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Comparative Effects of the Free Weights and Smith Machine Squat and Bench Press: The Important Role of Specificity for Strength Adaptations

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Purpose: Although previous studies have compared strength-training adaptations between free weights (FW) and machine-guided exercises, those studies did not use a Smith machine (SM), which most closely replicates the exercises performed with FW. Thus, the aim of the present study was to investigate the chronic effects of strength-focused, velocity-based training regimens using FW versus SM. ***Methods:*** Thirty-seven sport-science students (14 female) were assigned, balanced by sex and relative strength, to either an FW or SM training group. The training program lasted 8 weeks (2 sessions/wk), and participants performed 4 sets per exercise (back squat and bench press) at 70% of their 1-repetition maximum with moderate effort levels (20%–25% velocity loss). Load–velocity profile parameters (load-axis intercept, velocity-axis intercept, and area under the load–velocity relationship line), cross-sectional areas of the vastus lateralis and pectoralis major muscles, and the number of repetitions to failure in the bench-press exercise were assessed before and after the training program. Mechanical variables were assessed using both FW and SM. ***Results:*** All variables, with the exception of back-squat velocity-axis intercept ($P = .124$), improved in both training groups. The changes in load-axis intercept and area under the load–velocity relationship line were more pronounced when the training and testing conditions matched. Failure in the bench-press exercise and cross-sectional areas of the vastus lateralis and pectoralis major showed comparable improvements for both training groups, while velocity-axis intercept tended to improve more in the SM group. ***Conclusions:*** The general population, unconcerned with the specificity of strength adaptations, can choose a training modality (FW or SM) based on personal preferences.

Keywords: machine-guided exercises, velocity-based training, strength training, functional training, muscle cross-sectional area

Strength training can significantly enhance overall health and sport performance.[1,2] The parameters derived from the load–velocity profile (LVP), including the load-axis intercept (L_0), the velocity-axis intercept (v_0), and the area under the load–velocity relationship line (A_{line}), are indicators of the maximal capacities for producing force, velocity, and power, respectively.[3] These parameters have been shown to be sensitive enough to detect changes in muscle's mechanical capacities following strength training program.[4] Muscle cross-sectional area (CSA) is often measured to assess structural changes after strength training regimens.[5] Notably, 1 variable coaches can manipulate when prescribing exercise is the degree of movement restriction, with the use of free weights (FW) allowing for more degrees of freedom compared to guided machines (eg, Smith machine [SM]).[6] Gaining insight into the long-term effects of movement restriction on the changes in LVP parameters and muscle CSA could facilitate the prescription of more effective training strategies, ultimately contributing to maximize strength and performance outcomes.

Several studies have highlighted significant acute differences in maximal dynamic strength (1-repetition maximum [1RM]) and mechanical performance against the same absolute loads between similar FW and machine-based exercise modalities. For instance, greater 1RMs have been observed in the SM modality when performing bench press (BP) and Bulgarian split squat compared with FW,[7,8] while a greater 1RM was found in FW power clean compared with a machine-based power clean.[9] On the other hand, no significant differences were found in jump height and maximum velocity, force, and power between FW and SM squat (SJ), and countermovement jump (CMJ).[10-12] However, Pérez-Castilla et al[13] revealed a greater jump height in SM CMJ when calculated from the takeoff velocity, but not from the flight time. Consequently, the observed acute variations in mechanical performance between FW and machine-based exercises appear to be influenced by the exercise performed or the machine used. Notably, the SM is identified as the equipment that most closely facilitates the performance of exercises similar to those done with FW.

