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Comparison of muscle activation and fatigue levels in barbell squat exercise performed with machine and free weights

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Comparison of muscle activation and fatigue levels in barbell squat exercise performed with machine and free weights

Abstract

The squat exercise is a fundamental movement in resistance training that enhances athletic performance, supports joint stability, and increases bone density. The execution of squats using either free weights or machines can influence muscle activation and fatigue levels. This study aimed to compare the acute effects of barbell squat exercises performed with free weights and the Smith machine on muscle activation, perceived exertion, and jump performance. Seventeen university students (age: 23.0±2.8 years) with resistance training experience participated in this randomized crossover study. Participants performed barbell squats at 70% of their one-repetition maximum (1RM) using two different protocols: free weight squats and Smith machine squats (5 sets of 8 repetitions, with 3-minute rest intervals between sets). Findings indicated that muscle activation in the vastus lateralis was significantly higher in the Smith machine condition ($p<0.05$), while no significant differences were observed in perceived exertion (RPE) and countermovement jump (CMJ) performance between the two squat modalities ($p>0.05$). Additionally, both squat techniques resulted in similar decreases in CMJ performance after the exercise session. These results suggest that while the Smith machine increases muscle activation compared to free weights, the overall performance outcomes and perceived exertion levels are comparable between the two squat methods. Coaches and athletes may incorporate both methods into their training programs based on individual goals and preferences.

Keywords: Jump performance, Muscle activation, Perceived exertion, Resistance training, Smith machine

Makine ve serbest ağırlıklarla yapılan barbell squat egzersizinde kas aktivasyonu ve yorgunluk düzeylerinin karşılaştırılması

Özet

Squat egzersizi, direnç antrenmanlarında temel bir hareket olup, atletik performansı artırmanın yanı sıra eklem stabilitesini destekler ve kemik yoğunluğunu yükseltir. Squat egzersizlerinin serbest ağırlıklar veya makinelerle uygulanması, kas aktivasyonu ve yorgunluk düzeylerini etkileyebilir. Bu çalışmanın amacı, serbest ağırlıkla ve Smith makinesi ile uygulanan halter squat egzersizlerinin akut etkilerini kas aktivasyonu, algılanan yorgunluk ve sıçrama performansı açısından karşılaştırmaktır. Direnç antrenmanı geçmişi olan on yedi üniversite öğrencisi (yaş: 23,0±2,8 yıl) randomize çapraz desenli tasarım ile araştırmaya dahil edilmiştir. Katılımcılar, %70 bir tekrar maksimum (1RM) yükle, iki farklı protokol doğrultusunda halter squat uygulamıştır: serbest ağırlıkla squat ve Smith makinesiyle squat (5 set x 8 tekrar, setler arası 3 dakikalık dinlenme). Bulgular, vastus lateralis kasında kas aktivasyonunun Smith makinesi protokolünde anlamlı olarak daha yüksek olduğunu göstermiştir ($p<0.05$). Ancak algılanan yorgunluk (RPE) ve sıçrama performansı (CMJ) açısından iki squat yöntemi arasında anlamlı bir fark gözlenmemiştir ($p>0.05$). Ayrıca, her iki protokol de egzersiz sonrası CMJ performansında benzer düzeyde azalmaya yol açmıştır. Bu sonuçlar, Smith makinesinin serbest ağırlıklara kıyasla kas aktivasyonunu artırmasına rağmen, genel performans çıktıları ve algılanan yorgunluk düzeylerinin iki yöntem arasında benzer olduğunu göstermektedir. Antrenörler ve sporcular, bireysel antrenman hedefleri ve tercihlere göre her iki yöntemi de programlarına dâhil edebilir.

Anahtar Kelimeler: Sıçrama performansı, Kas aktivasyonu, Algılanan yorgunluk, Direnç antrenmanı, Smith makinesi

Introduction

Squat, one of the fundamental exercises commonly utilized in resistance training, not only enhances athletic performance metrics such as sprinting and jumping but also contributes to injury prevention by supporting muscle strength and mobility (Bashir et al., 2022; Stone et al., 2024). Moreover, the squat exercise exerts positive effects on overall health, such as enhancing joint stability and increasing bone density (Zuna, 2024). Depending on individual goals and experience levels, the squat exercise can be performed using free weights or machines. Due to their higher stabilization demands, free-weight squats engage a greater number of muscle groups and are therefore widely preferred among experienced individuals (Haff, 2000; Schwanbeck et al., 2009). Conversely, machine-based methods, such as the Smith machine, provide a more controlled environment by guiding the bar along a fixed path, making them a suitable option for novice trainees in resistance training (Schwanbeck et al., 2009).

