model c12015 SM-250) anchored to the upper wooden crossmember (**Figures 1a and 1b**). The crossmembers can be moved up or down so that the transducer is properly oriented (e.g., 90°) to the ankle harness. To determine MVC, an individual momentarily pauses from performing dynamic knee extensions and is quickly connected to the anchored transducer, and within two sec the MVC is initiated. At the conclusion of the two to four sec MVC, the leg is quickly released from the anchored transducer so that submaximal knee extensions may be resumed. Maximal voluntary contractions can be initiated as often as are appropriate.

The current knee-extension device with its expanded capabilities must provide comparable results to be accepted as a viable alternative to the modified cycle ergometers developed and utilized in other laboratories . Also, there must be a high degree of reproducibility of results between experimental sessions. The opportunities to validate and determine test-retest reliability of the device were presented in a recent, collaborative investigation between the Altitude Physiology and Medicine Division and Sargent College of Allied Health Professions at Boston University titled *"Muscle Fatigue in Humans During Dynamic Exercise in Hypobaric Hypoxia."* During the submaximal and peak power output exercise tests conducted in normoxic and hypoxic conditions, oxygen consumption, cardiac output, blood pressure, arterial oxygen saturation, ratings of perceived exertion, and electromyographic data were collected. Also measured was the decline in MVC force during exercise. However, the oxygen consumption data during the maximal power output session only at sea level will be used in this report to determine the validity of the device, since it is the only data that can be readily compared to previous studies (1,18). Day-to-day reproducibility of the device will be determined by comparing the oxygen consumption values collected for identical power outputs for the same individuals in normoxia and hypoxia. This comparison is considered valid because in steady-state exercise, an individual's oxygen consumption for a fixed power output using other types of exercise modes does not differ between the sea level and altitude environments (8,11,20). The advantages of the knee-extension device will be highlighted by presenting some of the results of the relationship between power output and rate of muscle fatigue at sea level.

METHODS

VOLUNTEERS

Eight male soldiers served as volunteers. All were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the volunteers were mean age 18.6 ± 0.3 yr (SE), weight 79.5 ± 5.1 kg, and height 179.1 ± 2.0 cm.

PROCEDURES

Volunteers participated in at least four practice sessions in normoxia (50 m, P_iO_2 = 159 Torr) over a two-week period prior to formal data collection to perform submaximal knee extensions and MVCs to ensure their familiarization with equipment, personnel, and procedures, and to learn to execute leg movements exclusively with the quadriceps muscles. All practice and subsequent testing sessions were conducted in the hypobaric chamber facility at USARIEM. Within the two-week practice session, volunteers attended the standard 45-min altitude chamber training session, which involves an actual chamber flight to altitudes less than 3200 m to acquaint them to the sensations of chamber flight and hypobaric exposure (volunteers were sedentary). Temperature and relative humidity during all sessions were comfortably maintained at 21 ± 2 °C and 50 ± 5%, respectively.

Each volunteer performed two peak power output tests: one session in normoxia and one session in hypobaric hypoxia (4300 m equivalent, P_iO_2 = 94 Torr). For a period of 24 hours prior to each scheduled test session, the volunteers were not allowed to perform any strenuous exercise involving their legs (weight lifting, running, etc.). On the day of the hypobaric session, the altitude chamber was decompressed to 4300 m (at the rate of 300 m/min). The volunteer was in hypobaria for approximately 30 min prior to the start of exercise. There was a minimum of two days between testing sessions to minimize the possibility of "low frequency" muscle fatigue of long duration (6,7). The testing sessions were conducted after a minimum of three hours post prandial. The dietary restriction was verified by dietary recall. Testing for each individual was conducted at approximately the same time of day to avoid possible performance variations due to diurnal factors.

The order of the normobaric and hypobaric testing sessions for the volunteers was randomly assigned. Exercise sessions were initiated with the volunteers performing knee-extension exercise with their right leg unattached to the device (0 watts) for four min then resting for four min. This was followed by a series of four-min exercise bouts with four min of passive rest between each bout. For each exercise bout, the amount of weight placed on the weight platform was increased. Volunteers performed at least four and as many as eight exercise bouts until in the final bout, power output could not be maintained for the full four min of exercise. For each volunteer, the amount of weight used for each exercise bout was based on his performance capabilities determined during the practice sessions prior to formal data collection. The four-min duration of the rest periods was chosen to minimize fatigue from the previous bout and also provide the benefit from previous warm up. Earlier observations (1) suggested that, in contrast to two-legged cycle exercise, a leveling-off criteria of oxygen consumption could not be used during one-legged knee extension due to unavoidable involvement of extraneous muscles. Therefore, peak power output and oxygen consumption were defined as the point at which the oxygen consumption/power output curve exhibits a large upward inflection (1).

To determine the rate of fatigue, maximal voluntary contractions were obtained prior to, during (at 2 min), and immediately after each four-min exercise bout. For measurement of MVC during dynamic exercise, the volunteer momentarily paused from performing submaximal knee extensions. The leg resting at 90° was quickly connected (by an investigator) to the fixed transducer anchored to a crossmember of the knee-extension device, and the MVC was initiated. At the conclusion of the MVC (2-3 sec), the leg was quickly released from the fixed transducer to resume submaximal knee extensions. Total elapsed time between dynamic exercise pause and resumption was 5 sec.

