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Cardiorespiratory and aerobic demands of squat exercise

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Squatting, a traditional resistance exercise classified as strength training, relies on anaerobic pathways, but its aerobic aspects remain unclear. We examined heart rate and oxygen demand during squats, exploring variations across different strength statuses. It fills gaps in understanding the cardiorespiratory effects of squatting, especially during multiple sets. Twenty-two young healthy resistance trained men (age: 28 ± 4 years) participated. Maximal oxygen consumption (VO_2max) and 1 repetition maximum (RM) of squat were measured. Participants performed 5 sets of squat exercises at 65% of 1RM for 10 repetitions with 3-min rest intervals. Heart rate and pulmonary gas exchange were measured during the squat exercise. Participants were divided into high strength (HS; upper 50%) and low strength (LS; lower 50%) groups based on a median split of their 1 RM squat values (normalized to their body weight). During 5 sets of squat exercise, oxygen consumption (VO_2) increased up to 47.8 ± 8.9 ml/kg/min, corresponding to 100.6% of predetermined VO_2max. The HS group achieved a greater highest point of VO_2 in relation to VO_2max than the LS group (108.0 vs. 93.7%). During the exercise intervals, VO_2 exceeded VCO_2, while during the rest intervals, VCO_2 surpassed VO_2. Our findings suggest that the oxygen demand during squatting is notably substantial, which may vary according to the training status.

Keywords Aerobic capacity, Powerlifting, Resistance exercise, Oxygen consumption, Exercise training

Resistance exercise is characterized by fewer repetitions and shorter periods of muscle contractions compared to continuous exercises. Due to its limited reliance on aerobic energy and the involvement of larger muscle groups, it has traditionally been classified as an anaerobic power exercise[1]. However, given the intricate interplay between aerobic and anaerobic energy systems in almost all types of exercises, it may not be accurate to classify resistance exercise as exclusively a strength or power exercise[2]. Emerging evidence suggests that aerobic metabolism is more involved in resistance exercise than previously understood. For example, the second sprint bout on a cycle ergometer has been shown to have a 49% aerobic contribution[3]. Additionally, performing 1 min of leg press induced VO_2 similar to that of performing 1 min of sprint in an ergometer cycle[4]. These findings highlight the possibility that aerobic metabolism can contribute relatively quickly, even during high-intensity, short-duration exercises[3].

Indeed, resistance exercises utilizing multiple joints and larger muscle mass (e.g., leg press vs. chest fly) are known to increase oxygen demands more than single-joint exercises[5–7]. There is also evidence that resistance exercises can increase VO_2max[8]. Additionally, Ratamess et al.[9] reported a significant increase in VO_2 up to 20–25 ml/kg/min during 10 reps of squats for five sets at 75% of their 1RM in resistance-trained men. This study[9] further reported higher VO_2 levels with shorter rest intervals and during squat exercises compared to bench press exercises. The result of this study[9] suggests aerobic demands of resistance exercise when performed in multiple sets, as demonstrated by the significant increase in VO_2. However, participants did not complete the assigned repetitions as the number of sets increased, posing a challenge to comprehensively understand the aerobic component of squat exercise. Furthermore, this study[9] did not report participants' VO_2 relative to VO_2max. Therefore, aerobic demand of squat exercises relative to maximal aerobic fitness was not determined. More recently, Garnacho-Castaño et al.[10] aimed to evaluate the VO_2 slow component and mechanical efficiency during half squat exercise at lactate threshold intensity. The results showed a gradual increase in VO_2 slow component and energy expenditure, alongside a decrease in half squat efficiency and jump performance post-exercise. Although

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these findings highlight the relatively high aerobic demands and fatigue mechanisms in resistance exercises. Therefore, a knowledge gap remains regarding whether multiple sets of squat exercise, when performed at an intensity where participants complete the assigned task, would lead to an increase in VO_2 relative to VO_2max. This information is critical as it may serve as an indicator of the aerobic intensity of such exercise.

Cardiorespiratory responses to aerobic exercise are known to vary according to training history and fitness levels[8,11–13]. Similar to individuals with higher cardiorespiratory fitness who tend to exercise at a higher intensity, leading to increased oxygen demand, those with greater muscle strength may engage in resistance exercise at an intensity that also elicits a higher oxygen demand. However, it is unknown whether sessions of squat exercise would trigger cardiorespiratory and physiological responses that could vary among individuals with differing levels of muscular strength.

Furthermore, two distinct cardiopulmonary responses emerge during resistance exercises are modulated by rest intervals and breathing patterns. Unlike continuous aerobic exercise such as running and cycling (unless they involve circuit or interval training), resistance exercise is performed with rest intervals. In addition, resistance exercises may involve multiple distinct phases: the pre-exercise phase, the exercise phase, and the inter-set rest phase. Therefore, observing cardiorespiratory responses is worthwhile not only during exercise but also during rest intervals because they can vary significantly. The unique breathing pattern in resistance exercises, where individuals breathe once per repetition during movements like squats, could impact cardiorespiratory responses. Pre-exercise sets may involve anticipatory increases in heart rate and VO_2, known as the central command[14], while the exercise phase typically encounters elevated VO_2 and heart rates due to muscular contractions[15]. Inter-set phases allow partial recovery but still maintain elevated cardiopulmonary activity compared with the baseline[15]. Yet, a comprehensive exploration of these responses during resistance exercise and rest intervals remains largely unreported in the existing literature.