Limited studies have compared muscle activation and fatigue levels between free weight and machine-based squats (Amritashish, 2015; Anderson & Behm, 2005; Hernández-Belmonte et al., 2023; Schwanbeck et al., 2009; Svensson et al., 2022). However, conflicting findings exist in the literature regarding the efficacy and performance differences between these two methods. Some research suggests that free-weight exercises, due to their increased stabilization requirements, may provide greater muscle activation and strength gains (Schwanbeck et al., 2009; Svensson et al., 2022). On the other hand, higher muscle activation has been observed in squats performed with the Smith machine compared to free weights (Anderson & Behm, 2005). Another study found no statistically significant difference between the two methods, but still observed higher muscle activation in Smith machine squats. Additionally, a study by Cotterman et al. (2005) indicated that the Smith machine yielded higher one-repetition maximum (1RM) values in women, whereas free weight bench press results were superior in men. However, it has also been reported that when training variables are appropriately controlled, machine-based exercises can be as effective as free weights in promoting muscle hypertrophy and strength development (Heidel et al., 2022; Hernández-Belmonte et al., 2023).

Parameters such as jump performance and perceived exertion are used to determine fatigue levels during and after resistance training (Alba-Jiménez et al., 2022; Cuevas-Aburto et al., 2022). Research has shown that squat exercises performed on a Smith machine lead to greater improvements in jump performance compared to free-weight squats (O'Grady et al., 2015; Schwarz et al., 2019). Similarly, perceived exertion levels during Smith machine squats are reported to be lower than those during free-weight squats (Carraro et al., 2018). Although the

Smith machine appears to be more effective in managing fatigue, the limited number of studies available affects the generalizability of these findings.

The conflicting findings regarding muscle activation outcomes in barbell squat exercises performed with machines and free weights, along with the limited data on jump performance and fatigue levels, highlight the need for further research in this area. Moreover, previous studies have measured muscle activation based on a single set. However, no studies have been identified that compare changes in muscle activation across multiple sets during a training session. Monitoring muscle activation changes over multiple sets could provide a more accurate assessment of fatigue levels. Therefore, this study aims to compare the effects of barbell squat exercises performed using machine-based and free-weight methods on muscle activation and fatigue levels. The following hypotheses were tested: a) Squat exercises performed with free weights will produce greater muscle activation compared to those performed with the Smith machine. b) Squat exercises performed with the Smith machine will more effectively reduce fatigue levels compared to the free-weight method.

Method

Research Design

A crossover design was selected to minimize inter-individual variability, ensuring that each participant served as their control for accurate comparison of physiological responses between exercise modalities.

Participants

Seventeen healthy university students (aged 18–29 years) from the Faculty of Sports Sciences participated in the study, all of whom had at least one year of resistance training experience. Participants were screened using inclusion criteria that required the absence of chronic illnesses or recent injuries and excluded those who had taken nutritional supplements in the past six months. Before participation, all individuals received detailed information about the study protocols and subsequently provided written informed consent. Participants were required to maintain consistent dietary habits and abstain from engaging in any additional resistance training throughout the duration of the study. Descriptive data of the participants are presented in Table 1.

Table 1. Descriptive characteristics of participants (n=17)

Metric	Min.	Max.	Mean	SD
Age (years)	18	29	23	2.8
Height (cm)	160	188	172.44	8.01
Weight (kg)	50	95	69.04	11.49
1RM (kg)	65	130	90.62	17.4

Experimental Procedures

The study was conducted over three sessions to allow for recovery and reduce carryover effects. Each session was separated by a 48-hour rest period. The first session included familiarization with protocols, consent collection, and anthropometric measurements. Participants practiced both Smith machine and free-weight squats, followed by one-repetition maximum (1RM) testing using a PUSH-BAND device and Maximum Voluntary Isometric Contraction (MVIC) assessments with sEMG sensors. The second and third sessions served as experimental trials, each randomized to focus on either the Smith machine or free-weight squat protocol to prevent order effects. A standardized warm-up consisting of 5 minutes of treadmill running and 5 minutes of dynamic stretching was performed at the beginning of each session. Participants then completed five sets of eight repetitions at 70% of their 1RM, with a 3-minute rest interval between sets. Muscle activation was monitored using sEMG sensors placed on the vastus lateralis muscle, adhering to SENIAM guidelines. Perceived exertion (RPE) was recorded after each set, and countermovement jump (CMJ) performance was assessed before and 10 minutes after the squat protocols.

