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Effects of squat training on energy expenditure, oxygen consumption, and heart rate in young healthy adults

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The main purpose of this study was to assess the changes in energy expenditure (EE), oxygen volume (VO_2), heart rate (HR), and velocity (V) measurements obtained during three sets of each of two squat training protocols in a group of healthy young adults. Twenty-nine students of Sports Sciences volunteered to participate in this study. They attended the laboratory on four different days and performed four sessions: two of 3 sets of 12 repetitions at 75% 1 repetition maximum (RM) and two of 3 sets of 30 repetitions at 50% 1RM while EE, VO_2, HR and V was evaluated. The major outcomes of this study indicated that EE, VO2, and HR tended to decrease in both protocols as the sets were performed. Despite this, assessing different strength levels and metabolic variables helps to explain the observed variations in physiological responses. Furthermore, these findings have important implications for the design of effective and personalized strength training programs.

Strength training has been shown to have numerous benefits, including improved muscle mass and bone density, increased metabolic rate, and decreased risk of chronic disease[1]. Among the various strength training exercises, squats are particularly popular due to their ability to target multiple muscle groups, engage both the anterior and posterior kinetic chains, and improve functional movement patterns[2]. These characteristics make squats not only valuable for athletes seeking to enhance performance[3], These characteristics make squats not only valuable for athletes seeking to enhance performance but also for the general population aiming to maintain mobility and prevent injury during daily activities, such as standing from a seated position or climbing stairs[4].

To optimize the effectiveness of strength training and, concretely, squat training, it is crucial to measure physiological metrics such as energy expenditure (EE), oxygen volume (VO_2), heart rate (HR), and velocity (V) while performing exercise[5]. These metrics provide quantitative insights into the metabolic and cardiovascular demands of the exercise, as well as neuromuscular performance[6]. For example, VO_2 and HR indicate the cardiovascular system's response to the exercise[7,8], while EE reflects overall caloric expenditure, which is particularly relevant for weight management and metabolic health[9]. Velocity, on the other hand, serves as a proxy for neuromuscular fatigue and training efficiency, offering trainers a tool for monitoring and adjusting training intensity in real time[10].

Understanding these physiological responses is particularly important for tailoring training programs to specific populations. For athletes, optimizing squat training can lead to improved performance outcomes, such as enhanced strength, power, and endurance. Meanwhile, for individuals undergoing rehabilitation or training for general health, monitoring these metrics can ensure safety, prevent overexertion, and maximize functional benefits[11]. Despite the potential significance of these metrics, limited research has explored their collective behavior during squat exercises under different training protocols, such as variations in intensity and volume.

To the best of our knowledge, a limited number of studies comprehensively evaluate physiological variables such as EE, VO_2, HR, and V collectively comparing different squat training protocols, but they have been individually studied during strength training[12,13]. These studies have provided valuable insights into the effects

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of varying the training parameters on specific physiological variables. Nevertheless, the study by Robergs et al.[14] differs significantly from our approach. Their study employed steady-state exercises, specifically bench pressing and parallel squats performed continuously for 5 min at different intensities, allowing for a more stable physiological response over time. In contrast, this study focused on short-duration, high-intensity squat protocols with distinct sets and repetitions, aiming to analyze the acute metabolic and neuromuscular responses during resistance training. Despite previous findings, there remains a notable gap in the literature regarding how physiological variables vary depending on the number of sets, repetitions, and rest time established in each training protocol[15]. This presents a gap in the current literature as it leaves unanswered questions regarding the potential differences in physiological responses between different training protocols and their implications for optimizing training outcomes. Understanding how they vary is crucial for prescribing different training programs to various population groups[16].

Understanding the effects of different squat training protocols on physiological variables such as EE, VO_2, HR, and V is of great importance for several reasons[6]. First, it can shed light on the metabolic demands and cardiovascular stress imposed by each protocol[10], helping trainers and coaches to tailor training programs to specific goals and target populations. Second, it can provide evidence-based guidance for optimizing training efficiency and effectiveness, ensuring that individuals maximize their potential gains while minimizing the risk of overexertion or injury[11]. Finally, by investigating these variables collectively and directly comparing the two protocols, we can gain a comprehensive understanding of their interplay and potential synergistic effects, which can further contribute to the overall body of knowledge in the field of exercise science[17].