For accurate monitoring of the distance and rate of knee extension, a position transducer was used (Celesco Transducer Products Inc., Canoga Park, CA, model PT101-0100-111-1110) in conjunction with a light emitting diode (LED) unit designed and manufactured at USARIEM. The housing unit of the position transducer was positioned beneath the weight platform with its guide wire attached to the underside center of the platform. The transducer provided a voltage output that was proportional to wire displacement. Thus, with each vertical ascent and descent of the platform, the wire was drawn from and returned to the housing by a length equal to the leg extension. To provide visual feedback to the subject about the distance and rate of knee extension, the LED unit, consisting of two adjacent columns of 14 LEDs, was placed directly in front of the subject. The right column of LEDs was wired in series to the position transducer such that the number of LEDs lighted was proportional to the length of wire manually displaced by the leg extension. The left column was connected to a synthesizer/function generator (Hewlett-Packard, model 3325a), which automatically and sequentially illuminated from 1 (at the 90° starting position) to 15 (at the 150° full extension position) to 1 LED (return to 90° starting position) at the predetermined rate (1Hz). To maintain the correct distance and rate of knee extension, the volunteer had to continually match the right column of LEDs, which he controlled by leg movement to the left column, which was controlled by the synthesizer/function generator, during both knee extension and return. Adherence was easily determined by the individual and investigator. Inability to synchronize the right column with the left column for three consecutive extensions constituted muscle exhaustion. Leg-extension distance was determined by measurement over the 60° range of motion. Force produced throughout each extension was measured with the force transducer attached at the ankle. Average force of each extension in kilograms (or kiloponds) was multiplied by the distance of leg extension (meters) to determine work (kpm). To determine power output (watts, Nm/sec or Joules/sec), kp was converted to newtons (1kp = 9.80665N) and divided by the time of the test interval (60 sec). For example, with an average force of 11 kp, a leg extension distance of 0.410 meters, and 59 knee extensions for a 60-sec period, power output would equal 43.50 watts.

A Sensormedics Metabolic Measurement Cart (MMC, model 2900) was used to collect respiratory metabolic data via low-resistance, one-way valves during the entire exercise session. Oxygen consumption was calculated and printed every 20 sec. The MMC was calibrated prior to each test with certified, medical grade gases. The metabolic data presented includes those collected in the last minute of each bout of exercise.

RESULTS

Peak power output decreased from (mean ± SD) 35.1 ± 13.7 watts (range 15.7 - 51.2 watts) at sea level to 26.6 ± 9.8 watts (14.3 - 42.6 watts) at altitude. Maximal oxygen consumption also decreased from 978.1 ± 170 ml/min (760 - 1296 ml/min) at sea level to 890.1 ± 152 ml/min (689 - 1174 ml/min) at altitude.

VALIDITY: COMPARISON TO PREVIOUS REPORTS

While several studies have used modified cycle ergometers to study knee-extension exercise under a variety of experimental conditions (1,2,3,18,20), only two have reported their data in such a way that the results can be directly compared to the results of the present study. Data from these two studies (1,18) are included in **FIGURE 2**. The data points represent mean sea-level values that are similar in range to the present study. The figure contains a regression line drawn for six mean values (range 0 to 50 watts) from one study (1) and a line connecting two mean values (25 and 50 watts) from the other study (18). There is no apparent difference between the two lines at the shared range (25 to 50 watts). Also included are all data (50 data points) collected at sea level from all volunteers during the present study. It is obvious that data from all three studies are comparable.

To facilitate comparison, it was necessary for current data to be analyzed similarly to those of previous studies (1,18). That is, the current data were collapsed into five-watt intervals (10-15, 15.1 to 20, etc), means of the intervals were calculated, and a regression line was drawn through the means. The result of this approach is illustrated in **FIGURE 3**. Note the striking similarities of the slopes, intercepts, and variance of the three studies. (The slope, intercept, and variance values of Richardson et al., (18) include a mean data point at 75 watts, which was omitted from the figure because it was far beyond the range of our volunteers). The slope in the present study is approximately the mean of the two published values and the intercept (at 0 watts) is nearly identical to that of Andersen et al. (1).

Another method of analyzing the present data is to perform regression analysis of oxygen consumption relative to power output for each volunteer, then determine and plot the mean slope and intercept of the eight regression equations. Representing data in this manner, however, has limited value for direct comparisons between the current and earlier studies (1,18) because the earlier studies did not report results in this manner. Also, with a small sample size (n=8), this type of analysis may not be appropriate, since only one or two atypical responses could result in misinterpretation of the data. For example, the result of this method of regression analysis is contrasted to the result obtained by performing regression analysis on means of the 5-watt increments and is illustrated in **FIGURE 4**. Note that the mean slope calculated from the individual regression analyses is slightly more steep than the slope of the raw data while the intercept and variation among the studies are very similar. The reason for the difference appears to be due to the slopes of two of the volunteers in the present study being much greater than expected. Not including the slope values of these two volunteers reduces the mean slope ± SD from 16.3 ± 5.9 to 13.4 ± 2.7 ml O_2/watt, a value similar to the slope of the combined group data and to the slopes reported by Andersen et al., (1) and Richardson et al. (18). Exactly why the data of these two volunteers differs is difficult to determine. However, they were the first and third smallest volunteers (based on body surface area) and had the smallest leg lengths, distance of leg travel with each extension, peak power output, and force development during MVC. It is unknown if smaller (or any) individuals in the previous studies also had steeper slopes of oxygen consumption relative to power output.