Therefore, the primary aims of the present study were (1) to determine the magnitude of the cardiorespiratory response during squat exercise, including rest intervals relative to maximal aerobic capacity, and (2) to examine whether the cardiorespiratory response to squat exercise varies between individuals with higher and lower relative strength. We hypothesized that the oxygen demand for squat exercises would be high (i.e., $\geq 85\%$ of or exceeding the VO_2max level).

Methods

Participants

Twenty-two healthy, young male adults, aged between 20 to 39 years old with over 1 year of experience performing resistance exercise (1RM for squat > 120% of their body weight) were recruited for the study. Participants were verbally asked about their resistance exercise habits/history, but they were not asked about other sport activities or the total time spent on resistance exercise. All participants provided written informed consent prior to participation in the study. The study protocol was approved by the Institutional Review Board of Yonsei University. All experiments were performed in accordance with relevant guidelines and regulations.

Study protocol

Participants visited the laboratory on three separate days at the same time of day, with a minimum interval of 48 h between the visits. The actual recovery intervals between testing for all study participants ranged from a minimum of 3 to 5 days. Participants were instructed to refrain from food and caffeine intake for at least 4 h, tooth brushing and smoking for 2 h, and alcohol consumption and strenuous lower-body exercise for 24 h prior to each examination. During the first visit, anthropometric variables were measured, and cardiorespiratory exercise testing was conducted to determine VO_2max. During the second visit, 1RM of the back squat exercise was assessed. Participants were divided into high and low strength groups based on 1RM squat strength/body weight using a median split. During the third visit, participants performed five sets of back squat exercises at 65% 1RM level after a general dynamic warm-up. The schematic of the study protocol is illustrated in Fig. 1.

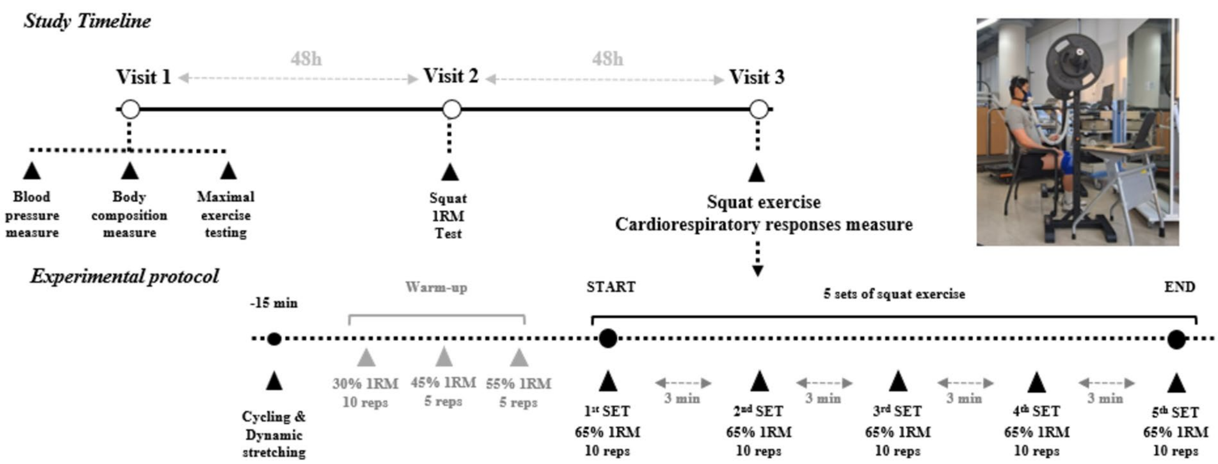

Figure 1. Schematic of the study protocol. 1RM: one-repetition maximum.

Measures

Anthropometry

Height to the nearest 0.1 cm and body weight to the nearest 0.1 kg were measured using an electric extensometer and scale (BSM 340, Biospace, Korea), respectively. Body fat percentage and skeletal muscle mass were calculated using raw data obtained from the bioelectrical impedance analysis (InBody 720; Biospace, Seoul, South Korea)[16].

Graded exercise testing

The exercise test was performed on a motorized treadmill and a computerized cardiac stress test system (Q-stress TM65, Cardiac Science, USA) using the Bruce protocol. Participants wore a non-rebreathing facemask (Rudolph series 7910, Hans Rudolph, USA) and their breath-by-breath $\dot{V}O_2$ was continuously sampled using a computerized metabolic measurement system (True One 2400, Parvo Medics, USA). $\dot{V}O_2$ data were recorded at 10-s intervals. The modified Borg's rating of perceived exertion scale (RPE; 1–10)[17] was used to monitor the participants' exertion levels every 2 min (at each stage). $\dot{V}O_2$max was determined if any 2 or more of the following 4 criteria were observed: (1) Respiratory exchange ratio (RER) ≥ 1.15; (2) heart rate ≥ 90% of age-predicted maximal heart rate (208 – (0.7 × age)[18]; (3) RPE ≥ 9; and a plateau in $\dot{V}O_2$ with increasing exercise intensity.