In the realm of strength training, the manipulation of training intensity has long been recognized as a pivotal factor influencing physiological adaptations and performance outcomes[18]. Specifically, varying the intensity, often expressed as a percentage of one-repetition maximum (1RM), exerts distinctive effects on muscle recruitment, metabolic demands, and overall training stimulus[19]. High-intensity protocols with lower repetitions and greater external loads predominantly target maximal strength gains and neural adaptations, while moderate to lower intensity, higher repetition schemes primarily contribute to muscular endurance and hypertrophy[20]. Therefore, investigating the physiological responses during squat training across differing intensity paradigms not only augments our understanding of strength training science but also provides practical insights for optimizing training strategies in diverse populations.

Despite numerous studies on squat training[13,21–23], there is still a lack of understanding of how physiological variables such as EE, VO_2, HR, and V are related to the performance of this exercise. Furthermore, we considered how these variables behave in two different squat exercise protocols. Therefore, the main purpose of this study was to assess the changes in EE, VO_2, HR, and V measurements obtained during three sets of each of the two squat training protocols (30 repetitions at 50% 1RM and 12 repetitions at 75% 1RM) in a group of healthy young adults. Thus, the results of this study could help better understand the differences and similarities between the two protocols and their impact on the studied physiological variables.

Methods

Experimental approach to the problem

This study employed a repeated measures approach to assess variations in EE, VO_2, HR, and V when performing three series of two different acute squat exercise protocols using functional electromechanical dynamometry (FEMD). Participants were familiarized, and their repetition maximum (RM) was determined prior to the start of the study. Each participant visited the laboratory four times in a two-week span, with a minimum of 48 h between visits, and performed three sets of 12 reps at 75% 1RM and three sets of 30 reps at 50% 1RM during each session. The order of the protocols was randomized.

Subjects

The study involved 29 Sports Science students, consisting of 13 males and 16 females. All participants were eligible to participate in the study by meeting the inclusion criteria, which required having no medical conditions and at least one year of experience in muscle strength training. Before participating in the study, each participant was informed of the specific details, objectives, and potential risks involved and provided informed consent. The study protocol was approved by the Committee on Human Research of the University of Granada (Nº. 2182/CEIH/2021) and was conducted in accordance with the Declaration of Helsinki.

In the initial interaction with the participants to confirm their eligibility for the study, female participants were queried about their menstrual cycle. This encompassed details such as the commencement and conclusion dates of their most recent menstruation, length of their menstrual cycle, any instances of intense discomfort or excessive bleeding, and use of hormonal contraceptives. Utilizing the data provided by these participants, we specifically assessed them during the luteal phase [32]. Additionally, none of them relied on hormonal contraceptives, and only two reported experiencing severe pain and heavy bleeding (Table 1).

Procedures

The study involved five separate sessions: one familiarization session and four experimental sessions. Throughout these sessions, participants were instructed to get a minimum of 8 h of sleep; avoid smoking, alcohol, or caffeine 24 h before testing; abstain from strenuous exercise for at least 12 h before testing; and eat no less than an hour before the session. Additionally, the participants arrived at the laboratory at the same time each day (within an hour window) and were exposed to similar environmental conditions, with a temperature of approximately 22 °C and humidity of 60%.

To standardize participants' nutritional conditions and eliminate any external factors that could affect the results, the diet of all participants was regulated a week prior to and throughout the study. This involved excluding any foods or beverages that could potentially influence the outcome, such as caffeine and supplements.

	Total (n = 29)		Men (n = 13)		Women (n = 16)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	24.9	4.6	25.7	3.9	24.3	5.1
Anthropometrics parameters						
BMI (kg/m^2)	23.5	3.0	24.6	3.4	22.6	2.4

Table 1. Descriptive characteristics of sample study according to gender.