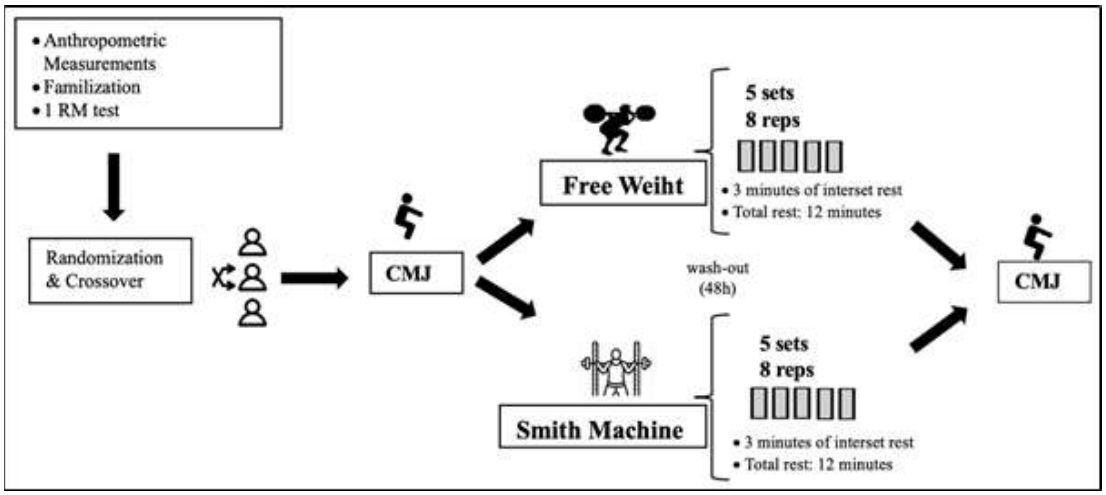


Figure 1. Experimental design of the study.

To ensure consistency, all sessions were conducted under controlled environmental conditions, and participants were instructed to follow standardized dietary and physical activity routines. The same equipment setup and methodological procedures were used across all sessions to ensure the reliability and validity of the collected data.

Measurement Tools

Muscle activation was assessed using a Delsys Trigno Research+ surface electromyography (sEMG) system, with sensors placed on the vastus lateralis muscle following SENIAM guidelines. Before electrode placement, participants were instructed to shave the measurement area, which was then cleaned with isopropyl alcohol to reduce impedance and enhance signal quality (Konrad, 2005). Electrodes were positioned on the dominant leg, two-thirds measured as the distance between the anterior superior iliac spine and the lateral edge of the patella. Raw EMG signals were recorded at a sampling rate of 2000 Hz and processed to calculate root mean square (RMS) and median frequency (MDF) values.

One-repetition maximum (1RM) was measured using the Push Band 2.0 device (Toronto, Canada). This device, known for its high reliability ($R^2 = 0.94$), utilized a load-velocity profiling method to determine 1RM based on five submaximal loads, each performed for three repetitions. The Push Band also assessed countermovement jump (CMJ) performance pre- and 10 minutes' post-squat exercises. Participants performed two CMJs with hands on their hips, and the highest jump height was recorded.

Perceived exertion (RPE) values were measured using the Borg Scale after each set, providing insights into the subjective difficulty of the exercises. MVIC was measured in the Smith machine squat position, with participants holding a 90˚ knee and hip flexion angle under verbal encouragement for 5 seconds. During both Smith machine and free-weight squat protocols, muscle activity was continuously recorded across all sets while participants received verbal motivation to maintain effort.

Data Analysis

The Descriptive statistics were calculated as mean and standard deviation. The distribution of the data was evaluated for normality using the Shapiro-Wilk test and by examining skewness and kurtosis values (acceptable range: ±2.0). A two-way repeated-measures ANOVA was conducted to examine the main effects of condition (Smith machine vs. free weight), set (1-5), and their interaction (condition × set) on mean and peak muscle activation, perceived exertion (RPE), and CMJ performance. Pairwise post hoc comparisons were conducted using the emmeans package in R, with Tukey adjustments applied to correct for multiple comparisons. Partial eta squared was used to calculate the effect sizes (ηp^2) to quantify the magnitude of observed effects. Mauchly's test of sphericity was conducted to assess the assumption of sphericity, and when violations were detected, Greenhouse-Geisser or Huynh-Feldt corrections

were applied as appropriate. All data analyses were performed using R software (version 4.3.0). The afex package was used for repeated-measures ANOVA, while ggplot2 was employed for data visualization to illustrate the findings clearly.