One-repetition maximum

The 1RM test of the back squat exercise was performed to measure muscular strength and determine the relative load (%1RM). The warm-up consisted of 5 min of pedaling on a cycle ergometer (95R Achieve Recumbent Lifecycle Bike, Technogym, Cesena, Italy) and six dynamic stretches. Then, participants performed the following specific warm-up sets of squatting at a percentage of their estimated 1RM (e1RM; based on training experience): one set of 10 repetitions at 50% e1RM followed by a 120-s rest (1 × 10 × 50% e1RM 120-s rest); 1 × 5 × 60% e1RM 120-s rest; 2 × 2 × 70% e1RM 120-s rest; 1 × 1 × 80% e1RM 120-s rest; 1 × 1 × 90% e1RM 180-s rest; 1 × 1 × 95% e1RM 180-s rest (100% or greater for 1RM attempts). Next, up to three trials of 1RM activity were performed with a minimum of 3 min of rest between each trial. This protocol was chosen because at least 3 min of rest interval allows for greater strength activities through the maintenance of training intensity, which aligns with the goal of optimizing muscular strength development[17]. Participants were encouraged to put forth their maximal effort to move as explosively as possible while maintaining a consistent technique and squat depth. The weight of the greatest load lifted from a full range of motion was recorded as the back squat exercise at 1RM.

Cardiorespiratory measurements

Participants underwent a warm-up routine that included 5 min of pedaling on a cycle ergometer and dynamic stretching exercises. Following the general warm-up, the participants performed the following warm-up squat exercises: one set of 10 repetitions at 30% 1RM, one set of 5 repetitions at 45% 1RM, one set of 5 repetitions at 55% 1RM. The participants rested for 5 min to restore their basal state $\dot{V}O_2$ and heart rate before commencing the squat exercise. During the entire squat exercise protocol, participants wore a non-rebreathing facemask (Rudolph series 7910, Hans Rudolph, USA), and breath-by-breath $\dot{V}O_2$ was continuously recorded using a computerized metabolic measurement system (True One 2400, Parvo Medics, USA). The highest $\dot{V}O_2$ and $\dot{V}CO_2$ for each set of the squat exercises were averaged, and the average of the highest $\dot{V}O_2$ and $\dot{V}CO_2$ of 5 sets was calculated. Peak $\dot{V}O_2$ during 5 sets was determined as the highest $\dot{V}O_2$ achieved during the entire squat exercise. Changes in minute ventilation (expired volume) and ventilation efficiency (minute ventilation/$\dot{V}CO_2$) were also recorded. Heart rate was continuously recorded using a heart rate monitor (Polar H7, Polar Electro, Finland), and the average heart rate of each set of the squat exercise was reported. The load was set at 65% 1RM, and the squatting protocol consisted of five sets of 10 repetitions with 3 min of inter-set rest interval. All participants completed all five sets with 10 repetitions. Trained research staff supervised the squat motion to ensure proper posture (i.e., greater trochanter of the femur lower than the top of the patella). The Borg RPE scale was used to monitor participants' exertion levels at the end of each set[17].

Statistical analyses

Statistical analyses were conducted using the SPSS software (IBM Corp., Chicago, IL, USA). Tests for normality were performed using the Shapiro–Wilk test. Participants' characteristics and cardiorespiratory responses were analyzed using descriptive statistics. The differences in cardiorespiratory variables during squat exercise between the high and low strength groups were analyzed using independent sample t-tests for variables exhibiting normal distributions or the Mann–Whitney U test for variables violating normality, as appropriate. Statistical significance was set at a two-tailed P-value < 0.05.

Informed consent statement

All participants provided written informed consent prior to participation in the study. Prior to participation, all participants provided written informed consent. This consent covered both participation in the study and the publication of any identifying information or images in an online open-access publication. Specific consent was obtained to publish information or images that could potentially lead to the identification of individual participants. All efforts have been made to ensure confidentiality and anonymity, and identifiable information has only been included with the explicit permission of the participants.

Results

Participants characteristics

Characteristics of the study participants are presented in Table 1. Participants in the high strength group had significantly higher body weight, skeletal muscle mass, 1RM of squats, 1RM of squat/body weight, and squat working load (65% of 1RM) than participants with low strength (all $P < 0.05$).

Cardiorespiratory responses during squat exercise

The cardiorespiratory outcomes of each set of squat are shown in Table 2. The highest heart rate was observed at 5th set, 175 ± 9 bpm, corresponding to 89.7% of maximal heart rate. The highest $\dot{V}O_2$ during squat exercise was observed at 5th set, 47.8 ± 8.9 ml/kg/min, corresponding to 99.4% of $\dot{V}O_2$max. When highest $\dot{V}O_2$ achieved during each set of five sets were averaged, participants were exercising at 92.2% of their $\dot{V}O_2$max.