A Nutrition and Dietetics graduate was tasked with creating an identical weekly diet plan for all participants during the week leading up to the study and throughout the exercise period tailored to their specific energy requirements. To determine these needs, various anthropometric measurements were taken for all participants one week before the study and subsequently during the following weeks. These measurements included weight (measured using a professional TANITA SC-240-MA scale with a biological suite), height (measured using a portable Seca 213 Stadiometer), skinfold measurements for the biceps, triceps, subscapular, abdominal, thigh, and mid-calf (measured using a Holtein HOL-98610ND mechanical caliper), and arm and mid-thigh circumferences (measured using a CESCORF measuring tape) by an ISAK level 1 anthropometrist. Basal EE was computed using the Harris-Benedict formula[24], total EE was determined using the corresponding activity factor, and body fat percentage was estimated using the Foulkner formula[25].

Participants followed the researcher's instructions upon arrival at the study. First, they were evaluated using the International Physical Activity Questionnaire (short version) (IPAQ), a reliable tool for assessing physical activity levels in adults aged 18 to 69 years. They were then outfitted with the FitMateTM metabolic system, including a mask positioned securely over their mouth and nose, and gas analysis commenced while they remained seated in a relaxed posture for five minutes. Subsequently, they donated a vest equipped with a carabiner connected to an FEMD cable. FEMD (Dynasystem, Model Research, Granada, Spain), a validated isokinetic multi-joint device that enables us to assess the parameters of strength, speed, power, work, and impulse using a single device, was used to conduct the half-squat[26,27]. Following this, they engaged in a five-minute warm-up on a cycle ergometer at 60% of their reserve heart rate, succeeded by ten repetitions at 10% of their 1RM to assess the exercise angle. After a five-minute rest period, they performed three sets of 12 repetitions at 75% 1RM or 30 repetitions at 50% 1RM. Following completion, they were seated for ten minutes for post-exercise gas analysis. Finally, the indirect calorimeter and vest were removed, and the participants were free to leave the laboratory. The FitMateTM metabolic system (Cosmed, Rome, Italy), a trustworthy and valid metabolic analyzer developed to measure oxygen consumption and energy expenditure during rest and activity, has been used to measure energy expenditure[6,28]. EE was determined indirectly using this metabolic cart, which analyzed respiratory gases (typically expired gases) to ascertain the volume of air passing through the lungs, the quantity of oxygen extracted (referred to as oxygen consumption or VO_2), and the amount of carbon dioxide generated as a metabolic byproduct, which was expelled into the atmosphere (CO_2 – VCO_2). All respiratory gas data were gathered and analyzed continuously from the initiation to the conclusion of the protocol. Importantly, the device's design—including its lightweight mask and harness system—did not hinder the execution of the squat protocol. This unobtrusive setup ensured that both the integrity of the respiratory measurements and the natural performance of the squat movements were maintained throughout the exercise session. The sequence of exercises was arranged in a random fashion, with a five-minute break provided between each set. Previous studies[26,29] have established the test–retest reliability of FEMD for squat exercises.

To ensure the temporal accuracy of our measurements, we recorded the exact beginning and end times for each experimental phase, baseline, warm-up, S1, S2 and S3, and the post-exercise period. This precise time stamping enabled us to synchronize the continuous recordings of respiratory and metabolic variables with the exact duration each participant took to complete each phase, thereby accurately capturing dynamic changes in physiological responses. Subsequently, all measurements of the series' durations were standardized to enable valid comparisons across different phases and participants. The study protocol is illustrated in Fig. 1.

During the first laboratory visit, participants underwent a 60-min session which aimed to help them become familiar with the FEMD and determine their one-repetition maximum (1RM). This session involved starting with a general warm-up comprising two sets of 10 squat repetitions with an initial load of 10 kg, followed by increments of 2 kg on each repetition, and 40 s of rest between sets, and (b) directly estimating the participants' squat 1RM by following the protocol explained in del-Cuerpo (2023)[26,29].

Once this is determined, the participant will have several options: (a) If the participant can perform more than one repetition, pushing to the point of failure, a 5 min rest period will follow. The initial load was taken as the maximum load achievable, with subsequent increments of 1 kg until the resistance became too challenging (up to a maximum of five repetitions). The last repetition will be considered the individual's 1RM. (b) If the participant was unable to complete any repetitions, a 2 min rest period was allowed. The initial load was set at 90% of the body weight for males and 70% of the body weight for females. Further increments of 1 kg were applied until the resistance was too strong (up to a maximum of five repetitions). The final repetition served as the participant's 1RM. (c) If the individual can only manage a single repetition, a 5 min rest will follow. The initial load will remain the same as before, with an additional 1 kg increment until the resistance is too formidable (up to a maximum of five repetitions). The last repetition was regarded as the participant's 1RM. Finally, (d) if the participant exceeds 120 kg (the device's load limit), we record the total number of repetitions they can perform and estimate the 1RM using Lombardi's equation[30].