Comparisons between FW and machine-based exercises extend beyond acute differences in mechanical performance. Two recent meta-analyses[14,15] have demonstrated that strength training adaptations are optimized when training and evaluation conditions align.[14,15] Specifically, the meta-analyses found greater strength gains in FW-trained groups during FW evaluations, and conversely, machine-trained groups showed greater improvements during machine-based evaluations. Notably, the meta-analyses revealed no significant between-groups differences in parameters, such as muscle CSA, or alternative measures of strength gains. However, previous longitudinal studies are subject to limitations. First, none of the studies included in the meta-analyses applied a velocity-based training (VBT) program, a method shown to offer

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greater precision in daily intensity adjustment compared to the other traditional methods for intensity prescription.[16] Second, strength adaptations are thought to be maximized when lifting at maximum intended velocity and avoiding failure,[17,18] a factor not accounted for in the analyzed studies. Third, some studies compared FW training against machine-based training but employed different exercises (eg, FW BP vs chest press), complicating direct comparison. Notably, the only 2 studies that used a VBT program, not included in the mentioned meta-analyses due to their recent publication, also did not use the same exercises for FW and machine-based exercises.[19,20]

Based on the previous literature, this study fills a gap by comparing the chronic effects of a VBT program in which the same exercises (back squat [SQ] and BP) are performed with (SM) or without (FW) restriction. The aim of the present study was to assess the effects of an 8-week VBT program differing only in movement restriction (FW or SM) on strength gains and muscle hypertrophy. Neuromuscular performance was assessed using both FW and SM modalities to determine whether training adaptations are influenced by the evaluation modality. Based on the literature reviewed, our hypotheses are: (1) greater strength gains in the FW-trained group in FW evaluations, (2) greater strength gains in SM-trained group during SM evaluations, and (3) no significant between-groups differences in muscle CSA.

Methods

Experimental Protocol

A longitudinal pre–post design, with participants randomly divided into 2 parallel groups (FW and SM), was implemented to compare movement restriction effects on LVP parameters (L_0, v_0, and A_{line}) during SQ and BP, performed with both FW (Ruster), and a SM (Multipower Fitness Line, Peroga). Groups assignment was based on gender and on the sum of their relative strength (1RM divided by body mass) in the 2 exercises executed. Additionally, pre–post differences in BP repetitions until failure ($BP_{Failure}$) and CSA of the vastus lateralis (VL_{CSA}) and pectoralis major (PM_{CSA}) muscles were also assessed. The study protocol comprised 2 familiarization sessions, 3 pretest sessions, 16 training sessions (twice weekly, at least 48 h apart), and 3 posttest sessions. The 2 familiarization sessions consisted of performing SQ and BP with FW and SM at maximal velocity against various loads (mean velocity [MV] ranged from 1.20 to 0.65 $m \cdot s^{-1}$ and 1.45 to 0.50 $m \cdot s^{-1}$ in SQ and BP, respectively). Pretest and posttest sessions included the determination of FW and SM LVPs (S1 and S2, in a randomized order, constant for pretest and posttest) and CSAs (S3). There was a minimum of 2 days between S1 and S2, and 4 days between S2 and S3. Consistency was maintained across all testing and training sessions, conducted at a fixed time (±2 h) for each participant.

Participants

Thirty-seven sports sciences students (14 females) were randomly, and counterbalanced, assigned to 2 training groups (FW or SM). Inclusion criteria included maintaining an active lifestyle and the ability of performing SQ and BP at maximal intended velocity with proper technique. Eight participants (FW = 3; SM = 5) dropped out for personal reasons. For the remaining participants, all but one (SM group, 15/16 sessions) completed 100% of the training sessions. Seven participants experienced lower limb injuries, preventing them from squatting (5 unrelated to this study). The 2 injuries related to the intervention occurred in different groups. In the SM group, 1 male sustained a distal tear of the vastus medialis muscle. In the FW group, 1 female reported low back pain. Descriptive data of participants considered for statistical analyses is shown in Table 1. The study was conducted according to the Declaration of Helsinki and approved by the Ethics Commission of the Local University (ID: 3666/CEIH/2023). All subjects signed a written consent form after being informed of the study's purpose and procedures.