When cardiorespiratory response to multiple sets of squat were observed according to participants muscular strength, participants in the high strength group reached higher $\dot{V}O_2$ in relation to $\dot{V}O_2$max during squat exercise (108.0 vs. 93.7%; Fig. 2) compared to participant with the low strength group. When highest $\dot{V}O_2$ achieved during each set of five sets were averaged, participants with higher strength reached significantly higher $\dot{V}O_2$ in relation to $\dot{V}O_2$max compared to participants with lower strength (98.3 ± 8.0 vs. 86.1 ± 5.9%; $P = 0.026$; Fig. 3).

Changes in cardiorespiratory measures during the five sets of squat exercises and rest intervals in representative participants are presented graphically (Fig. 4). During exercise, both $\dot{V}O_2$ and $\dot{V}CO_2$ increased rapidly in response to squat exercise and then decreased during rest intervals. However, $\dot{V}CO_2$ remained higher than $\dot{V}O_2$ during rest intervals, which resulted in extremely high $\dot{V}CO_2/\dot{V}O_2$.

To enhance the understanding of the changes in the relationship between ventilation volume and CO_2 production after the five sets of squat exercises, the change in ventilation efficiency is presented graphically (Supplemental Fig. 1). Overall, minute ventilation, heart rate, and ventilation efficiency increased across increasing exercise sets.

The cardiorespiratory outcomes of each set of squat exercises across two groups with different strength are shown in Supplemental Table 1. There were no significant group differences in patterns of cardiorespiratory responses during five sets of squat exercise between the groups. The comparison of relative exercise intensity, as assessed by the heart rate peak in relation to the maximal heart rate during the squat exercise, is presented in Supplemental Fig. 2. Peak relative heart rate in relation to maximal heart rate were 90.0%, 91.0%, and 90.0% for all, high, and low strength groups, respectively, with no significant difference between the groups ($P = 0.245$). The heart rate responses during squat exercise between high and low strength groups are shown in Supplemental

	All (n = 22)	High strength (n = 11)	Low strength (n = 11)	P-value
Age, years	27.6 ± 4.1	27.4 ± 4.5	27.9 ± 3.8	0.761
Height, cm	176 ± 6	179 ± 6	174 ± 6	0.084
Body weight, kg	84.0 ± 11.5	90.7 ± 10.4	77.4 ± 3.1	0.004
Skeletal muscle mass, kg	38.6 ± 4.7	41.8 ± 3.5	35.3 ± 3.1	< 0.001
Body fat, %	19.6 ± 5.0	19.5 ± 5.6	19.8 ± 4.5	0.892
Squat 1RM, kg	141.4 ± 31.3	168.4 ± 16.4	114.4 ± 13.4	< 0.001
Squat 1RM/body weight, %	167.3 ± 23.6	186.5 ± 15.0	148.2 ± 11.6	< 0.001
$\dot{V}O_{2max}$, ml/kg/min	47.5 ± 4.9	46.0 ± 5.5	49.0 ± 3.8	0.155
HR_{max}, bpm	195 ± 9	191 ± 7	198 ± 10	0.056

Table 1. Selected participant characteristics. Data are presented as means ± SD. P-value tests for the difference between squat strength statuses were performed using independent samples t-tests or the Mann–Whitney test, as appropriate. 'High strength' and 'Low strength' groups indicate higher relative strength (above median) and lower relative strength (below median), respectively. 1RM: one-repetition maximum; $\dot{V}O_{2max}$: maximal oxygen consumption; HR_{max}: maximal heart rate.

	$\dot{V}O_2$, ml/kg/min		$\dot{V}CO_2$, ml/kg/min		VE, L/min		HR, bpm		
All	Exercise	Rest	Exercise	Rest	Exercise	Rest	Exercise	Rest	RPE (1–10)
1st set	39.6 ± 8.9	15.8 ± 3.0	33.2 ± 6.7	19.8 ± 3.4	61.3 ± 14.0	38.3 ± 8.6	156 ± 14	119 ± 13	7 ± 1
2nd set	42.0 ± 8.6	14.9 ± 2.9	35.8 ± 7.4	19.1 ± 3.1	69.4 ± 15.1	39.9 ± 10.0	164 ± 12	125 ± 15	7 ± 1
3rd set	43.0 ± 7.6	15.3 ± 2.9	35.9 ± 5.3	18.6 ± 3.3	75.6 ± 13.7	41.7 ± 15.3	170 ± 11	133 ± 15	8 ± 1
4th set	46.2 ± 8.4	16.3 ± 2.4	37.3 ± 6.4	19.2 ± 3.7	80.6 ± 14.3	44.6 ± 16.3	173 ± 10	138 ± 14	9 ± 1
5th set	47.8 ± 8.9	15.8 ± 3.1	37.7 ± 6.7	18.0 ± 4.5	85.7 ± 12.9	44.4 ± 15.8	175 ± 9	135 ± 15	10 ± 1
Average of 5 sets	43.7 ± 3.3	15.6 ± 0.5	36.0 ± 1.8	19.0 ± 0.7	74.5 ± 9.5	41.8 ± 2.8	167 ± 11	130 ± 8	8 ± 1

Table 2. Cardiorespiratory responses during squat exercise. Data are means ± SD. Values at each set indicate the highest value for exercise intervals and the average value for rest intervals. $\dot{V}O_2$: oxygen consumption; VE: minute ventilation or expired volume; HR: heart rate; RPE: rating of perceived exertion.