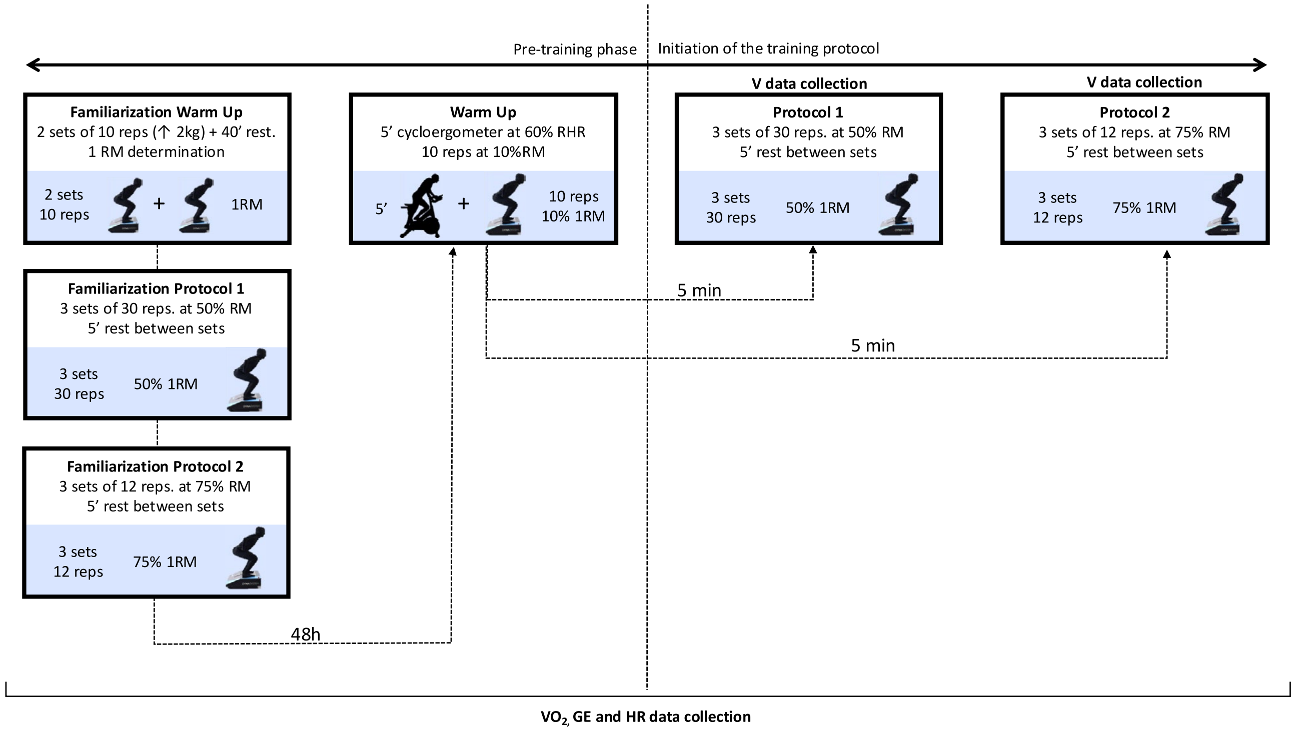

Fig. 1. Protocol measurement of the squat exercise.

EE during both protocols was measured using the FitMate™ metabolic system (Cosmed, Rome, Italy), which is a dependable and validated metabolic analyzer specifically designed for assessing oxygen consumption and EE during both rest and exercise. This system captures breath-by-breath ventilation, as well as measurements of expired oxygen and carbon dioxide[31–33]. Notably, this indirect calorimeter does not require a warm-up period and autonomously undergoes calibration before testing each subject. Once the warm-up phase was completed, the mask was affixed to the patient's face and remained in position for an additional ten minutes post-test. If the mask was not properly secured, a warning was displayed on the device's screen. All respiratory gas data were gathered and analyzed from the initiation to the conclusion of the protocol. Notably, the use of this device did not hinder execution of the squat protocol.