LVP Assessment

The SQ and BP LVP were evaluated during the same testing session in a sequential order. Each session began with a standardized warm-up, encompassing 10 minutes of lower and upper body dynamic mobility. The SQ- and BP-specific warm-up consisted of 1 set of 5 repetitions (20 kg) at comfortable velocity, followed by 3 sets of 3 repetitions at maximum velocity with load increments until 50% of self-perceived 1RM. The specific characteristics of the SQ and BP testing procedures are provided below.

SQ Assessment

The test began performing 3 repetitions of ballistic SQ against 2 light loads (6 kg, 20 kg). The test continued with the traditional SQ (without jumping) at maximum velocity, performing 3 repetitions with 15-kg load increments until MV was lower than 0.90 $m \cdot s^{-1}$. Two repetitions were then performed with 10-kg increments until MV was below 0.60 $m \cdot s^{-1}$. Finally, 1 repetition was performed with 5-kg increments until MV was lower than 0.50 $m \cdot s^{-1}$, similar to previous studies.[21] Participants were instructed to descend until thighs were parallel to floor and ascend as fast as possible. The descending phase was consistent for all participants and verified by the downward displacement provided by the linear position transducer.

BP Assessment

The test started with 3 repetitions against light loads (6 kg, 20 kg) throwing the barbell for the SM evaluation, and using the traditional BP (without throwing) in the FW evaluation for safety reasons. The test continued with the traditional BP at maximum velocity, performing 3 repetitions with 15-kg increments until MV was lower than 0.80 $m \cdot s^{-1}$. Then, 2 repetitions were performed with 10-kg increments until MV was below 0.50 $m \cdot s^{-1}$. Finally, 1

Table 1 Descriptive Data of Participants Considered for the Statistical Analysis

Variable	FW	SM
Age, y	20.9 (2.1)	19.8 (1.7)
Body mass, kg	68.4 (9.2)	69.2 (8.0)
Height, cm	172.1 (6.8)	173.8 (8.1)
Sample size SQ	13 (5 F)	9 (4 F)
Sample size BP	16 (5 F)	13 (6 F)
Relative strength in FW SQ, a.u.	1.28 (0.19)	1.32 (0.16)
Relative strength in SM SQ, a.u.	1.18 (0.21)	1.23 (0.14)
Relative strength in FW BP, a.u.	0.90 (0.24)	0.86 (0.19)
Relative strength in SM BP, a.u.	0.86 (0.22)	0.78 (0.18)

Abbreviations: a.u., arbitrary units; BP, bench press; F, female; FW, free weight; SM, Smith machine; SQ, back squat. Note: Data are presented as mean (SD).

repetition was performed with 5-kg increments until MV was lower than 0.30 $m \cdot s^{-1}$. Participants were instructed to descend until their lower sternum and ascend as fast as possible. Five minutes after completing the incremental test, participants performed maximum repetitions until failure with 80% 1RM. In the posttest sessions, the same absolute load as in the pretest sessions was used.

A rest period of 3 minutes was established between different loads for both exercises. Velocity was measured by a linear position transducer (GymAware RS, Kinetic Performance Technologies). For each load, only the fastest repetition was considered for analysis. All the loads and velocities were modeled by a linear regression model to obtain the L_0 and the slope. The v_0 was calculated as $v_0 = L_0/\text{slope}$, while the A_{line} was calculated as $A_{line} = L_0 v_0/2$.[3] The linear regression model was used to estimate the 1RM as the load linked to a MV of 0.33 and 0.17 $m \cdot s^{-1}$ for SQ and BP, respectively.[21,22]

