

ORIGINAL RESEARCH

Muscle activation in squat jumps with barbell vs. hex-bar: Effects of load magnitude

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Abstract

Background: The use of hex-bar equipment has recently gained attention in strength and conditioning. Vertical jump mechanics are fundamental to many sport-specific tasks, including sprinting, change-of-direction, and acceleration. Understanding how load magnitude and the choice of hex-bar versus traditional barbell influence neuromuscular responses can inform targeted training interventions designed to enhance performance and reduce injury risk. **Objective:** This study examined lower-limb muscle activation during squat jumps (SJs) across different jump time intervals and external loads, using traditional barbell and hex-bar. **Methods:** Fifteen resistance-trained men (age 25.0 ± 3.0 years) performed SJs at 100%, 120%, 140%, and 160% of their body mass. Electromyographic activity (EMG) from eight lower-limb and back muscles, as well as vertical ground reaction force, was recorded. EMG amplitudes and average ground reaction force were analysed across six time-normalized intervals (five during push-off, one pre-initiation). **Results:** Repeated-measures analysis of variance revealed that muscle activation responses were muscle- and load-specific. Hamstring activation remained unchanged across all conditions, whereas erector spinae, gluteus maximus, soleus, rectus femoris, and vastus lateralis generally showed greater activation with heavier loads, with ~50% of comparisons reaching statistical significance. Equipment-specific differences were most evident in rectus femoris activation, which was consistently lower during hex-bar SJs from initiation through mid-push-off. Participants jumped higher with the hex-bar, and jump height declined with increasing load. **Conclusions:** These findings indicate that external load systematically alters muscle activation strategies, resulting in corresponding changes in force production, while the effects of equipment are more subtle and muscle-specific.

Keywords: activation patterns, muscle coordination, ballistic, power training, performance

Introduction

The use of the hex-bar in loaded jump training has gained increasing attention due to several practical advantages, including a lower perceived risk of injury from the low load position, no need for a spotter, the ability to safely drop the load from a low height, easier load adjustment, and reduced risk of upper back injury during landing. In addition, the hex-bar may facilitate squat technique execution, particularly in less flexible athletes who struggle to position a barbell across the upper back. Previous studies have shown that hex-bar squat jump can elicit greater jump height, peak power, and rate of force development compared with barbell squat jump (Swinton et al., 2012). These improvements have been attributed to differences in load positioning, with the hex-bar placing the load at arm's length rather than on the shoulders, which may also enhance comfort and safety during performance (Swinton et al., 2012). Furthermore, peak power output in the hex-bar squat jump is optimized at relatively low training loads (10–20% of one-repetition maximum), making it an efficient and accessible option for athletes across varying strength levels (Turner et al., 2015). However, technical

execution might differ between the two; hex-bar technique typically involves greater hip displacement and reduced knee displacement, which may influence muscle activity and jump performance outcomes (Stahl et al., 2024; Suchomel et al., 2019, 2023). Moreover, even when controlling for execution, the center of mass tends to shift closer to the ground when using the hex-bar, despite the load being externally attached at a similar body location (shoulders). These factors may alter movement control and muscle activation patterns. Yet, the extent to which equipment choice influences these neuromuscular strategies and how this translates to sport-specific performance tasks such as sprinting, change of direction, and acceleration remains unclear.

Previous research has shown that increased external load enhances ground reaction force (GRF) output during squat jumps (Giroux et al., 2015), but no changes were found in lower-body muscle activation signal patterns across seven load conditions (Giroux et al., 2014). However, alterations in trunk angle have been shown to modulate activation strategies. When the trunk is maintained in a more vertical position, ankle plantar flexors are activated first and contribute most to propulsion, while the hip and

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knee extensors primarily stabilize the center of mass and control trunk posture (Kopper et al., 2012). Additionally, Salvadore et al. (2023) analyzed individual muscle forces using motion capture and computational modeling during loaded hex-bar squat jumps with 0%, 20%, 40%, and 60% of hex-bar deadlift one-repetition maximum, respectively. They reported no significant changes in the forces of m. gluteus maximus, m. biceps femoris, and m. soleus across conditions, whereas m. vastus intermedius and m. gastrocnemius demonstrated increased force production with rising loads. In contrast, m. rectus femoris showed a decrease in muscle force output as external load increased.

Weakley et al. (2021) compared hex-bar and barbell loaded countermovement jumps over a 4-week mesocycle in rugby players, and found improvements in jump height, velocity, power and rate of force development in unloaded countermovement jump for hex-bar group only. Despite this, little is known about how different equipment, such as hex-bar versus barbell, affects neuromuscular activation during ballistic tasks. As mentioned earlier, equipment differences may alter the mechanical demands placed on the hip and knee joints due to changes in load distribution and center of mass positioning.

Understanding muscle activation under different loading strategies has practical implications for strength and conditioning. Vertical jump mechanics underpin a wide range of sport-specific tasks, including sprinting, change-of-direction, and acceleration. Thus, identifying the neuromuscular effects of load magnitude and equipment can guide targeted training interventions aimed at improving performance and reducing injury risk. Cormie et al. (2007) suggested that loaded vertical jumps should be used as a strength-power training tool for athletes required to move light loads at high velocities, for instance, sprinters, jumpers, and basketball and volleyball players.

The aim of this study was to evaluate lower-limb muscle activation across different jump-time intervals during squat jumps (SJs) performed under varying external loads, using both barbell and hex-bar. Based on previous findings (Giroux et al., 2014, 2015; Spudić et al., 2021), we hypothesized that (a) muscle activation patterns would not differ significantly between the two types of equipment, but (b) within each type of equipment, increasing load would be associated with corresponding increases in electromyographic (EMG) activity signal amplitude due to greater neuromuscular demand.