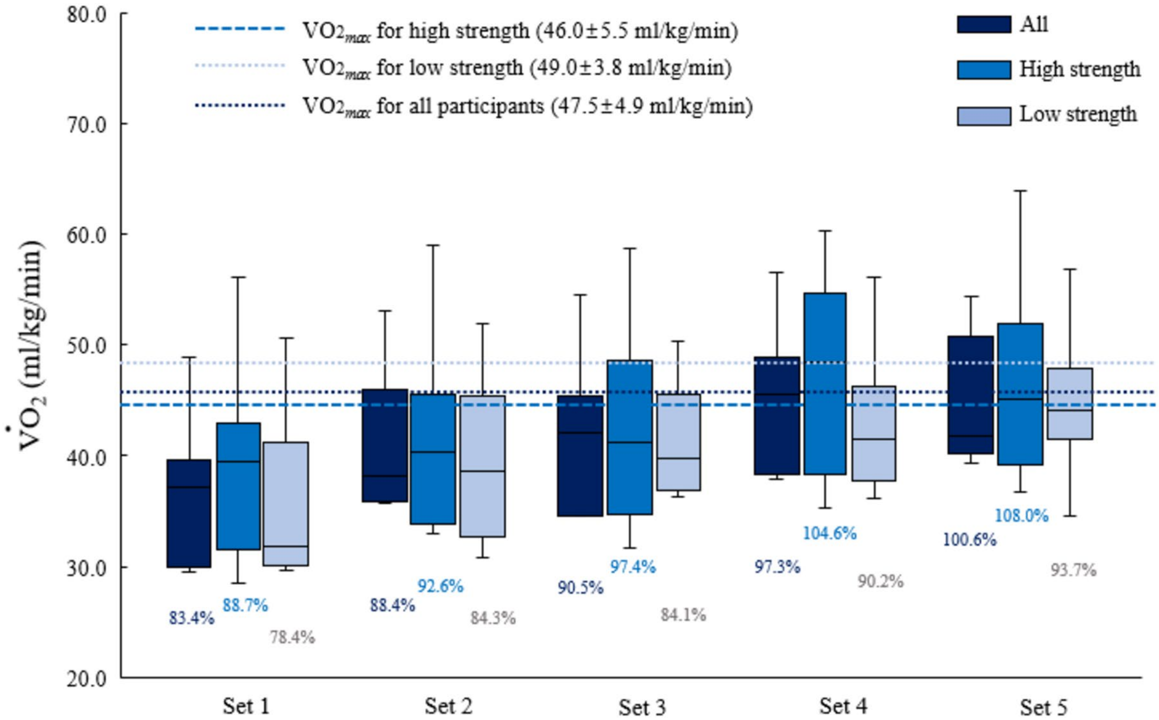

Figure 2. Oxygen consumption and the mean highest oxygen consumption in relation to maximal oxygen consumption of five sets during squat exercise (exercise intervals only). Data are presented as means ± SD. 'High strength' and 'Low strength' groups indicate higher relative strength (above median) and lower relative strength (below median), respectively. The top and the bottom lines of the box indicate the 75th percentile and 25th percentile values, respectively, and the line in the middle indicates the 50th percentile value. The whiskers indicate the maximum and minimum values that were not extreme values. Values under each box indicate the precent rate of oxygen consumption in relation to maximal oxygen consumption. No significant differences in oxygen consumption were observed between the two groups within any sets of squat exercises.

Fig. 3. No significant differences in heart rate were observed between the two groups within any sets of squat exercises.

Discussion

The main questions of our study are to examine the maximal $\dot{V}O_2$ achieved during five sets of squat exercises (10 reps per set, 5 sets, 3 min rest interval, 65% of 1RM) in relation to predetermined $\dot{V}O_2$max and how these values differ according to participants' training status. Our study showed that the highest $\dot{V}O_2$ was observed during the 5th set of squat exercises, almost reaching 100% of the participants' predetermined $\dot{V}O_2$max. When the highest $\dot{V}O_2$ values were presented according to training status, participants with higher strength experienced an increase in $\dot{V}O_2$ during squat exercise up to 108% of their $\dot{V}O_2$max, while the highest $\dot{V}O_2$ of participants with lower strength was 93.7% of their $\dot{V}O_2$max, measured immediately after the final set. When the highest $\dot{V}O_2$ during five sets were averaged, participants reached over 90% of their $\dot{V}$O2max. Regardless of participants' training status, oxygen demand during squat exercise was extremely high.