Results

Descriptive Statistics of Measured Features

Descriptive statistics for measured features, including mean and peak muscle activation, CMJ performance, and RPE values, are shown in Table 2. The table presents the minimum, maximum, mean, and standard deviation for each metric under Smith machine and free weight conditions.

Table 2. Descriptive statistics of all the features measured in the study for the Smith machine and free weight groups

Metric	Condition	Mean	SD	Min.	Max.
Mean Activation (%)	Smith Machine	34.61	11.21	18.68	65.30
	Free Weight	30.82	9.39	18.80	56.57
Peak Activation (%)	Smith Machine	79.15	23.83	42.99	139.71
	Free Weight	71.02	23.05	38.16	121.68
Jump Performance Pre (cm)	Smith Machine	38.74	8.79	25.10	56.00
	Free Weight	38.90	7.76	27.20	52.30
Jump Performance Post (cm)	Smith Machine	36.98	8.14	23.80	52.40
	Free Weight	36.99	7.92	24.30	48.90
RPE (1-10)	Smith Machine	5.06	1.18	3.00	7.00
	Free Weight	4.62	1.25	2.00	7.00

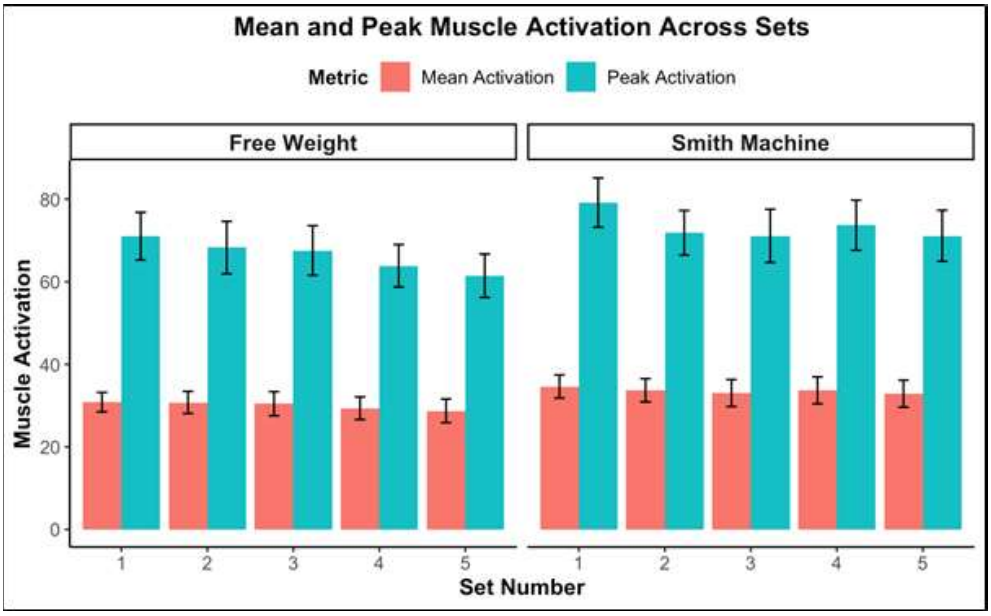
Muscle Activation Results

The results of the repeated-measures ANOVA for mean and peak muscle activation are presented in Table 3. Significant main effects were found for condition ($p<0.05$) for both mean and peak activation, with higher activation observed in the Smith machine condition. A significant main effect of set was observed for peak activation ($p<0.001$), indicating variability across sets, while the interaction effect (condition × set) approached significance ($p = 0.058$).

Table 3. Results of repeated-measures ANOVA for mean and peak muscle activation

Metric	Effect	F	p	ηp^2
Mean Muscle Activation (%)	Condition	6.50	0.022	0.30
	Set	2.08	0.137	0.12
	Condition: Set	0.65	0.528	0.04
Peak Muscle Activation (%)	Condition	8.28	0.011	0.36
	Set	5.33	0.003	0.26
	Condition: Set	2.42	0.085	0.14

Graphic 1 depicts the changes in mean and peak muscle activation across five sets for Smith machine and free weight conditions. Error bars represent the standard error of the mean (SEM), providing an indication of the reliability of the observed differences.