Methods

Study design

A cross-sectional study design was used to investigate differences in EMG of the lower limb and back muscles and corresponding vertical GRF during SJs with additional loads under two conditions: (a) using a traditional Olympic bar (barbell) placed on the upper back, and (b) using a hex-bar. For each condition, jumps were performed with four loads: 100%, 120%, 140%, and 160% of the individual's body mass. As a reference, a bodyweight SJ (free SJ) with hands akimbo was performed at the beginning of

the testing session. All tests were conducted in a randomized order to minimize learning effects and fatigue-related bias. Participants attended the laboratory once, and the testing session lasted approximately 60 min. The study was approved by the National Medical Ethics Committee (no. 0120-690/2017/8) and was conducted in accordance with the tenets of the Oviedo Convention and the Declaration of Helsinki.

Participants

Fifteen healthy, trained men (age 25.0 ± 3.0 years, body height 1.79 ± 0.06 m, body mass 82.3 ± 8.8 kg) participated in the study. The inclusion criterion required adult participants to have a minimum of one year of consistent strength training experience, defined as performing resistance exercises at least twice per week. Participants had prior experience with both barbell and hex-bar SJs and routinely performed loaded SJs in their training programs. Exclusion criteria were established to ensure participant safety and consistency in performance measures. Individuals with a history of knee injuries (such as ligament tears, meniscus damage, or cartilage deterioration) were excluded due to potential impacts on knee stability and function.

Additionally, participants with chronic diseases, including systemic, cardiac, respiratory, or neuromuscular disorders, were excluded to minimize health risks and ensure consistency in physical performance. Those with a history of lower back pain were also excluded to prevent exacerbation of existing conditions and to ensure proper jumping technique. Finally, individuals who had experienced acute injuries within the previous six months that could affect maximal jumping performance were not included, ensuring that all participants were at a comparable physical baseline for the study. Sample size was determined based on the design of previous studies, analyzing lower limb muscle activation during SJs with or without additional loads (Giroux et al., 2015; Goodwin et al., 1999; Jones & Caldwell, 2003; Pandey & Zajac, 1991; Pereira et al., 2008). Participants were informed about the testing procedures and provided written informed consent prior to their participation. They were instructed to avoid any strenuous exercise for at least two days prior to the testing session.

Testing procedures

The participants performed SJs on a force plate (Kistler 9287A; Kistler Group). First, SJs without additional load were performed with the hands placed akimbo. Subsequently, participants performed SJs with loads corresponding to 100%, 120%, 140%, and 160% of their individual body mass (BM), using either a barbell placed on the shoulders or a custom-made hex-bar held with the hands extended alongside the hips (at arm's length). BM was determined using the force plate upon participants' arrival at the laboratory, while wearing the testing equipment. To replicate hand position during the 100% BM condition, a plastic barbell was placed on the shoulders, and the sides of a 0.8 m diameter plastic ring were held with the hands extended at the hips. This setup ensured that hand position, and consequently, the center of body mass, did not

influence differences between loads. Additional mass was added to the barbell (10 kg) and to the hex-bar (10 kg) using weightlifting plates, with a precision of 0.5 kg.

At the start of each test, participants were required to attain a squat position (hip and knee angles at 90°) in the center of the force plate. This starting position was verified before each jump using a manual goniometer (S104, Saehan Co.). Prior to testing, foot placement was standardized and marked on the force plate using adhesive tape, and an elastic rope was positioned just below the gluteal region to control for vertical displacement during the jumps. If a participant was unable to attain and stabilize the starting position within three seconds, the attempt was repeated after a 1-min rest period. Participants were instructed to initiate the jump as explosively as possible from the starting position to achieve maximum vertical jump height. Before take-off, they were required to inhale, stabilize the core, and fully extend the hips, knees, and ankles during push-off. Countermovement was monitored visually by an experienced researcher using the vertical GRF data. If a countermovement was detected, the jump was repeated. No more than five repetitions were needed to obtain three valid jumps for statistical analysis. A 60-s rest was provided between individual jumps, and a 5-min rest between various loads.

EMG activity was assessed using a Trigno Delsys Wireless System (Delsys Inc.) with pre-amplified, self-adhesive wireless electrodes (dimensions: 27 × 37 × 15 mm; mass: 14.7 g; electrode material: silver; contact area: 5 × 1 mm). Following skin preparation (including shaving, light abrasion, and cleaning with alcohol to maintain impedance below 5 kΩ) electrodes were unilaterally placed on the soleus, lateral gastrocnemius, semimembranosus, biceps femoris, vastus lateralis, rectus femoris, gluteus maximus, and erector spinae muscles, in accordance with the recommendations for surface EMG (Hermens et al., 2000). Electrodes were secured using flexible adhesive tape. Placement was performed on the participant's preferred push-off leg, determined as the leg opposite to the dominant kicking leg.

Before EMG measurements and SJ testing, participants completed a standardized 10-min warm-up consisting of: 2 min of alternating step-ups on a 25-cm bench (80 repetitions per minute); joint mobility exercises for the arms, hips, knees, and ankles (10 repetitions each); dynamic stretching of the hip flexors, knee extensors, knee flexors, and ankle extensors (10 repetitions each); and resistance exercises, including heel raises, squats, and crunches (10 slow repetitions each). Following the general warm-up, participants performed five maximal free SJs, countermovement jumps, and jump push-ups.

Data acquisition and analysis procedures

EMG and GRF data were simultaneously acquired using a PowerLab system (16/30-ML880/P; ADInstruments) at a sampling frequency of 2000 Hz. Data were visualized using LabChart software (Version 8; ADInstruments). Curve analyses were performed in RStudio (Version 4.3.3; Posit).

The start of the jump was defined as the first time point when GRF exceeded three standard deviations above the

system weight (i.e., body mass or body mass plus additional load). System weight (baseline signal) was recorded when the participant stabilized in the squat position. Take-off was defined as the first time point when GRF dropped below 10 N (Pérez-Castilla et al., 2019). Jump height (in meters) was calculated using the impulse-momentum method (Linthorne, 2001).