An increase in $\dot{V}O_2$ during resistance exercises has been previously reported. However, there are substantial differences in the amount of $\dot{V}O_2$ between our study and previous studies[9,19]. Previous studies reported $\dot{V}O_2$ during squat exercises ranging from approximately 16 to 31.3 ml/kg/min depending on the length of the rest intervals[9,19]. In the present study, we observed values above 40 ml/kg/min, and in some participants, $\dot{V}O_2$ increased above 50 ml/ kg/min, exceeding their pre-determined $\dot{V}O_2$max. A significantly greater $\dot{V}O_2$ observed among our participants could be due to training status and the specific exercise protocol. The 1RM among our participants was 141.4 ± 31.3 kg, whereas the 1RM reported by Ratamess et al.[9] was 127.9 ± 31.1 kg. Furthermore, Ratamess et al.[9] employed higher intensity resistance exercise, set at 75% of 1RM, whereas our study employed a lower intensity, 65% of 1RM. Given that all participants in our study successfully completed 10 reps of squats until the fifth set whereas participants from Ratamess et al.[9] did not, the exercise in the current study elicited a higher demand for aerobic metabolism. Another rationale for the relatively higher $\dot{V}O_2$ during our squat exercise could be due to different squat techniques. In the present study, all participants were instructed to perform a full squat with a full range of motion. In contrast, other studies either utilized only half squats or did not specify the depth of the squat. Performing full squatting is likely to elicit a higher oxygen demand.

Interestingly, the levels of $\dot{V}O_2$ relative to $\dot{V}O_2$max and the highest heart rate relative to maximal heart rate clearly showed that multiple sets of resistance exercise could be considered as vigorous- or high-intensity cardiovascular activity[20–22]. When viewed from an intensity perspective, squat exercise can be classified as a form of vigorous- or high-intensity activity[22]. However, since vigorous- or high-intensity aerobic activity is defined

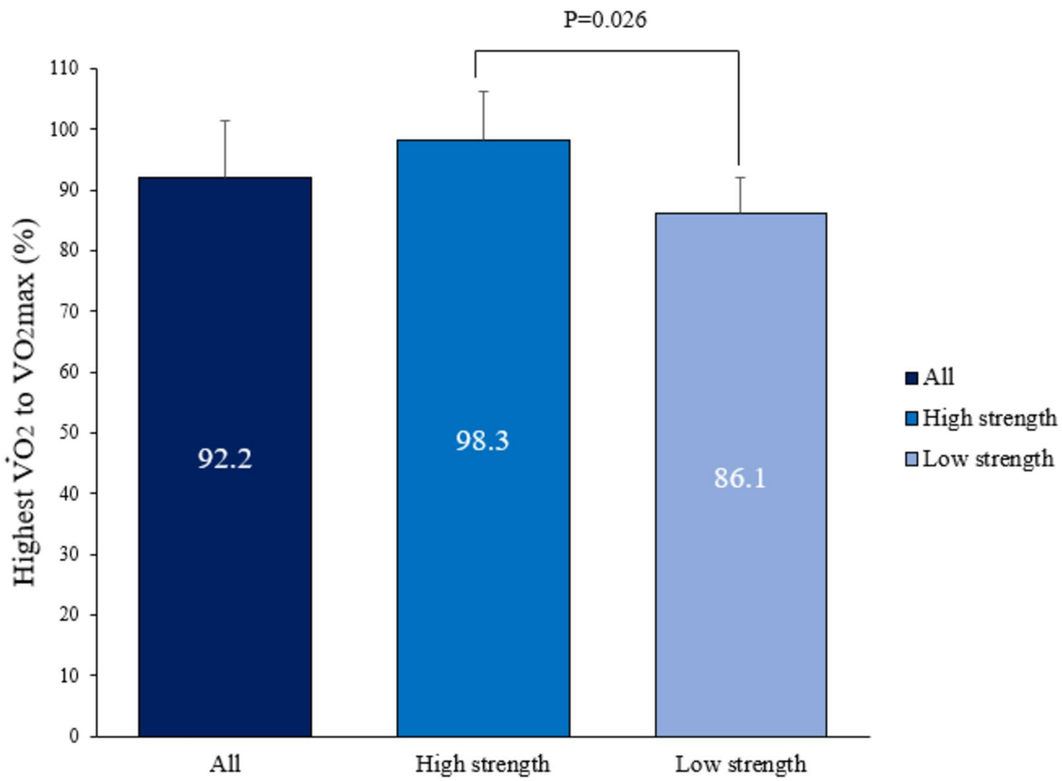

Figure 3. The mean highest oxygen consumption in relation to maximal oxygen consumption of five sets during squat exercise (exercise intervals only). Data are presented as means ± SD. 'High strength' and 'Low strength' groups indicate higher relative strength (above median) and lower relative strength (below median), respectively.

as an activity sustained for a prolonged period (e.g., ≥ 10 min)[22], squat exercise does not meet this criterion given the rest interval periods and therefore may not be described as such. Furthermore, our findings suggest that aerobic demand of resistance exercise is much greater when individuals could exercise at a higher intensity without sacrificing the volume, represented as number of repetitions. Among the participants with high strength, $\dot{V}O_2$ exceeded their pre-determined $\dot{V}O_2$ max at the 4th set of squat exercise, while participants with low strength reached up to 91.69% of their $\dot{V}O_2$max at the 4th set. One noteworthy implication of our study is that we examined the fluctuations in cardiorespiratory responses and RPE throughout the progression of squatting repetitions and sets. This stands in contrast to merely assessing the average and peak $\dot{V}O_2$ observed during one bout (i.e., session) of squatting.