REPRODUCIBILITY: WITHIN-STUDY COMPARISON

Individual oxygen consumption values collected for identical power outputs in normoxia and hypoxia are plotted with respect to a line of identity in **FIGURE 5**. Because peak power output was reduced for all volunteers during hypoxic exposure, the number of power outputs available for comparison between the two sessions was necessarily reduced (to 33 data points). As shown, there are no meaningful differences in slope or intercept between the line of identity and the data from the current study. In fact, within the range of actual data collection (350 to 1100 ml/min), the lines are nearly identical with little variation from one testing session to another ($r^2 = 0.90$).

MUSCLE FATIGUE DURING SUBMAXIMAL KNEE-EXTENSION EXERCISE

An example of the data collected for determination of rates of fatigue are illustrated in **FIGURE 6**. Mean data for 50%, 75%, and 100% of peak power output at two min and at the end of exercise are presented as percentage declines relative to pre-exercise MVC. As shown, the percentage fall in MVC increases with increases in power output in dynamic exercise. The decline in MVC is apparent after at least two min of dynamic exercise. At the end of four min of exercise, there is a 10% (ns), 18.5% ($p=0.003$), and 38.4% ($p<0.001$) decline in MVC for 50%, 75%, and 100% peak power output, respectively. Also, the peak forces developed during dynamic knee extension (data not shown) at the three exercise intensities are 14.3%, 20.5%, and 27.0%, respectively, of the MVC determined at the start of exercise. It is interesting that significant accelerations in fatigue rate occurred only when the peak force of each knee extension required to maintain power output was approximately equal to or greater than 20% of MVC. These results are similar to those obtained during sustained, static exercise, which has indicated that rapid muscle fatigability occurs when the sustained force exceeds 15% MVC (23).

DISCUSSION

Modifying a standard bicycle ergometer to study isolated quadriceps muscle activity during dynamic exercise, as other laboratories have done (1,2,3,18,20), involves skilled engineering capabilities, is costly, is restricted to exercise with one leg only, and may alter its suitability as a standard bicycle ergometer. Furthermore, while physiological and other changes (e.g., lactate, ATP, and glycogen) during an exhausting exercise bout have been studied, all of the reports have lacked a means of relating the changes to a quantitative index of fatigue such as a decline in MVC. The current knee-extension device was designed and built to overcome these limitations.

For the current device to be accepted as an alternative to knee-extension devices using modified bicycle ergometers (1,18), it must provide a similar slope of relationship between an increase in work rate and change in oxygen consumption. The slope of 13.8 ml O_2/watt in the present study is midway between the derived values of 13.1 ml O_2/watt of one (1) and the 14.7 ml O_2/watt of the other (18). This agreement indicates that there is similarity among subjects regarding the relationship of work rate to oxygen consumption even though the participants in each study had apparently differing exercise capabilities, as judged by differences in reported maximal power outputs. Intraindividual oxygen consumptions for identical power outputs also were similar among testing days in the current study (**FIGURE 5**). Small deviations in oxygen consumption from the line of identity for any given external mechanical work rate likely represent normal day-to-day biological variation, since the components defining power output--distance of leg travel, force output, and rate of knee extension--remained constant among testing sessions.

The knee-extension exercise device also provides a simple yet precise means for measuring reduction in force generating capacity as a quantitative index for the monitoring of muscle fatigue. That differences in muscle fatigability could be discerned for relatively small changes in exercise intensity and elapsed exercise time (every two min) indicates that the precision of the current knee-extension device is acceptable for other related applications of major interest to the Armed Forces, such as the effect of environmental, nutritional, or pharmacological intervention on dynamic exercise performance.