Muscle activation data were first band-pass filtered using a second-order Butterworth filter (20–500 Hz) and then rectified using a root mean square function with a 50-ms window. GRF and electromyography time-series data were time-normalized to 1000 points across all participants and conditions and divided into five equal time intervals. An additional pre-jump interval was included to assess potential muscle activation before GRF changes, accounting for the electromechanical delay (Cavanagh & Komi, 1979).

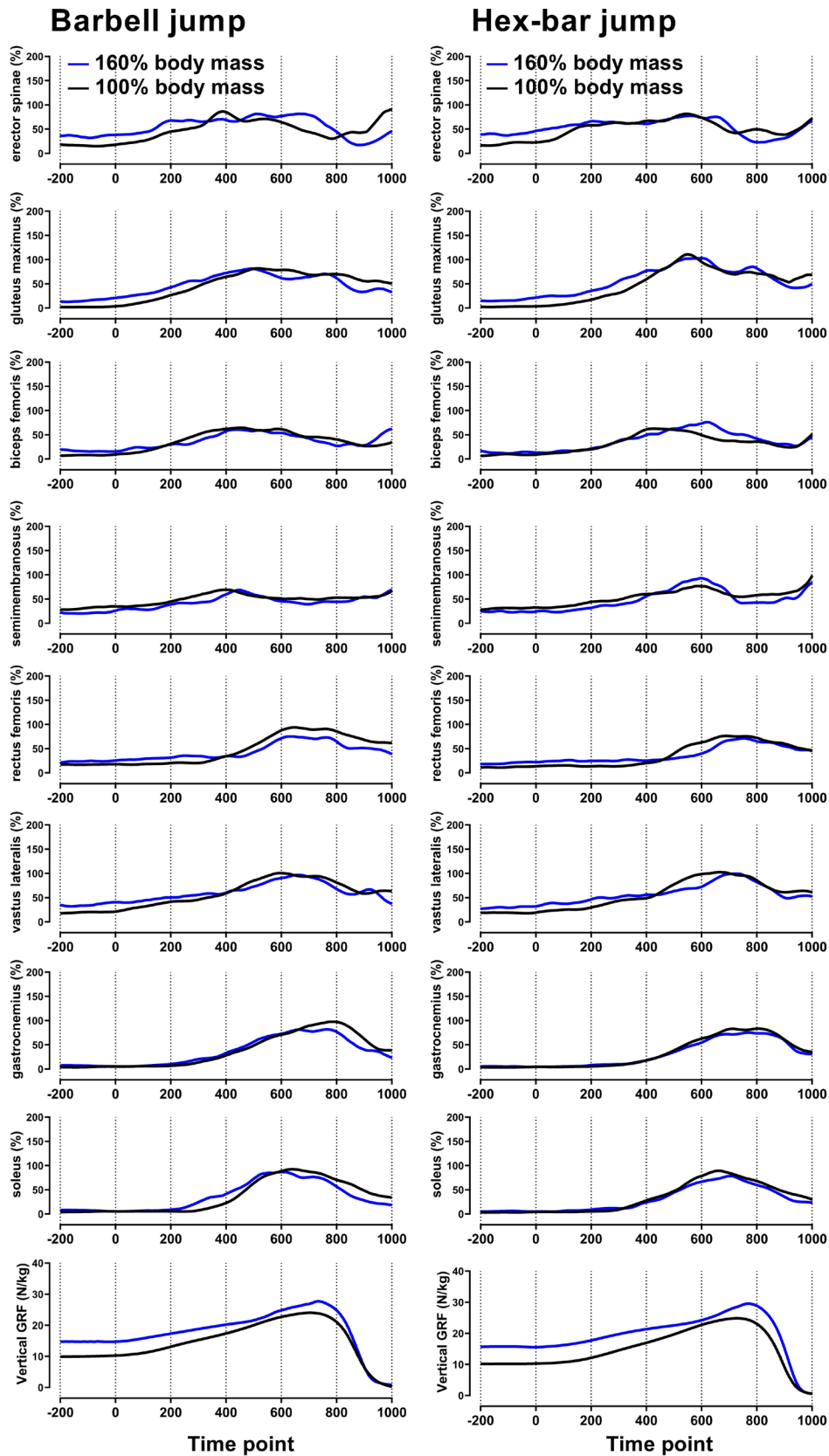
Individual muscle EMG amplitudes and average GRF (expressed relative to body mass in N/kg) were calculated for each of the six time intervals (i.e., five during the jump and one pre-jump), separately for barbell and hex-bar conditions and each load intensity. EMG and GRF values for each time interval were normalized to the maximum value observed across the six intervals during the free squat jump (free SJ) performed with hands akimbo (i.e., a classical SJ). Consistently, the fifth time interval served as the reference. All values are presented as percentages. Average processed GRF and EMG curves for all participants, along with corresponding EMG signals for the barbell (100% and 160% BM) and hex-bar (100% and 160% BM) conditions, are presented in Figure 1.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics (Version 28 for Windows; IBM), and data visualization was conducted with GraphPad Prism (version 9.2.0; GraphPad Software). Descriptive statistics are reported as mean ± standard deviation. The normality of data distribution for each variable was assessed using the Shapiro-Wilk test, homogeneity of variances was verified with Levene's test, and sphericity was evaluated with Mauchly's test. When the sphericity assumption was violated, the Greenhouse-Geisser correction was applied.

A two-way repeated-measures analysis of variance (ANOVA) was used to compare the effects of equipment (barbell vs. hex-bar) and load (100%, 120%, 140%, and 160% of body mass) on EMG activity and GRF, separately for each of the six time intervals and for each of the six muscles. Partial eta squared (η_p^2) effect sizes were calculated, with values of .01, .06, and .14 interpreted as small, medium, and large effects, respectively (Kotrlík & Williams, 2003). In cases where a significant main effect of load or a significant equipment × load interaction was found, Bonferroni-corrected post hoc tests were performed to identify pairwise differences between loads (100% vs. 120% vs. 140% vs. 160% of body mass). Statistical significance was set at $p < .05$.