Statistical analyses

Descriptive data are presented as mean ± standard deviation (SD). Normal distribution of the data (Shapiro–Wilk test) and homogeneity of variances (Levene test) were confirmed ($P > 0.05$). For the main analysis, a repeated-measures analysis of variance (ANOVA) was conducted using the Holm Post-Hoc analysis. The Greenhouse–Geisser correction was used when the Mauchly sphericity test was violated. Omega squared (ω^2) was calculated for the ANOVA, where the values of the effect sizes 0.01, 0.06 and above 0.14 were considered small, medium, and large, respectively[34]. Statistical significance was set at $p < 0.05$. The JASP statistics package (version 0.11.1) was used for the statistical analyses. The sample size for this experimental study was determined using statistical software (G*Power version 3.0.10), based on a test power of 90% and a statistical significance level of 5%, with an effect size of 0.8.

Results

There are significant differences for the variables of EE at 50% 1RM ($p = 0.001$; $\omega^2 = 0.012$) and 75% 1RM ($p = 0.001$; $\omega^2 = 0.008$) in the comparison of three series S1 vs S2 vs S3. The post hoc analysis using Holm's correction revealed that EE significantly increased for 50% 1RM protocol between S1 and S3 (S1: 21.53 (5.52) vs S3: 23.26. (5.70), $p < 0.001$) and for 75% 1RM protocol between S1 and S2 (S1: 16.37 (3.92) vs S2: 17.19 (4.95), $p = 0.006$) and between S1 and S3 (S1: 16.37 (3.92) vs S3: 17.33 (4.59), $p = 0.002$) (Fig. 2a).

There are significant differences for the variables of VO_2 at 50% 1RM ($p = 0.001$; $\omega^2 = 0.012$) and 75% 1RM ($p = 0.001$; $\omega^2 = 0.008$) in the comparison of three series S1 vs S2 vs S3. The post hoc analysis using Holm's correction revealed that VO_2 significantly increased for 50% 1RM protocol between S1 and S3 (S1: 10.75 (1.66) vs S3: 11.18 (1.72), $p < 0.001$) and for 75% 1RM protocol between S1 and S2 (S1: 8.71 (1.07) vs S2: 9.11 (1.43), $p < 0.001$) and between S1 and S3 (S1: 8.71 (1.07) vs S3: 9.20 (1.34), $p = 0.002$) (Fig. 2b).

There are significant differences for the variables of HR at 50% 1RM ($p < 0.001$; $\omega^2 = 0.119$) and 75% 1RM ($p < 0.001$; $\omega^2 = 0.030$) in the comparison of three series S1 vs S2 vs S3. The post hoc analysis using Holm's correction revealed that HR significantly increased for 50% 1RM protocol between S1 and S2 (S1: 92.61 (11.72) vs S2: 100.68 (14.42), $p < 0.001$), between S1 and S3 (S1: 92.61 (11.72) vs S3: 104.97 (15.07), $p < 0.001$), and