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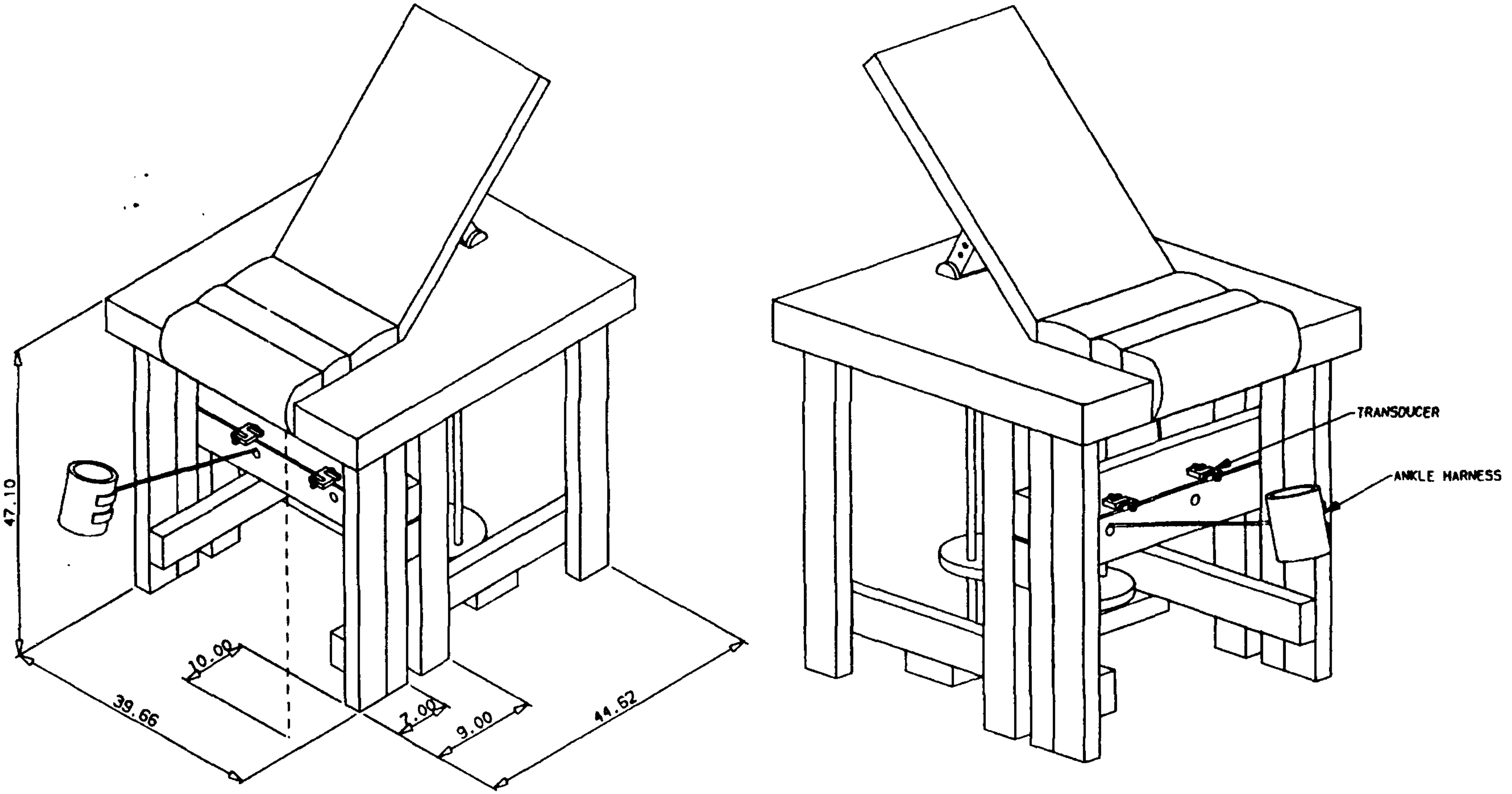
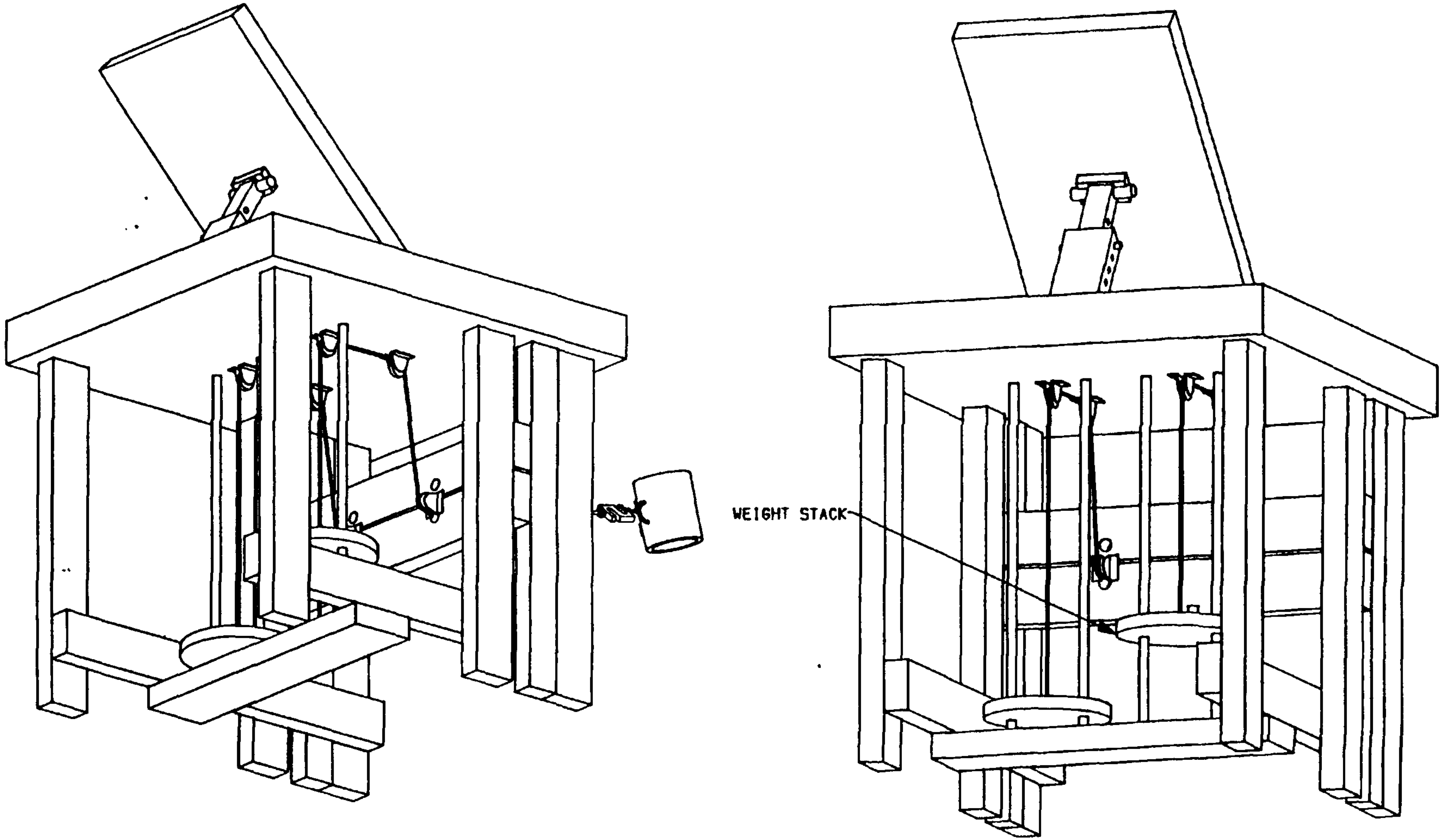
FIGURE 1