Figure 1 Representation of processed ground reaction force and electromyography signals



Note. Curves represent the average time-normalized vertical ground reaction force (GRF) and corresponding electromyography (EMG) signals from all acquired squat jumps performed with a traditional barbell (left column) and a hex-bar (right column) at 100% (black curves) and 160% (blue curves) of body mass conditions. All EMG signals (except force curves) were normalized to the peak EMG amplitude of the corresponding muscle during the free squat jump with hands akimbo, and are presented as a percentage of that peak. The push-off phase was time-normalized to 1000 points and divided into five equal intervals. A 200-point pre-jump interval (from -200 to 0) was included to capture potential muscle activation prior to jump initiation.

Results

Summary ANOVA statistics for EMG amplitudes and GRF are provided in the supplementary Tables S1 and S2. Normalized values relative to the free SJ (SJ without added load) are reported for EMG amplitudes of the erector spinae (Table 1), gluteus maximus (Table 2), soleus (Table 3), rectus femoris (Table 4), and vastus lateralis (Table 5) and average GRF (Table 6). Additional data for the semimembranosus, biceps femoris, and gastrocnemius muscles are presented in supplementary Tables S3–S5.

Table 1 shows a significant increase in m. erector spinae activation with increasing load within time intervals 1 and 2 ($p < .001$, $\eta_p^2 = .347-.525$; large effect size), regardless of the bar used. The differences were significant between loads (%BM) 100 and 140, 100 and 160, 120 and 140, and 120 and 160 for time interval 1 (all $ps < .008$), and between loads (%BM) 100 and 140, and 100 and 160 for time interval 2 (all $ps < .007$). Furthermore, at time interval 6, differences in ES activation between loads were dependent on the equipment used (equipment $\times$ load interaction:

$p = .026$, $\eta_p^2 = .315$; large effect size). Differences were found between 120 and 160 BM% only for barbell condition ($p = .043$).

Table 2 shows a significant increase in m. gluteus maximus activation with increasing load within time intervals 1, 2, 3 and 5 ($p < .040$, $\eta_p^2 = .204-.648$; large effect size), regardless of the bar used. The differences were significant between loads (%BM) 100 and 140, 100 and 160, 120 and 140, 120 and 160, and 140 and 160 for time interval 1 (all $ps < .005$), between loads (%BM) 100 and 160, 120 and 140, and 120 and 160 for time interval 2 (all $ps < .020$), between loads (%BM) 100 and 140, and 100 and 160 for time interval 3 (all $p < .001$). In time interval 4, m. gluteus maximus activation was significantly higher using hex-bar than barbell, regardless of load ($p = .004$, $\eta_p^2 = .506$; large effect size).

Table 3 shows a significant increase in m. soleus activation with increasing load within time intervals 2, 3 and 6 ($p < .020$, $\eta_p^2 = .253-.553$; large effect size), regardless of the equipment used. The differences were significant

Table 1 Average m. erector spinae activation across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4 (r)	TI 5	TI 6
Free							
100	mV*100	3.34 $\pm$ 1.71	10.12 $\pm$ 10.89	15.98 $\pm$ 19.24	17.89 $\pm$ 12.19	15.07 $\pm$ 11.44	9.42 $\pm$ 17.86
100	%	23.2 $\pm$ 25.3	53.6 $\pm$ 48.7	78.5 $\pm$ 63.8	96.7 $\pm$ 52.8	77.7 $\pm$ 47.9	29.6 $\pm$ 32.9
Barbell							
100	%	20.2 $\pm$ 12.2	41.2 $\pm$ 24.1	61.5 $\pm$ 31.5	79.7 $\pm$ 23.4	51.0 $\pm$ 31.3	23.2 $\pm$ 13.9
120	%	24.9 $\pm$ 15.9	46.3 $\pm$ 27.6	63.2 $\pm$ 36.4	72.0 $\pm$ 40.3	55.1 $\pm$ 28.5	19.4 $\pm$ 10.3
140	%	34.7 $\pm$ 21.0	51.6 $\pm$ 30.2	67.9 $\pm$ 37.4	81.6 $\pm$ 25.8	59.5 $\pm$ 35.0	23.0 $\pm$ 11.5
160	%	36.5 $\pm$ 23.5	52.0 $\pm$ 29.4	70.0 $\pm$ 37.3	68.8 $\pm$ 38.8	62.6 $\pm$ 37.2	23.0 $\pm$ 12.4
Hex-bar							
100	%	20.5 $\pm$ 12.2	36.4 $\pm$ 22.2	63.9 $\pm$ 18.1	69.1 $\pm$ 40.0	55.0 $\pm$ 35.9	20.9 $\pm$ 11.7
120	%	24.5 $\pm$ 13.6	43.3 $\pm$ 18.9	63.5 $\pm$ 26.3	69.8 $\pm$ 34.8	73.9 $\pm$ 37.8	24.2 $\pm$ 10.8
140	%	35.7 $\pm$ 16.3	52.2 $\pm$ 20.6	59.0 $\pm$ 22.2	70.7 $\pm$ 33.2	68.1 $\pm$ 29.9	25.0 $\pm$ 14.4
160	%	33.1 $\pm$ 19.4	47.1 $\pm$ 25.6	66.7 $\pm$ 44.8	73.3 $\pm$ 45.6	62.3 $\pm$ 31.9	21.1 $\pm$ 11.1

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak electromyography amplitude interval). Data are presented as means $\pm$ standard deviations.