CSA Assessment

The B-mode option of an ultrasound device (Versana Active, GE Healthcare) was used to determine VL_{CSA} and PM_{CSA} (Figure 1), both previously validated against magnetic resonance imaging.[23,24] Participants lay supine on an examination bed with knees resting flexed at 150° (180° = full extension) over a foam roller. The VL_{CSA} was marked at 60% of femur length (0% = knee, 100% = hip), as this is one of the most valid and reliable thigh regions to evaluate VL_{CSA}.[25] This position was marked with weather stripping to ensure consistent position within sessions and to keep the probe perpendicular. Femur length was defined as the distance between the bottom of the lateral condyle and the top of the greater trochanter. PM_{CSA} was marked at the origin of the pectoralis minor,[26] determined just over the nipple. PM images were only acquired in males. After 15 minutes to allow fluid distribution stabilization, VL images were taken. A trained operator blinded to the training group acquired 3 good panoramic images per muscle using a 38-mm linear-array probe (6–13 MHz). A generous amount of transmission gel (GIMA) was applied to exert minimal pressure. Consistency in measurement sites between pretesting and posttesting days was ensured using easily identifiable infiltrations of fatty and connective tissues as landmarks. Ultrasound images were recorded and digitally analyzed (ImageJ 1.54d, NIH) by the same operator. All images were assessed, and if the coefficient of variation exceeded 5%, the most discrepant image was removed. From 246 images, 13 were removed for exceeding the 5% threshold, and the mean coefficient of variation between the analyzed images was 2.08%. The average value from all the analyzed images was considered for analysis.

Training Procedures

Over 8 consecutive weeks, both training groups were scheduled twice weekly. Both groups performed 4 sets per exercise (SQ first, BP second), applying the same intensity (70% 1RM), effort levels (20% and 25%MV loss for SQ and BP, respectively), and rest between sets (3 min). The general warm-up mirrored the general warm-up of the evaluation protocol. Thereafter, 3 (training load < 100 kg) or 4 (training load ≥ 100 kg) approximation sets of 3 repetitions were performed. In the last approximation set, 2 repetitions were performed with the load from the previous training session. An experienced researcher provided verbal encouragement to maximize velocity during every repetition, and verbal feedback on MV following each repetition. Daily load adjustments were made based on the MV to align with the targeted

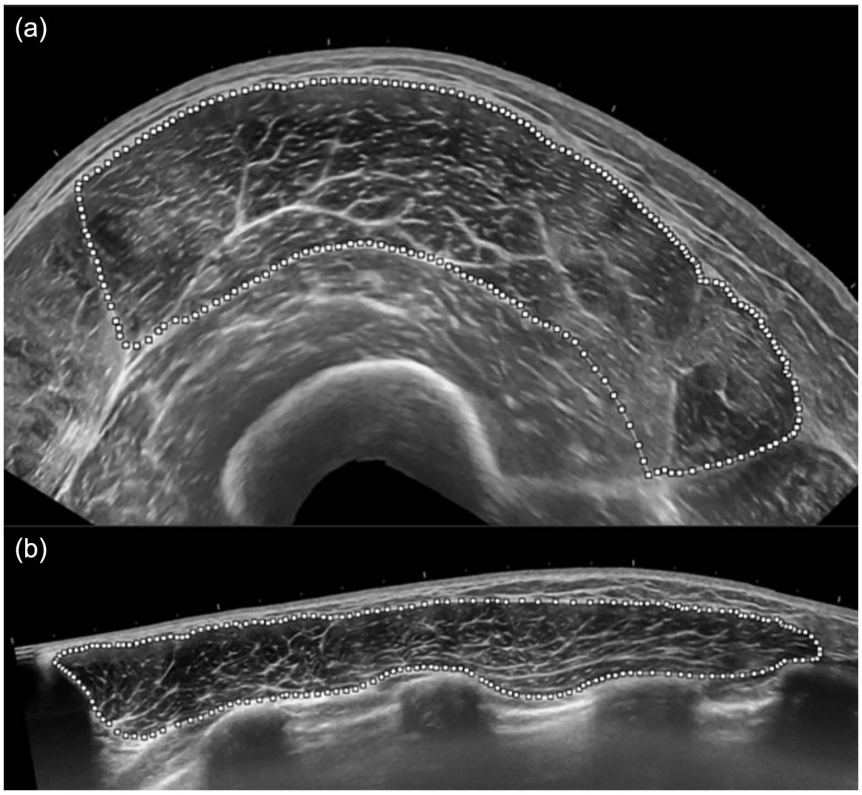

Figure 1 — Representative image illustrating (a) vastus lateralis cross-sectional area and (b) pectoralis major cross-sectional area.