(a)

(b)

FIGURE 1 (continued)



(c) (d)

FIGURE 2
RELATIONSHIP OF OXYGEN CONSUMPTION AND POWER OUTPUT:
RAW DATA OF PRESENT STUDY COMPARED TO PREVIOUS STUDIES

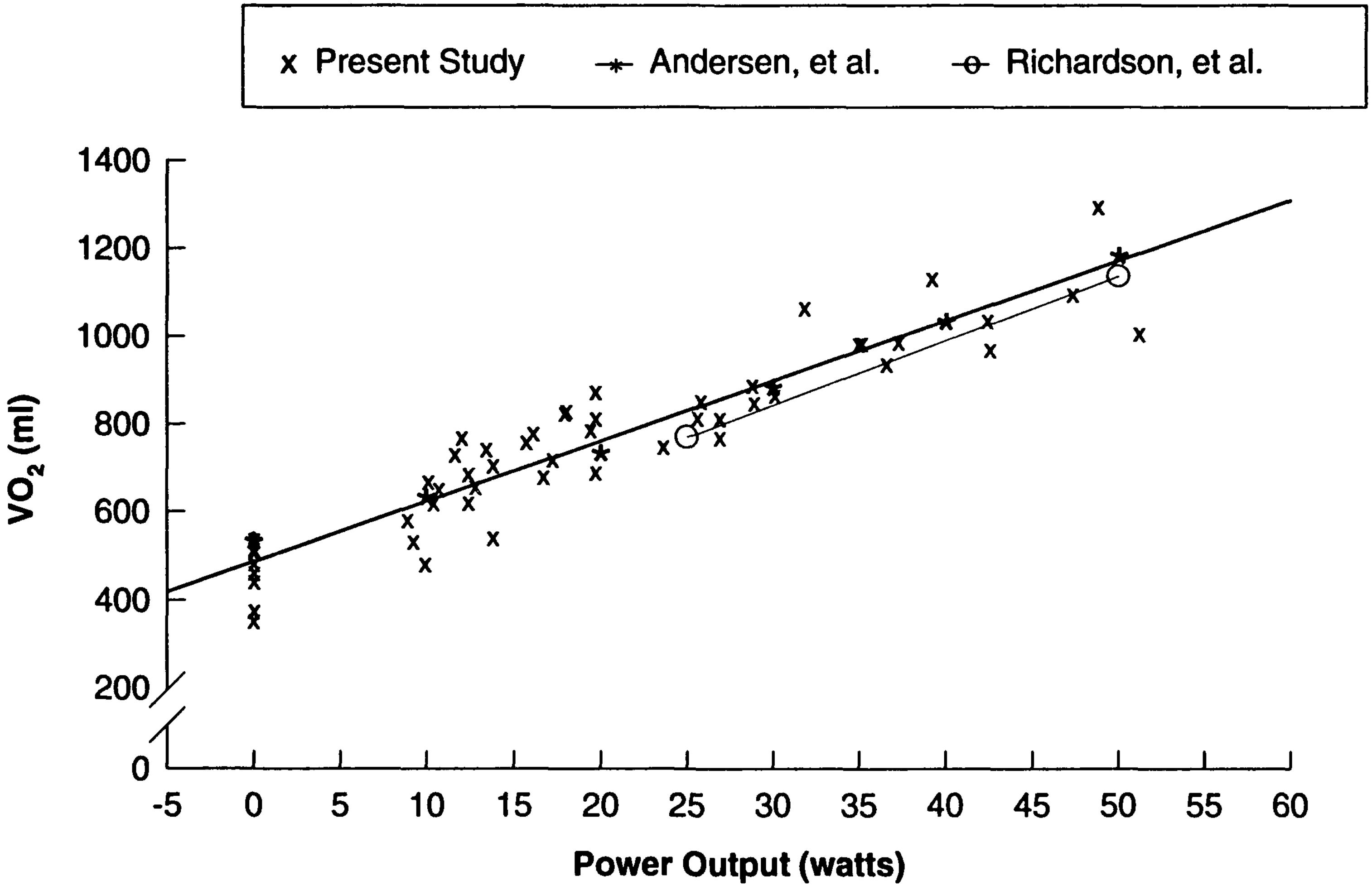


FIGURE 3
RELATIONSHIP OF OXYGEN CONSUMPTION AND POWER OUTPUT:
GROUPED DATA OF PRESENT STUDY COMPARED TO PREVIOUS STUDIES

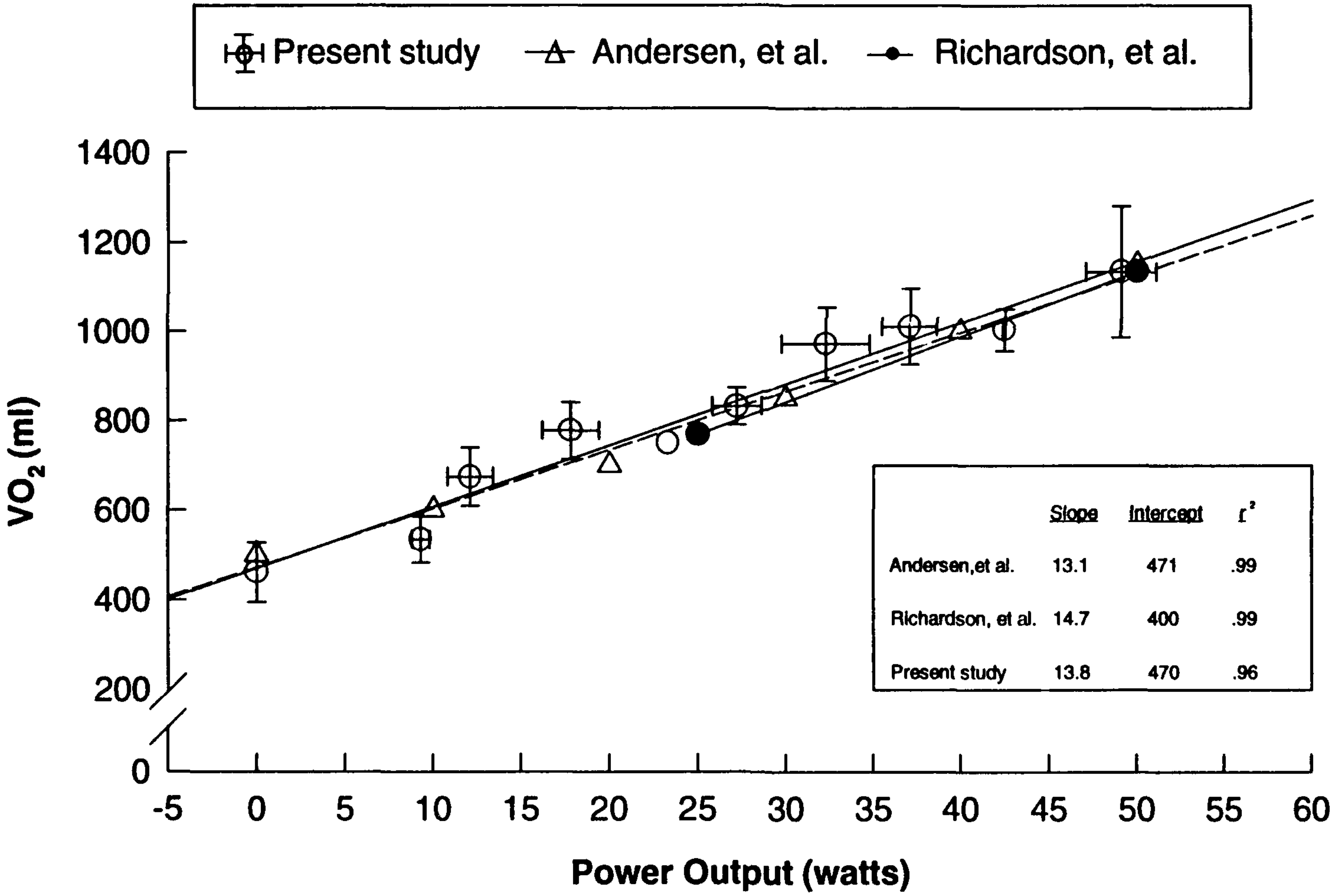