Table 2 Average m. gluteus maximus activation across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4 (r)	TI 5	TI 6
Free							
100	mV*100	0.33 $\pm$ 0.18	2.47 $\pm$ 3.13	7.5 $\pm$ 5.38	12.93 $\pm$ 7.58	10.65 $\pm$ 7.89	6.16 $\pm$ 3.88
100	%	2.3 $\pm$ 1.2	15.3 $\pm$ 16.3	48.8 $\pm$ 29.1	82.0 $\pm$ 31.6	67.0 $\pm$ 30.6	38.8 $\pm$ 14.5
Barbell							
100	%	2.8 $\pm$ 2.0	10.7 $\pm$ 7.5	45.1 $\pm$ 27.0	73.8 $\pm$ 27.0	74.1 $\pm$ 28.2	47.2 $\pm$ 15.7
120	%	4.9 $\pm$ 5.5	12.3 $\pm$ 6.7	50.7 $\pm$ 25.9	70.9 $\pm$ 21.3	66.9 $\pm$ 26.2	38.4 $\pm$ 12.0
140	%	7.8 $\pm$ 7.7	14.8 $\pm$ 6.4	48.6 $\pm$ 20.1	69.7 $\pm$ 22.6	63.8 $\pm$ 24.3	41.2 $\pm$ 17.4
160	%	10.7 $\pm$ 8.6	18.8 $\pm$ 9.8	55.3 $\pm$ 29.6	65.0 $\pm$ 21.1	60.3 $\pm$ 29.3	42.8 $\pm$ 20.5
Hex-bar							
100	%	3.6 $\pm$ 3.2	14.3 $\pm$ 14.4	32.8 $\pm$ 13.6	83.9 $\pm$ 32.9	77.7 $\pm$ 30.3	47.9 $\pm$ 22.2
120	%	3.8 $\pm$ 2.9	14.1 $\pm$ 8.7	47.1 $\pm$ 23.5	86.7 $\pm$ 33.3	73.8 $\pm$ 30.0	50.2 $\pm$ 18.6
140	%	8.3 $\pm$ 5.4	23.2 $\pm$ 11.6	55.0 $\pm$ 16.7	80.4 $\pm$ 24.3	74.6 $\pm$ 20.2	47.0 $\pm$ 17.8
160	%	13.4 $\pm$ 11.6	26.0 $\pm$ 11.5	50.6 $\pm$ 15.2	84.8 $\pm$ 29.0	80.4 $\pm$ 36.9	46.4 $\pm$ 15.7

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak electromyography amplitude interval). Data are presented as means $\pm$ standard deviations.

between loads (%BM) 100 and 140 for time interval 3 ($p = .035$), between loads (%BM) 100 and 120, and 100 and 140, and 100 and 160 for time interval 6 (all $ps < .019$). Furthermore, differences in m. soleus activation between loads were dependent on the equipment used (equipment $\times$ load interaction; $p = .004$, $\eta_p^2 = .387$; large effect size). Differences were found between 100 and 120, 100 and 140, and 100 and 160 only for barbell condition (all $ps < .007$), and between 100 and 140 for hex-bar condition ($p = .035$).

Table 4 shows a significant increase in m. rectus femoris with increasing load within time intervals 2, 5 and 6 ($p < .041$, $\eta_p^2 = .259$ –.399; large effect size), regardless of the bar used. The differences were significant between loads (%BM) 120 and 160, and 140 and 160 for time interval 2 (all $ps < .043$). In time intervals 1, 2, 3, and 4, m. rectus femoris activation was significantly higher using barbell than hex-bar, regardless of load (all $ps < .040$, $\eta_p^2 = .329$ –.625; large effect size).

Table 5 shows a significant increase in m. vastus lateralis with increasing load within time intervals 1, 2 and 6 (all $ps < .047$, $\eta_p^2 = .196$ –.728; large effect size), regardless

of the bar used. The differences were significant between loads (%BM) 100 and 120, and 100 and 140, 100 and 160, 120 and 160, and 140 and 160 for time interval 1 (all $ps < .049$) and between loads (%BM) 100 and 140, and 100 and 160, 120 and 140, and 120 and 160 for time interval 2 (all $ps < .013$). In time interval 4, m. vastus lateralis activation was significantly higher using barbell than hex-bar, regardless of load ($p = .042$, $\eta_p^2 = .325$; large effect size).

Table 6 shows a significant increase in average GRF with increasing load across all time intervals (all $ps < .001$). Post hoc test revealed differences ($p < .05$) between all pairs of loads. Only in time interval 5, hex-bar GRF was significantly higher than barbell GRF, regardless of the load ($p = .003$, $\eta_p^2 = .471$; large effect size).

Participants achieved the greatest SJ height without added load (0.319 ± 0.097 m). Barbell SJ height decreased from 0.312 ± 0.110 m at 100% body weight to 0.245 ± 0.078 m at 120%, 0.191 ± 0.067 m at 140%, and 0.150 ± 0.057 m at 160%. Similarly, hex-bar SJ height declined from 0.314 ± 0.084 m at 100% to 0.259 ± 0.071