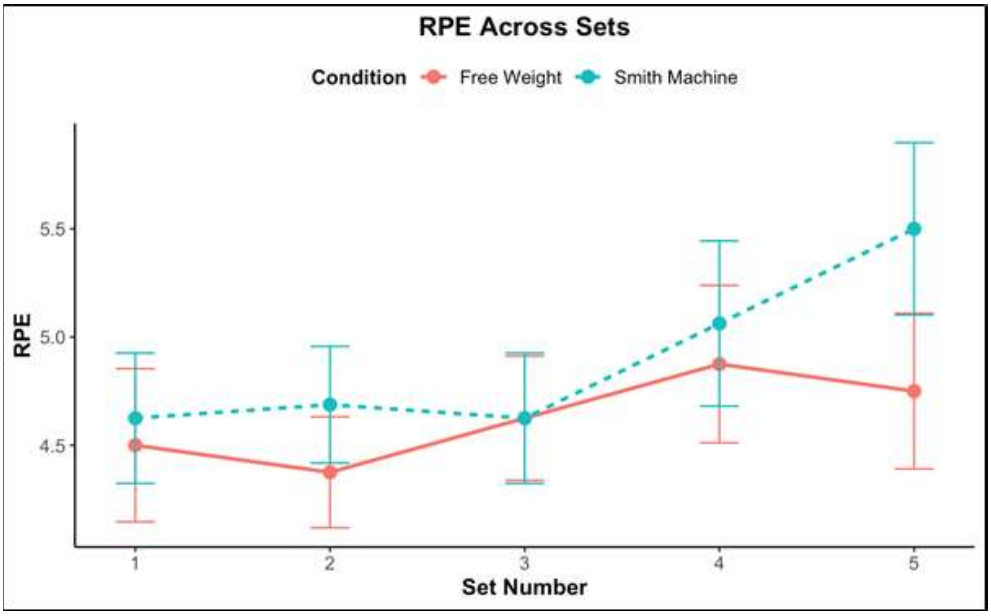
Graphic 1. Mean and peak muscle activation across sets for free weight and Smith machine exercise

Table 4 presents the results of the repeated-measures ANOVA for countermovement jump (CMJ) performance and perceived exertion (RPE) across Smith machine and free weight conditions. A significant main effect of Time was observed for CMJ performance ($F(1, 15)=23.04$, $p<0.001$, $\eta p^2=0.61$), indicating a decline in performance post-exercise. However, no significant main effect of Condition or Condition × Time interaction was found, suggesting that the decline in performance was consistent across both exercise modalities. For RPE, no significant main effects or interactions were observed, reflecting similar perceived exertion levels in both conditions and across sets.

Table 4. CMJ and Perceived Exertion (RPE) across sets for Smith machine and free weight conditions

Metric	Effect	F	p	ηp²
CMJ (cm)	Condition	0.03	0.85	0.00
	Set	23.04	0.00	0.61
	Condition: Set	0.06	0.79	0.00
RPE (1-10)	Condition	1.00	0.33	0.06
	Set	2.08	0.09	0.12
	Condition :Set	1.25	0.29	0.08

Graphic 2 illustrates the perceived exertion (RPE) scores across the five sets for Smith machine and free weight exercises. Error bars represent the standard error of the mean (SEM), highlighting the variability of RPE scores within each set. No significant differences were detected between the two conditions or across sets, as supported by the ANOVA results.



Graphic 2. Perceived Exertion (RPE) across sets for Smith machine and free weight conditions

Discussion

This study is the first to compare muscle activation, jump performance, and perceived exertion levels in squat exercises performed with machines and free weights. The Smith machine provided higher muscle activation compared to free weights, while no significant differences were observed between the two methods in terms of exertion and perceived effort. Both methods led to similar decreases in jump performance. These findings indicate that while the Smith machine increases muscle activation, it is not significantly superior to free weights in terms of overall performance and perceived exertion.