During rest intervals, we observed higher CO_2 production than $\dot{V}O_2$ consumption, whereas the opposite was observed during the squat exercise periods. Typically, individuals only breathe once at each descending and ascending motion within a repetition during squat exercise, resulting in this distinctive breathing pattern that may cause a difference between pulmonary and cellular metabolic demands. During squatting exercises, participants may not be able to exhale sufficient amounts of CO_2 produced as a result of bicarbonate buffering process. Breathing is modulated by central and peripheral chemoreceptors, which may respond to CO_2 and H^+[23,24]. Although elevations in CO_2 and H^+ during squat exercise are the primary precursors to an increase in breathing, breathing is limited to the exercise rhythm during squatting, which may cause hypercapnic acidosis[24,25]. When breathing was no longer limited to the exercise rhythm during rest intervals, participants hyperventilated and exhaled CO_2. The increase in $\dot{V}CO_2$ in relation to $\dot{V}O_2$ was significant. While we did not measure the partial pressure of arterial CO_2, our results indicated that participants experienced hypercapnia during the five sets of squat exercise. This was demonstrated by the ventilatory efficiency (Supplemental Fig. 2), which showed a continuous increase with successive sets. Diverse breathing techniques employed during squatting may yield varying $\dot{V}O_2$ and $\dot{V}CO_2$ responses.

It is unclear whether training proficiency and subsequent muscular strength are determinants of cardiorespiratory fitness[26–29]. Highly trained individuals are accustomed to a higher training intensity and frequency than relatively less-trained individuals, leading to greater neuromuscular output and adaptation[30]. As such, highly trained individuals can perform a greater volume (load, repetitions, intensity) of squat exercises, which may result in a higher level of $\dot{V}O_2$ than those with low strength during resistance exercise. Interestingly, we observed that the high strength group showed a higher level of $\dot{V}O_2$ (relative; normalized to body weight) at the same relative intensity compared with the low strength group. These results suggest that aerobic demand of resistance exercise may be more evident among individuals with certain levels of resistance training status. In addition, the