FIGURE 4
COMPARISON OF TWO METHODS OF REGRESSION ANALYSES

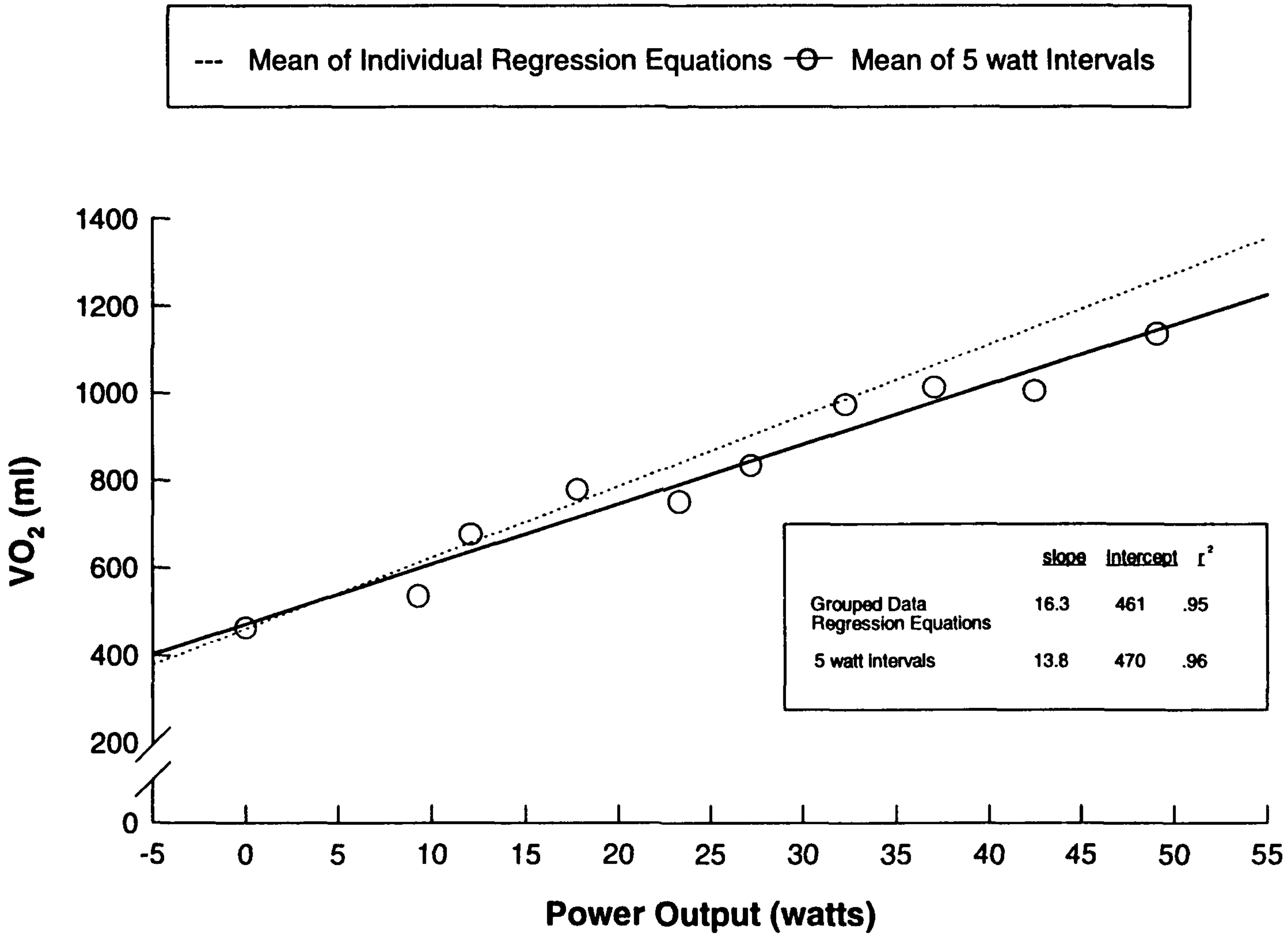


FIGURE 5
OXYGEN CONSUMPTION
IDENTICAL POWER OUTPUT

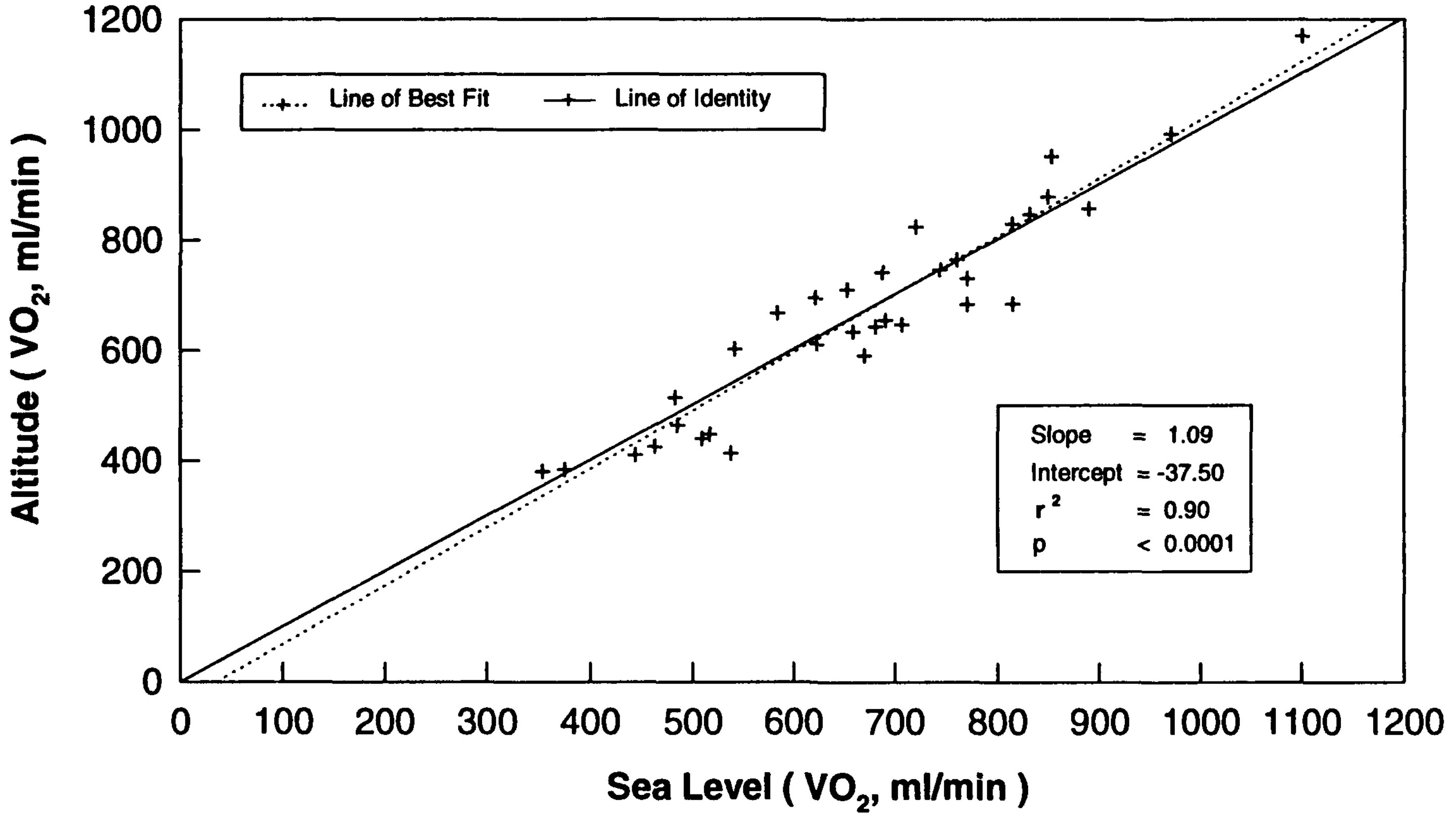