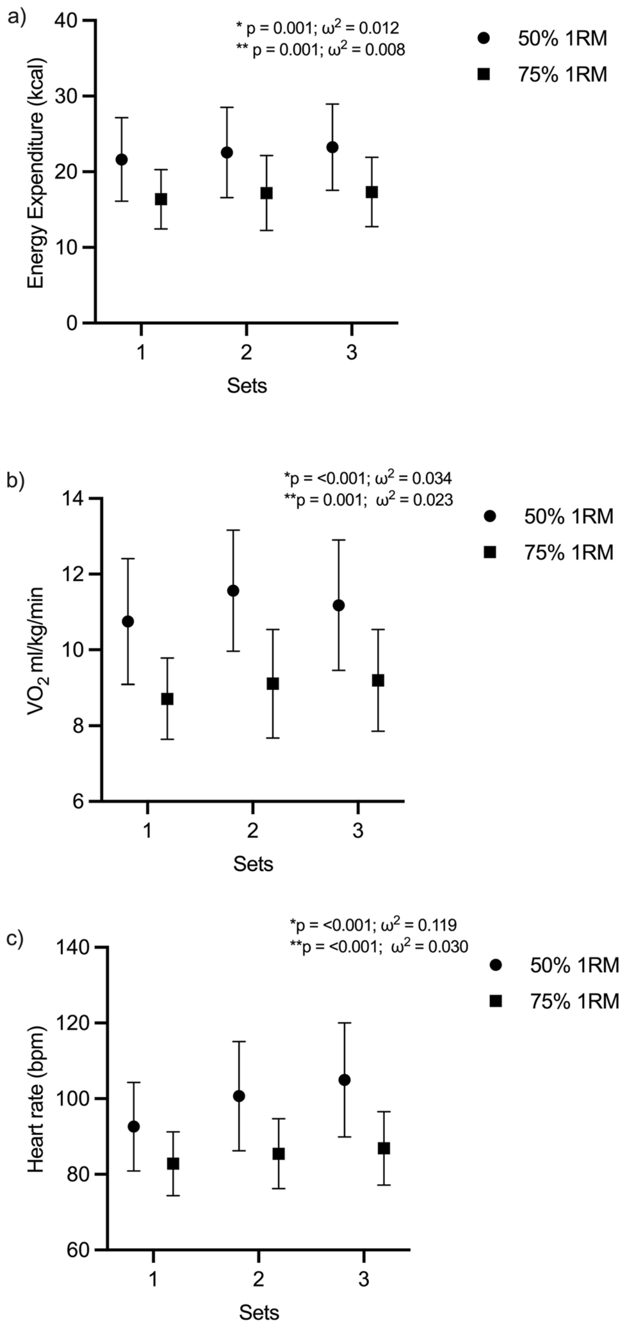

Fig. 2. EE, VO2, and HR measurements obtained during both protocols for the three series.

between S2 and S3 (S2: 100.68 (14.42) vs S3: 104.97 (15.07) and for 75% 1RM protocol between S1 and S2 (S1: 82.82 (8.43) vs S2: 85.45 (9.24), $p = 0.003$) and between S1 and S3 (S1: 82.82 (8.43) vs S3: 86.88 (9.69) , $p < 0.001$) (Fig. 2c).

There are significant differences for the variables of V at 50% 1RM ($p < 0.001$; $\omega 2 = 0.007$) and 75% 1RM ($p = 0.033$; $\omega 2 = 0.004$) in the comparison of three series S1 vs S2 vs S3. The post hoc analysis using Holm's correction revealed that V significantly increased for 50% 1RM protocol between S1 and S2 (S1: 76.39 (21.59) vs S2: 79.26 (22.48), $p = 0.007$) and between S1 and S3 (S1: 76.39 (21.59) vs S3: 80.98 (22.51), $p < 0.001$) and for 75% 1RM protocol between S1 and S3 (S1: 67.13 (17.73) vs S3: 70.24 (17.37), $p < 0.028$) (Table 2).

Discussion

The main purpose of this study was to assess the changes in EE, VO_2, HR, and V measurements obtained during three sets of each of the two squat training protocols (30 repetitions at 50% 1RM and 12 repetitions at 75% 1RM) in a group of healthy young adults. The major outcomes of this study indicated that EE, VO_2, and HR tended to decrease in both protocols as the sets were performed. These changes suggest enhanced movement economy

Variable		S1 Mean (SD)	S2 Mean (SD)	S3 Mean (SD)	ANOVA
V (cm/s)	50% 1RM	76.39 (21.59)	79.26 (22.48)	80.98 (22.51)	F (2.00, 56.00) = 12.13; p < 0.001; ω^2 = 0.007
	75% 1RM	67.13 (17.73)	68.71 (17.27)	70.24 (17.37)	F (2.00, 56.00) = 3.64; p = 0.033; ω^2 = 0.004

Table 2. V measurements were obtained during both protocols for the three series. *S1* serie 1, *S2* serie 2, *S3* serie 3, *SD* standard deviation, *V* velocity.

and reduced cardiovascular strain, benefiting both performance and recovery[35,36]. Additionally, the reduction in HR and VO_2 highlights improved cardiovascular and neuromuscular coordination, reinforcing the role of squat training in optimizing endurance and rehabilitation[37,38]. This finding holds practical significance, as it suggests an adaptive response in energy utilization and cardiovascular demand over the course of multiple repetitions within a set, potentially influencing training strategies for improved efficiency and performance optimization.