Table 2 Three-Way Mixed ANOVA Comparing Back-Squat Load–Velocity-Profile Variables Between the Time, Training, and Evaluation Conditions

Variable	Training condition	Evaluation condition	Time		ES (95% CI)	ANOVA	
			Pre	Post		Main effect	Interaction
L_0, kg	FW (n = 13)	FW	110.8 (24.3)	137.0 (25.3)*	0.99 (0.54 to 1.56)	**Time: $F = 206.2$; $P < .001$**	Time × Eval: $F = 0.7$; $P = .414$
		SM	103.7 (25.8)	124.4 (22.2)*	0.80 (0.48 to 1.23)	**Eval: $F = 595.9$; $P < .001$**	Time × Train: $F < 0.1$; $P = .995$
	SM (n = 9)	FW	111.8 (18.1)	130.4 (24.4)*	0.78 (0.36 to 1.36)	Train: $F < 0.1$; $P = .855$	**Eval × Train: $F = 18.1$; $P < .001$**
		SM	106.3 (15.5)	134.5 (23.5)*	1.28 (0.65 to 2.18)		**Time × Eval × Train: $F = 9.6$; $P = .006$**
v_0, m·s^{-1}	FW (n = 13)	FW	1.68 (0.11)	1.69 (0.17)	0.07 (–0.33 to 0.47)	Time: $F = 2.6$; $P = .124$	Time × Eval: $F = 1.3$; $P = .263$
		SM	1.59 (0.15)	1.61 (0.14)	0.10 (–0.14 to 0.35)	Eval: $F = 2.3$; $P = .144$	Time × Train: $F = 1.7$; $P = .211$
	SM (n = 9)	FW	1.51 (0.59)	1.71 (0.15)	0.43 (–0.39 to 1.31)	Train: $F = 0.6$; $P = .438$	Eval × Train: $F = 0.2$; $P = .630$
		SM	1.55 (0.13)	1.58 (0.13)	0.25 (–0.11 to 0.65)		Time × Eval × Train: $F = 1.5$; $P = .236$
A_{line}, kg·m·s^{-1}	FW (n = 13)	FW	93.9 (25.1)	116.6 (28.1)*	0.80 (0.44 to 1.25)	**Time: $F = 199.1$; $P < .001$**	Time × Eval: $F = 0.2$; $P = .668$
		SM	83.9 (26.9)	101.0 (24.2)*	0.63 (0.37 to 0.96)	**Eval: $F = 63.4$; $P < .001$**	Time × Train: $F < 0.1$; $P = .849$
	SM (n = 9)	FW	95.4 (21.2)	112.1 (26.2)*	0.63 (0.27 to 1.12)	Train: $F < 0.1$; $P = .963$	Eval × Train: $F = 2.1$; $P = .166$
		SM	82.8 (17.3)	106.9 (23.0)*	1.07 (0.56 to 1.80)		**Time × Eval × Train: $F = 9.9$; $P = .005$**

Abbreviations: A_{line}, area under the load–velocity relationship line; ANOVA, analysis of variance; ES, effect size; Eval, evaluation condition; FW, free weight; L_0, load-axis intercept; SM, Smith machine; Train, training condition; v_0, velocity-axis intercept. Data are presented as mean (SD).

*Significant differences compared to Pre ($P < .05$). Bold values indicate $P < .05$ for ANOVA main effects and interactions.