Table 3 Average m. soleus activation across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4	TI 5 (r)	TI 6
Free							
100	mV*100	1.60 $\pm$ 1.00	1.79 $\pm$ 1.02	6.37 $\pm$ 6.55	23.53 $\pm$ 15.19	29.07 $\pm$ 9.48	20.68 $\pm$ 9.43
100	%	6.1 $\pm$ 4.2	6.5 $\pm$ 3.0	21.0 $\pm$ 15.9	79.9 $\pm$ 37.5	108.5 $\pm$ 23.9	81.0 $\pm$ 44.7
Barbell							
100	%	5.4 $\pm$ 2.7	6.0 $\pm$ 2.7	12.8 $\pm$ 6.9	65.6 $\pm$ 29.8	99.2 $\pm$ 1.5	72.7 $\pm$ 14.4
120	%	4.5 $\pm$ 2.2	5.6 $\pm$ 2.4	16.7 $\pm$ 8.8	72.9 $\pm$ 24.2	87.8 $\pm$ 19.3	61.6 $\pm$ 26.9
140	%	4.5 $\pm$ 2.4	6.2 $\pm$ 2.6	16.5 $\pm$ 6.1	66.2 $\pm$ 22.3	86.2 $\pm$ 22.7	53.2 $\pm$ 21.8
160	%	5.6 $\pm$ 3.5	7.9 $\pm$ 4.5	21.7 $\pm$ 12.2	70.3 $\pm$ 23.6	80.9 $\pm$ 26.5	48.7 $\pm$ 18.9
Hex-bar							
100	%	4.2 $\pm$ 2.0	4.8 $\pm$ 2.4	15.9 $\pm$ 14.1	57.0 $\pm$ 34.3	87.8 $\pm$ 37.8	54.5 $\pm$ 26.1
120	%	4.4 $\pm$ 2.3	5.5 $\pm$ 3.3	18.8 $\pm$ 14.1	53.8 $\pm$ 34.3	83.2 $\pm$ 36.3	60.4 $\pm$ 40.4
140	%	3.5 $\pm$ 1.8	7.4 $\pm$ 4.4	23.8 $\pm$ 15.2	57.9 $\pm$ 39.8	82.4 $\pm$ 37.0	48.3 $\pm$ 25.9
160	%	4.5 $\pm$ 2.2	7.5 $\pm$ 3.9	26.5 $\pm$ 15.8	62.4 $\pm$ 40.3	81.5 $\pm$ 39.2	54.2 $\pm$ 36.2

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak electromyography amplitude interval). Data are presented as means $\pm$ standard deviations.

Table 4 Average m. rectus femoris activation across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4	TI 5 (r)	TI 6
Free							
100	mV*100	5.89 $\pm$ 5.60	6.31 $\pm$ 4.33	10.57 $\pm$ 12.84	18.45 $\pm$ 12.94	24.09 $\pm$ 8.93	21.92 $\pm$ 11.71
100	%	22.8 $\pm$ 16.8	25.2 $\pm$ 11.0	38.4 $\pm$ 31.2	74.0 $\pm$ 37.7	101.6 $\pm$ 30.5	90.9 $\pm$ 33.0
Barbell							
100	%	18.8 $\pm$ 9.0	22.8 $\pm$ 7.2	29.9 $\pm$ 11.1	61.1 $\pm$ 25.8	95.0 $\pm$ 9.3	84.3 $\pm$ 14.8
120	%	16.8 $\pm$ 8.3	22.3 $\pm$ 12.2	30.1 $\pm$ 12.6	57.1 $\pm$ 20.1	93.1 $\pm$ 16.1	76.0 $\pm$ 25.1
140	%	20.2 $\pm$ 11.3	23.0 $\pm$ 11.5	29.4 $\pm$ 10.3	54.7 $\pm$ 24.5	83.4 $\pm$ 20.9	70.1 $\pm$ 28.0
160	%	20.2 $\pm$ 9.6	28.1 $\pm$ 13.5	36.4 $\pm$ 16.7	51.5 $\pm$ 23.6	82.4 $\pm$ 23.1	65.4 $\pm$ 28.1
Hex-bar							
100	%	13.5 $\pm$ 7.8	17.2 $\pm$ 9.2	21.6 $\pm$ 9.8	50.8 $\pm$ 30.2	79.2 $\pm$ 32.7	80.7 $\pm$ 18.3
120	%	13.2 $\pm$ 7.9	15.5 $\pm$ 8.2	20.0 $\pm$ 8.6	36.5 $\pm$ 22.4	81.9 $\pm$ 29.6	77.8 $\pm$ 19.0
140	%	15.7 $\pm$ 10.7	19.8 $\pm$ 13.0	27.0 $\pm$ 13.9	35.5 $\pm$ 21.6	76.3 $\pm$ 30.7	64.6 $\pm$ 32.1
160	%	19.2 $\pm$ 12.5	22.2 $\pm$ 13.9	26.4 $\pm$ 16.8	35.3 $\pm$ 18.3	76.0 $\pm$ 26.1	80.0 $\pm$ 15.4

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak electromyography amplitude interval). Data are presented as means $\pm$ standard deviations.

m, 0.213 ± 0.060 m, and 0.173 ± 0.046 m at the respective loads. ANOVA indicated a significant effect of equipment type ($F = 6.103$, $p = .027$, $\eta_p^2 = .304$) and a progressive decrease in jump height with increasing load ($F = 75.542$, $p < .001$, $\eta_p^2 = .844$). The equipment $\times$ load interaction was not significant ($F = 1.472$, $p = .248$, $\eta_p^2 = .095$), indicating that load-related declines in jump height were similar between equipment types. Pairwise comparisons revealed significant differences between all load conditions (all $ps < .001$).

Discussion

The present study aimed to examine the magnitude of lower-limb muscle activation during different SJ time intervals performed with varying external loads, using both barbell and hex-bar. To the best of the authors' knowledge, no previous research has directly investigated these neuromuscular responses across these two loading modalities, highlighting the novelty and relevance of the current findings. The results can be summarized as follows: (a) Muscle activation analyses revealed mixed findings: no significant

differences were observed in hamstring activity (m. semi-membranosus and m. biceps femoris) across loads or equipment, whereas the m. erector spinae, m. gluteus maximus, m. soleus, m. rectus femoris, and m. vastus lateralis generally demonstrated increased activation with higher loads, with approximately 50% of the variables reaching statistical significance. Furthermore, equipment-related differences were most pronounced in the m. rectus femoris, where activation was lower in hex-bar SJ from the initiation to the mid-push-off phase. (b) Participants on average jumped higher with the hex-bar, and jump height progressively decreased with increasing load (100–160% BM), regardless of the equipment used (barbell vs. hex-bar). (c) When comparing six time-normalized intervals of the SJ across barbell and hex-bar conditions, GRF increased in all intervals with increasing load, independent of equipment; however, in interval 6, where peak GRF occurred in all conditions, GRFs were higher with the hex-bar.