Taken together, these findings suggest that this trend may be indicative of several factors. First, participants may experience an improvement in movement efficiency as they become more familiar with exercise[39]. This can lead to decreases in EE and VO_2 over the course of the series[40]. Additionally, the decrease in HR may be related to cardiovascular adaptation that occurs in response to the strength-training stimulus[38,41]. Regarding V, accumulated fatigue after each set tends to lead to a reduction in the execution speed of the movement as well as an increase in the time taken to complete each set[42,43].

Despite this, having conducted an extensive review of the published literature on this topic, as far as we know, you could not find any studies that assess EE, VO_2 and HR during the different sets of the same training protocol. Conversely, studies have been conducted on how these variables change after the application of a specific training program in different population groups. Thus, we believe that this is the novelty of this study.

Regarding EE and VO2, to the best of our knowledge, one of the few articles found dates back to 1968. Seliger et al. (1968)[40] examined EE and VO2 in 15 athletes during 13 weeks of strength training. Half of the athletes were trained in a traditional manner by lifting dumbbells, whose weight corresponded to 90–95% of the 1RM (concentric contraction). The other half was trained only by lowering dumbbells, whose weight corresponded to 145–150% of the 1RM (eccentric contractions). Subsequently, both VO_2 and EE decreased significantly. These results, although they do not assess how EE and VO2 vary in each of the training sets, are similar to what is intended to be evaluated in this study, and they align with the results obtained. This is because apart from the training adaptations mentioned previously, the participants' level of training. According to Pontzer et al. (2016)[36], untrained participants experience an increase in EE at low activity levels. In the case of trained individuals, such as those included in our study, who were required to have a minimum of one year of strength training experience, EE tends to stabilize and even decrease[44].

With regard to HR, a similar phenomenon occurs. The variation in HR after exercise has been widely studied, and there is abundant scientific literature indicating that individuals adapted to exercise show a lower resting heart rate and cardiac hypertrophy[45,46], but not as much during exercise. In HR during exercise, to the best of our knowledge, the variation in HR during exercise has been less investigated. Despite this, some studies have investigated it, such as the systematic review published by Periard et al. (2016)[47], which sought to examine the cardiovascular adaptations that occur in parallel with improved heat loss responses during exercise-heat acclimation. They realized that cardiovascular adaptations supporting this challenge include a reduction in heart rate during exercise at a given work rate, among other adaptations[47]. These results align with those obtained in our study, indicating that the reduction in HR during training at a sustained intensity is one of the cardiovascular adaptations generated by training in trained individuals, such as those included in this study[38].

In the case of V, it is different, since studies have been conducted to investigate how these variable changes during the execution of different strength-training protocols, observing and comparing its variation between repetitions and between sets. For instance, Dos Santos et al. (2021)[48] examined the immediate effects of performing four sets of high-velocity parallel squats, whether taken to the point of momentary failure or not, and they showed notable reductions in both maximum and average velocity loss, as well as power output loss. Likewise, Sanchez-Medina et al.[43] examined the reduction in V following three sets of 10RM and three sets of 12RM loads, both with a 5-min rest period between sets, during the full back squat in trained male participants. They noted that after completing 3 × 10 and 3 × 12, there were reductions in the mean propulsive velocity of 45% and 46%, respectively. Similarly, Gonzalez-Badillo et al.[49] and Pareja-Blanco et al.[42] observed mean propulsive velocity reductions of 44% in protocols involving 3 × 8[49] and 3 × 12[42] sets, with 5 min of rest between sets during the full squat in trained men. These findings align with those of our study, in which we observed a tendency for V to decrease in both squat training protocols. This is attributed to accumulated fatigue during exercise, which leads to a gradual reduction in V in each set.