Our findings on higher vastus lateralis muscle activation during squat exercises performed on the Smith machine are consistent with the results of the study conducted by Anderson and Behm (2005), in which participants performed a single repetition squat at three different loads (body weight, 29.5 kg, and a load equivalent to 60% of their body weight). On the other hand, there are also studies reporting higher quadriceps activation during squat exercises performed with free weights (Schwanbeck et al., 2009; Svensson et al., 2022). In the study conducted by Schwanbeck et al. (2009), during an 8-repetition maximum squat exercise, the activation of the Vastus Medialis, Biceps Femoris, and Gastrocnemius muscles was higher in free weight squats. Similarly, in the study by Svensson et al. (2022), which involved squats performed with an external load equivalent to body weight, the average quadriceps muscle activation was higher in free weight squats. This inconsistency may be due to differences in foot positioning across studies. In the study by Svensson et al. (2022), which reported higher quadriceps activation in

free weight squats, the feet were in a more natural position, aligned with and directly beneath the barbell. In contrast, in the study by Anderson and Behm (2005), where higher quadriceps activation was observed in the Smith machine squats, the feet were positioned slightly forward relative to the barbell. On the other hand, whether the loads were adjusted for each exercise condition could also contribute to the differences in muscle activation results. In the study where higher activation was observed in free weight squats, the loads were adjusted according to each exercise condition (Schwanbeck et al., 2009), whereas in the study where higher activation was found in the Smith machine squats, the same load was used for both exercise conditions (Anderson & Behm, 2005). However, in our protocol, the foot position was directly under the barbell, and the same load was used for both exercise conditions. This makes it difficult to draw a clear conclusion regarding which method provides higher quadriceps activation when the feet are positioned under the barbell. Additionally, using the same load in both methods might have caused the weight to feel heavier in the free weight condition, requiring greater engagement of abdominal stabilizers, which could have relatively reduced quadriceps activation.

Our findings regarding similar jump performance and perceived exertion values between the two methods show inconsistencies with previous studies (Carraro et al., 2018; O'Grady et al., 2015; Schwarz et al., 2019). In the study conducted by O'Grady et al. (2015), peak power, peak force, peak velocity, and peak jump height were assessed before and at 4 and 8 minutes after a 5-repetition maximum squat exercise. The results showed higher peak power values in the Smith machine condition, whereas no significant difference was observed in peak jump height between methods. However, a post-activation potentiation (PAP) effect was detected in the final test of the Smith machine condition. In the study by Schwarz et al. (2019), squat exercises were performed at 70% of 1RM (with progressive load increases each week), and vertical jump tests were conducted before and after six weeks of training. The results showed higher jump performance values in the Smith machine condition. Additionally, Carraro et al. (2018) found that perceived exertion scores were lower following squat exercises performed on the Smith machine at 6 and 12 RM loads.

This inconsistency may be due to the use of higher loads in some studies, which could have triggered the PAP effect, as well as the inclusion of multiple performance parameters such as peak power, peak velocity, and peak force in jump assessments. Regarding perceived exertion, performing squat exercises with free weights while using the leg press machine in the machine-based condition may have influenced the results. Considering that these studies were conducted

with recreationally active individuals, these findings may not necessarily be applicable to elite-level athletes.

This study has some limitations. Muscle activation was measured in only one muscle, and it remains unclear whether similar results would be observed in other lower extremity muscle groups. Additionally, these findings may not be generalizable to different conditions where maximum loads are determined separately for each method, different load levels are used, or different populations and exercises are considered. Although the literature suggests that both methods yield similar effects on strength gains and muscle hypertrophy (Hernández-Belmonte et al., 2023; Schwanbeck et al., 2020), further studies are needed to examine muscle activation in a broader range of muscle groups for both methods, to assess jump performance not only in terms of jump height but also peak power, peak force, and peak velocity, to evaluate perceived exertion levels across different sets, and to investigate the chronic effects of these training methods.

Conclusion

The results of this study indicate that in individuals with strength training experience, squat exercises performed on the Smith machine lead to higher vastus lateralis activation, while exertion levels during and after the workout were similar between both methods.

Recommendations

It is recommended that strength and conditioning coaches, sports scientists, and experienced strength training practitioners use the Smith machine for squat exercises to enhance force production during training. However, since exertion levels were similar for both methods, machine-based and free-weight squats can be used interchangeably depending on the training goals and individual needs.

Author Contribution

Conceptualization, Methodology, Supervision, Writing, Review & Editing, Project Administration: FG; Investigation, Data Curation, Formal analysis, Writing, Original Draft: BS; Validation, Resources, Writing, Review & Editing: VA.

Conflict of Interest

All authors declare that there is no conflict of interest.

Ethical Statement

Ethical approval was obtained from Pamukkale University's Ethics Committee (Approval number: E-60116787-020-526525), and all procedures adhered to the guidelines outlined in the Helsinki Declaration.

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