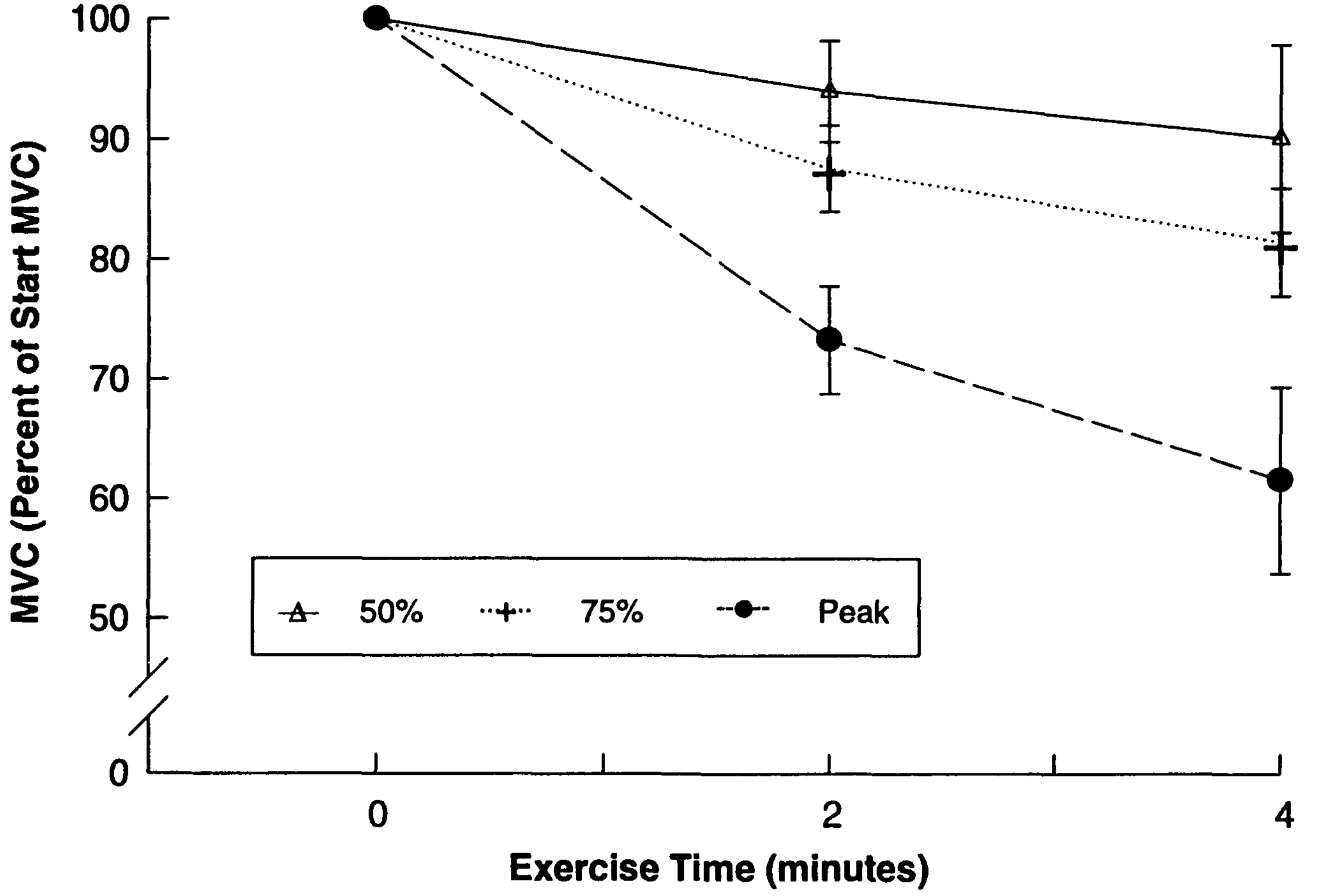


FIGURE 6
FATIGUE RATE AT 50%, 75% and 100% of PEAK POWER OUTPUT



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