In contrast to Giroux et al. (2015), who found no changes in EMG activity with increasing load, our study demonstrated both increased (m. erector spinae, m. gluteus maximus, m. soleus, m. rectus femoris, m. vastus lateralis)

Table 5 Average m. vastus lateralis activation across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4	TI 5 (r)	TI 6
Free							
100	mV*100	6.90 $\pm$ 3.15	12.37 $\pm$ 7.03	22.78 $\pm$ 22.02	36.69 $\pm$ 28.08	42.01 $\pm$ 21.97	28.39 $\pm$ 13.65
100	%	17.9 $\pm$ 10.6	30.9 $\pm$ 16.9	50.2 $\pm$ 22.3	80.9 $\pm$ 20.2	95.5 $\pm$ 11.0	64.3 $\pm$ 15.6
Barbell							
100	%	19.5 $\pm$ 5.8	33.0 $\pm$ 15.6	52.3 $\pm$ 17.7	82.6 $\pm$ 17.1	96.2 $\pm$ 5.2	73.6 $\pm$ 18.2
120	%	22.5 $\pm$ 9.3	33.1 $\pm$ 14.8	55.9 $\pm$ 20.6	83.8 $\pm$ 16.8	91.4 $\pm$ 8.1	62.2 $\pm$ 13.4
140	%	24.4 $\pm$ 10.6	40.1 $\pm$ 17.2	54.5 $\pm$ 18.9	72.4 $\pm$ 15.8	98.9 $\pm$ 13.2	66.8 $\pm$ 16.5
160	%	29.0 $\pm$ 11.7	47.3 $\pm$ 21.8	57.4 $\pm$ 21.1	79.1 $\pm$ 16.8	92.6 $\pm$ 16.3	69.9 $\pm$ 15.3
Hex-bar							
100	%	15.5 $\pm$ 4.8	30.4 $\pm$ 11.5	46.1 $\pm$ 11.2	77.4 $\pm$ 17.4	100.7 $\pm$ 15.1	70.3 $\pm$ 19.0
120	%	21.3 $\pm$ 7.4	35.4 $\pm$ 17.3	46.3 $\pm$ 14.3	75.5 $\pm$ 19.7	95.2 $\pm$ 12.8	67.7 $\pm$ 13.8
140	%	24.1 $\pm$ 9.3	42.9 $\pm$ 15.5	56.7 $\pm$ 14.3	75.9 $\pm$ 17.6	93.7 $\pm$ 16.5	67.2 $\pm$ 17.0
160	%	27.9 $\pm$ 11.6	43.8 $\pm$ 20.2	61.3 $\pm$ 19.8	76.6 $\pm$ 13.3	89.4 $\pm$ 14.9	68.6 $\pm$ 21.9

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak electromyography amplitude interval). Data are presented as means $\pm$ standard deviations.

Table 6 Average vertical ground reaction force across time intervals in free squat, barbell squat, and hex-bar squat jumps under incremental loads

Equipment/%BM	Unit	TI 1	TI 2	TI 3	TI 4	TI 5 (r)	TI 6
Free							
100	N/kg	9.38 $\pm$ 1.20	11.26 $\pm$ 1.49	15.91 $\pm$ 2.70	19.73 $\pm$ 2.99	22.14 $\pm$ 2.54	13.36 $\pm$ 2.01
Barbell							
100	%	42.8 $\pm$ 4.5	51.3 $\pm$ 6.3	72.2 $\pm$ 8.7	89.1 $\pm$ 8.1	100.0 $\pm$ 6.1	60.2 $\pm$ 9.3
120	%	53.6 $\pm$ 10.8	63.0 $\pm$ 11.4	83.4 $\pm$ 10.6	95.4 $\pm$ 7.6	104.2 $\pm$ 6.9	64.6 $\pm$ 10.8
140	%	62.8 $\pm$ 11.2	71.9 $\pm$ 11.5	89.5 $\pm$ 10.9	100.0 $\pm$ 8.9	108.9 $\pm$ 7.3	70.6 $\pm$ 16.3
160	%	71.2 $\pm$ 10	80.9 $\pm$ 10.5	97.7 $\pm$ 10.0	106.5 $\pm$ 9.9	115.6 $\pm$ 7.6	74.8 $\pm$ 16.3
Hex-bar							
100	%	44.0 $\pm$ 4.5	51.5 $\pm$ 5.1	71.6 $\pm$ 7.7	91.2 $\pm$ 7.2	103.5 $\pm$ 3.0	62.6 $\pm$ 9.0
120	%	52.2 $\pm$ 5.0	59.7 $\pm$ 6.0	78.3 $\pm$ 8.0	92.4 $\pm$ 5.6	107.9 $\pm$ 5.4	69.6 $\pm$ 9.5
140	%	61.6 $\pm$ 5.9	70.6 $\pm$ 7.0	89.5 $\pm$ 8.1	99.9 $\pm$ 5.9	114.8 $\pm$ 5.6	75.0 $\pm$ 10.0
160	%	70.3 $\pm$ 7.5	78.8 $\pm$ 8.2	96.6 $\pm$ 8.5	106.8 $\pm$ 6.0	120.5 $\pm$ 6.1	78.3 $\pm$ 9.8

Note. %BM = load as percentage of participant's body mass; TI = time interval; r = reference interval (peak force interval). Data are presented as means $\pm$ standard deviations.

and decreased (*m. soleus*) activation under different loads across various time intervals. In accordance with our hypothesis, we found statistically significant differences in muscle activation patterns between the hex-bar and barbell only in one of the six analyzed time intervals for *m. erector spinae*, *m. gluteus maximus*, and *m. vastus lateralis*.

In contrast, the *m. rectus femoris* exhibited a differential response between the two conditions in four of the six analyzed intervals, pointing out distinct neuromuscular demands between equipment types specifically for this multi-joint knee extensor muscle. Overall, an increase in EMG amplitude with increasing load was observed regardless of equipment type, reflecting greater neuromuscular demand. Conversely, analysis of distal muscles (*m. gastrocnemius* and *m. soleus*) revealed reduced activation at higher loads in certain intervals, suggesting lower neuromuscular demand for ankle extensors as load increased.