The practical implications of these findings are significant for both exercise professionals and trainers. It could help exercise professionals, trainers, and athletes in different areas, such as (a) optimization of strength training: understanding how the studied variables vary during squat training provides valuable insights for designing effective and personalized strength training programs. Trainers can adjust the intensity and volume of training based on individual goals and athlete capabilities, (b) movement efficiency: observing the trend of decreasing EE and VO_2 throughout the sets highlights the importance of proper technique in performance. Encouraging efficient techniques can help athletes conserve energy and improve performance over time. (c) Monitoring progress and performance: observing changes in HR and VO_2 throughout training can serve as an indicator of progress. Regular monitoring can help adjust training strategies according to the changing needs of the athletes.

Taken together, these findings provide a solid scientific foundation for decision-making in strength-training program designs. Exercise professionals and coaches can use this information to maximize the benefits of training and enhance athletic performance. However, it is important to note that each individual is unique and training adaptations may vary. Personalized approach and expert supervision are recommended to achieve the best results.

Nevertheless, this study has certain limitations that should be considered in future research. The participants consisted exclusively of young, healthy adults with a 1RM below 160 kg. Consequently, future studies should include a more diverse population, such as powerlifters, overweight or obese individuals, and those with varying health conditions. Additionally, this study focused on half squats, and evaluating full squats could provide further insights into EE and physiological responses.

Another limitation is the lack of gender-based analysis, which should be addressed in future research to better understand potential differences. Moreover, incorporating accelerometer-based EE measurements could have facilitated a comparative analysis between different assessment tools. It would also have been beneficial to continue monitoring EE for at least an hour post-exercise, but time constraints among participants prevented this.

Additionally, gas exchange analysis in short-duration exercises (<60 s) may not fully capture real-time metabolic fluctuations, requiring careful data interpretation. Furthermore, the high cost and limited accessibility of metabolic carts may restrict their practical application in daily training. Alternative cost-effective tools, such as velocity-based training and HR variability, could offer more practical monitoring solutions for fatigue and performance fluctuations.

A key methodological limitation of this study is related to the estimation of EE through VO_2 during short-duration, high-intensity resistance exercise. Due to the delayed oxygen uptake response (oxygen kinetics), gas exchange may not fully capture the immediate metabolic cost of anaerobic activity. This temporal mismatch can introduce variability in the EE estimates, particularly when no steady state is reached. Therefore, the use of VO_2 in this context should be interpreted with caution, and future studies should consider complementary methods, such as blood lactate analysis, accelerometry, or calorimetry, to more accurately quantify EE during predominantly anaerobic efforts.

Lastly, future studies using longitudinal or mechanistic approaches (e.g., randomized controlled trials with diverse training interventions) will be essential for a more comprehensive exploration of causality.

On the other hand, this study highlights the use of a FEMD for the precise and objective assessment of physiological responses during squat training. This technology enables greater training personalization by providing detailed metabolic and neuromuscular data in real time.

Future research should explore long-term adaptations, assess FEMD's application in diverse populations (e.g., athletes, older adults, and rehabilitation patients), and integrate it with more accessible monitoring tools to enhance its practical use in strength training. Investigating how alternative methodologies compare with FEMD-based assessments will further refine training strategies and improve the applicability of performance monitoring tools. It would also be valuable for future research to investigate these variables under protocols designed to reach steady state, thereby extending and validating our findings.

In conclusion, the main findings of this study showed that all the variables measured (EE, VO_2, HR, and V) during both squat training protocols decreased as the sets were performed. Despite this, assessing different strength levels and metabolic variables helps to explain the observed variations in physiological responses. Furthermore, these findings have important implications for the design of effective and personalized strength training programs. Future research should further explore these phenomena in diverse populations and training contexts.

Data availability
The data supporting the findings of this study are available and can be shared upon reasonable request to the corresponding author.

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Author contributions

ICR lead the project, the methodology design, data collection, and the manuscript writing. DJM, PDF, and MAF contribute to data analysis and manuscript review. LJCR revised the manuscript critically. All authors read and approved the final version of the manuscript. All authors read and approved the final version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Ethics declaration
Each participant received detailed information on the study's specifics, objectives, and potential risks, and provided informed consent. The study protocol was approved by the Committee on Human Research of the University of Granada (Nº. 2182/CEIH/2021) and was conducted in accordance with the Declaration of Helsinki.

Additional information
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