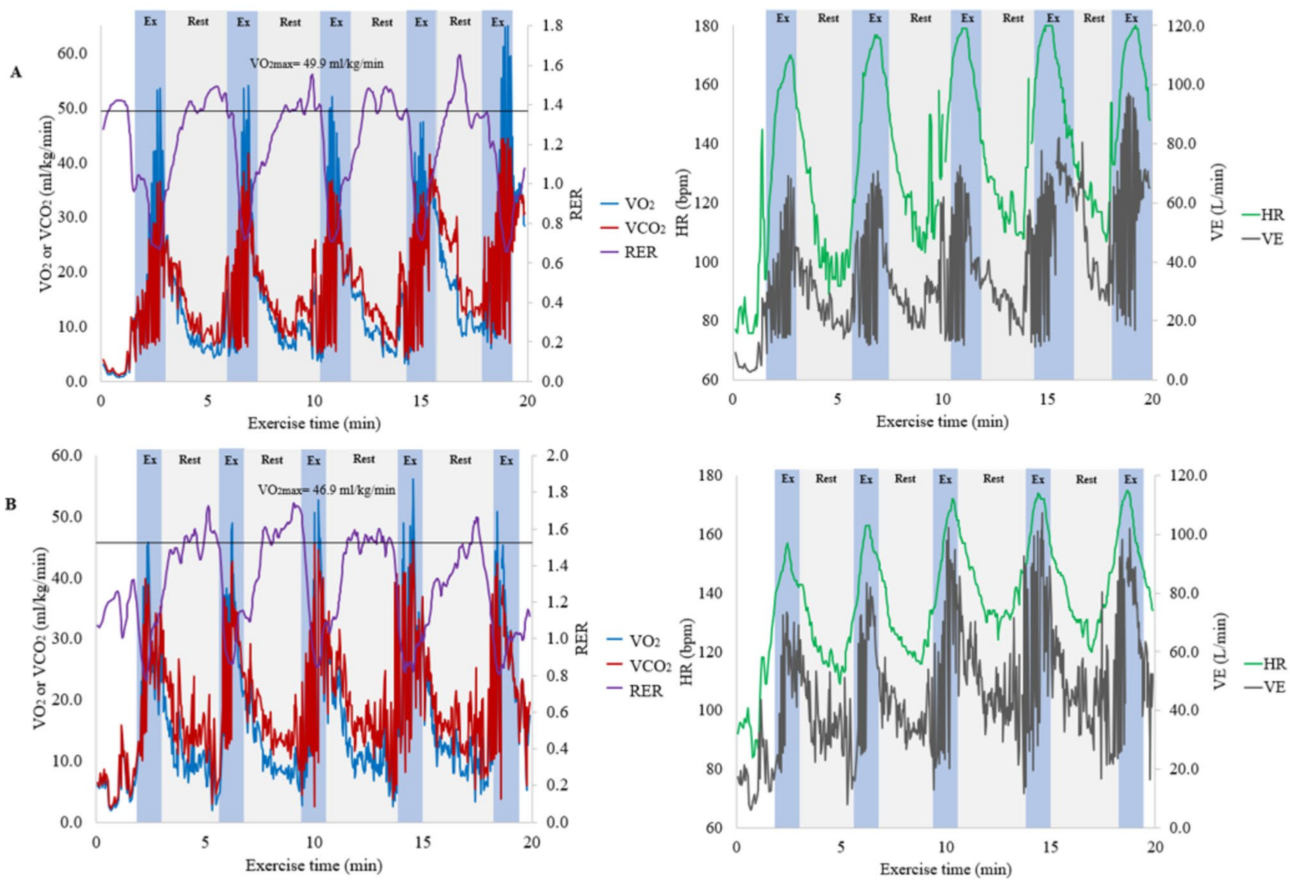

Figure 4. Changes in physiological response and ventilatory outcomes during 5 sets of squat exercise (individual data). Participant A, high strength group: Age: 24; Weight: 91.2 kg; Squat 1RM: 170 kg; 1RM/body weight: 186.4%; VO_2max: 49.9 ml/kg/min; Participant B, low strength group: Age: 27; Weight: 82.5 kg; Squat 1RM: 120 kg; 1RM/body weight: 145.5%; VO_2max: 46.9 ml/kg/min. 'High strength' and 'Low strength' groups indicate higher relative strength (above median) and lower relative strength (below median), respectively. VE, minute ventilation or expired volume; HR, heart rate; RER, respiratory exchange ratio; RM, repetition maximum.

predetermined VO_2max level was lower in the high strength group compared to the low strength group, although this difference was not statistically significant. Furthermore, it is crucial to note that all study participants performed the squat exercise at 65% of their individual 1RM. This indicated that the squat load was obviously higher in the high strength group compared to the load used by the low strength group. Therefore, the high strength group may exhibit higher VO_2 responses compared to the low strength group due to relatively lower aerobic efficiency and/or the absolute training load during exercise in the high strength group. Individuals, who are not accustomed to resistance exercise, may not have the same cardiorespiratory response as observed in our study.

The effort inherent to the execution of squatting exercises at 65% of 1RM, as performed in our study, is submaximal. This relative intensity corresponds to a margin of repetitions that is less than maximal exertion, influencing the VO_2 observed. Previous research[11,31] has established a relationship between the number of repetitions and selected percentages of one repetition maximum in both trained and untrained men. These studies[11,31] indicate that the effort required at 65% of 1RM is substantial but not maximal, which aligns with our findings of significant oxygen demand during the exercise intervals. Our study further highlights that the substantial oxygen demand observed during the squatting exercise is influenced by both the training status of the participants and the submaximal nature of the effort. The high strength group demonstrated a higher VO_2 relative to their VO_2max compared to the low strength group. This suggests that individuals with higher strength capacity may be able to sustain higher aerobic demands during resistance exercises, even at submaximal intensities.

This study has several limitations. First, the findings of this study are specific to the squat exercise protocol used and cannot be generalized to other resistance exercise protocols, such as chest presses or arm curls. Different volumes (i.e., intensity, repetition, and training load) of squat exercises may result in different outcomes[11]. Second, nutritional and hydration intakes, which may be potential confounders, were not controlled for in this study. These factors may have impacted the association between squatting and cardiorespiratory outcomes. Lastly, our findings may not be generalizable to wider populations, given that we examined young, healthy, well-trained, male participants only.

Conclusions

Study findings suggest that squat exercise can elicit a very high level of oxygen demand. Additionally, individuals with higher relative muscle strength could exert a greater aerobic demand than those with lower strength. Therefore, squat exercise can be considered an exercise training modality with substantial involvement of aerobic energy metabolism. While our results indicate a significant increase in VO_2, the exact contributions of oxidative phosphorylation versus other metabolic processes, such as metabolic acidosis leading to increased CO_2 concentrations, remain to be fully elucidated. Further research, including direct measurements at the mitochondrial level, is needed to investigate the potential effects of squat exercise interventions on improving aerobic capacity and the specific metabolic pathways involved[32]. Moreover, further research is needed to investigate the potential effect of squat exercise intervention in improving aerobic capacity[33]. Lastly, future research comparing the squat exercise with specific aerobic exercises and exploring different squat variations, such as increasing the number of repetitions or reducing rest periods, is warranted to determine if these modifications can approximate the metabolic demand of aerobic exercises.

Data availability

The data that support the findings of this study are available from the corresponding author, [MO & JYJ], upon reasonable request.

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Author contributions
SH conceived and designed research, performed experiment, analyzed data, interpreted results of experiments, prepared figures, and drafted and edited manuscript. MO analyzed data, interpreted results of experiments, prepared figures, drafted manuscript, and edited and revised manuscript. CGO performed experiments and edited and revised manuscript. SHS, HP, SL, and HT drafted, edited, and revised manuscript. JYJ conceived and designed research, interpreted results of experiments, and drafted, edited, and revised manuscript. All coauthors approved final version of manuscript.

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The authors declare no competing interests.

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