Despite maximal effort across all jumps, the higher EMG amplitudes observed under greater loading conditions may be explained by reduced movement velocity and the associated increase in force production (Sugi & Ohno, 2019), which requires greater neural drive. This is achieved through increased motor unit recruitment (particularly of type II motor units, which are activated near maximal force levels) as well as increased firing frequency and motor unit synchronization (Cormie et al., 2011a, 2011b). Our results confirmed that GRF increased across all intervals with increasing load, which aligns with the observations of Zink et al. (2006), who similarly reported a load-dependent increase in GRF during explosive jumps. Furthermore, we observed higher jump heights with the hex-bar compared to the barbell. Consistent with our findings, Swinton et al. (2012) reported that the use of the hex-bar in loaded jump training provides clear practical advantages, enabling athletes to achieve significantly greater jump height, peak power, and rate of force development. Higher jump height could be a consequence of greater GRF production during interval 5 of hex-bar squat jumping; however, differences in jump height cannot be explained by the distinct muscle activation patterns observed in our study.

Although activation of proximal muscles preceded that of distal muscles, peak activation interval of proximal muscles was expected to occur earlier (for example, in intervals 1–3, i.e., the first half of the push-off). Specifically, *m. erector spinae* was expected to reach maximal activation within the first two intervals, consistent with its role in trunk extension. Likewise, peak activation interval of *m. gluteus maximus* occurred later than anticipated. This observation only partially aligns with previous findings that emphasize the importance of a sequential proximal-to-distal recruitment pattern of the major leg extensors, which facilitates energy transfer from proximal to distal body segments via biarticular muscles and enhances the effectiveness of power generation in SJs (Bobbert & van Ingen Schenau, 1988; Fessl et al., 2022; Gregoire et al., 1984; Pandey & Zajac, 1991; Spudić et al., 2021). Typically, EMG activity during SJ rises to a plateau in the order: *m. semitendinosus*, long head of *m. biceps femoris*, *m. gluteus maximus*, *m. vastus medialis*, *m. rectus femoris*, *m. soleus*, and *m.*

gastrocnemius (Bobbert & van Ingen Schenau, 1988). However, variations have also been reported. For example, Pereira et al. (2008) noted a distal-to-proximal sequence in untrained individuals, and Giroux et al. (2015) observed *m. soleus* peaking before *m. rectus femoris*, regardless of the magnitude of the external load. These discrepancies suggest that inter-muscular activation coordination during ballistic movements may be influenced by training history and task-specific factors. Taken together, although not the primary aim of our study, the findings partially support the general proximal-to-distal recruitment strategy. Peak EMG amplitude intervals remained unchanged despite load increases, suggesting that additional barbell or hex-bar load does not alter the timing of peak muscle activity, which aligns with the results of Giroux et al. (2015) exploring the phenomenon for barbell SJs only. But, the finding contrasts with the findings of Spudić et al. (2021), who reported that higher loads lead to reorganization of underlying muscle coordination mechanisms in flywheel squats. Based on these results, we can speculate that increasing the load during flywheel resistance training provides distinct muscle activation sequence changes in comparison to gravity-based resistance training (barbell or Hex-bar SJs). Most importantly, distinct activation patterns were not found between the two training equipment types in our study.

The main strength of the present study lies in its comprehensive approach, including the simultaneous examination of eight muscles' EMGs alongside GRF data. Multiple repetitions of each condition were performed to reduce heterogeneity of the measures. Another notable advantage is the analysis of EMG activity across six time intervals, which accounts for electromechanical delay variability between individuals and muscles, an important factor that can bias results when analyzing point variables such as time-to-peak muscle activity (Spudić et al., 2021). Nevertheless, several limitations should be acknowledged. The sample size, while consistent with similar studies, was relatively small, which may increase the risk of a Type II error and limit the generalizability of the study's findings. Despite all participants engaging in physical activity at least twice per week, considerable variability in fitness levels and performance capacities could have influenced results, despite efforts to standardize the starting position of each jump.

Additionally, although EMG is widely used for assessing muscle activation in jumping tasks and provides insights into both timing and magnitude (Pereira et al., 2008), it remains susceptible to variability and artifacts. Furthermore, measurements from a single electrode site may not fully represent activation across the entire muscle, which should be considered when interpreting the findings. Furthermore, loads were prescribed relative to body mass rather than relative to maximal strength (e.g., one-repetition maximum), which may not fully account for inter-individual differences in strength and neuromuscular capacity.

Future research should further investigate neuromuscular and mechanical responses to SJs using different loading modalities across broader athlete populations and training levels. Additionally, longitudinal studies comparing chronic adaptations to hex-bar versus barbell SJ training could

provide valuable insights for optimizing power development and load prescription. Such evidence would enable strength and conditioning professionals to make more informed recommendations when selecting between these two modalities for explosive lower-limb training.

Conclusions

This study demonstrated that only m. rectus femoris activation differed between equipment types: barbell SJs elicited higher m. rectus femoris activation during the early and mid-push-off phases, whereas other muscles generally exhibited load-dependent increases. GRF increased progressively across loads, with peak values being greater in the hex-bar condition. Jump height decreased with increasing external load but remained consistently higher when using the hex-bar compared to the barbell. It remains unclear whether these acute activation differences are sufficient to induce long-term changes in motor control or recruitment strategies, and how such adaptations might transfer to unloaded bodyweight SJs, one of the most relevant performance measures in sport. From a practical perspective, the hex-bar appears more effective for maximizing SJ height, peak force, and power output, whereas the barbell may better target m. rectus femoris activation under heavy loads. Future research should therefore examine how long-term training with these implements influences neuromuscular patterns and impacts sport performance outcomes.

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Conflict of interest

The authors report no conflict of interest.

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