Table 3 Three-Way Mixed ANOVA Comparing Bench-Press Squat Load–Velocity-Profile Variables and Repetitions Until Failure Between the Time, Training, and Evaluation Conditions

Variable	Training condition	Evaluation condition	Time		ES (95% CI)	ANOVA	
			Pre	Post		Main effect	Interaction
L_0, kg	FW (n = 16)	FW	67.8 (21.9)	78.1 (22.8)*	0.44 (0.29 to 0.63)	**Time: $F = 291.2$; $P < .001$**	**Time × Eval: $F = 8.6$; $P = .007$**
		SM	64.9 (19.8)	73.8 (20.9)*	0.41 (0.27 to 0.60)	**Eval: $F = 28.1$; $P < .001$**	Time × Train: $F = 0.2$; $P = .693$
	SM (n = 13)	FW	65.8 (19.8)	72.4 (20.6)*	0.31 (0.15 to 0.49)	Train: $F = 0.2$; $P = .627$	Eval × Train: $F < 0.1$; $P = .889$
		SM	59.8 (18.1)	71.5 (19.8)*	0.58 (0.34 to 0.89)		**Time × Eval × Train: $F = 26.6$; $P < .001$**
v_0, m·s^{-1}	FW (n = 16)	FW	2.01 (0.24)	2.04 (0.27)	0.13 (–0.01 to 0.28)	**Time: $F = 9.8$; $P = .004$**	**Time × Eval: $F = 8.3$; $P = .008$**
		SM	2.07 (0.23)	2.07 (0.22)	–0.01 (–0.25 to 0.24)	Eval: $F = 3.1$; $P = .090$	**Time × Train: $F = 4.5$; $P = .043$**
	SM (n = 13)	FW	1.94 (0.17)	2.08 (0.20)*	0.72 (0.24 to 1.27)	Train: $F < 0.1$; $P = .988$	Eval × Train: $F = 0.2$; $P = .683$
		SM	2.06 (0.23)	2.10 (0.21)	0.16 (–0.11 to 0.55)		Time × Eval × Train: $F = 1.9$; $P = .184$
A_{line}, kg·m·s^{-1}	FW (n = 16)	FW	69.6 (27.4)	81.7 (30.7)*	0.39 (0.25 to 0.58)	**Time: $F = 146.1$; $P < .001$**	Time × Eval: $F = 0.7$; $P = .406$
		SM	68.7 (26.3)	78.0 (28.4)*	0.32 (0.19 to 0.49)	Eval: $F = 1.8$; $P = .196$	Time × Train: $F = 0.9$; $P = .355$
	SM (n = 13)	FW	64.2 (20.9)	76.1 (24.1)*	0.49 (0.25 to 0.80)	Train: $F = 0.2$; $P = .639$	Eval × Train: $F = 0.8$; $P = .377$
		SM	63.1 (23.9)	76.3 (25.5)*	0.50 (0.29 to 0.78)		**Time × Eval × Train: $F = 5.2$; $P = .031$**
$BP_{Failure}$, repetitions	FW (n = 16)	FW	10.3 (2.0)	16.4 (3.5)*	2.03 (1.17 to 3.07)	**Time: $F = 115.0$; $P < .001$**	**Time × Eval: $F = 11.6$; $P = .002$**
		SM	9.4 (2.5)	16.7 (3.2)*	2.44 (1.43 to 3.68)	Eval: $F = 2.2$; $P = .146$	Time × Train: $F = 0.4$; $P = .521$
	SM (n = 13)	FW	9.7 (2.9)	14.4 (2.2)*	1.71 (0.85 to 2.78)	Train: $F = 0.2$; $P = .700$	**Eval × Train: $F = 4.6$; $P = .042$**
		SM	10.2 (2.5)	17.4 (3.6)*	2.20 (1.20 to 3.46)		Time × Eval × Train: $F = 1.2$; $P = .276$

Abbreviations: A_{line}, area under the load–velocity relationship line; ANOVA, analysis of variance; $BP_{Failure}$, repetitions until failure in bench press with the same absolute load; ES, effect size; Eval, evaluation condition; FW, free weight; L_0, load-axis intercept; SM, Smith machine; Train, training condition; v_0, velocity-axis intercept. Note: Data are presented as mean (SD).
*Significant differences compared to Pre ($P < .05$). Bold values indicate $P < .05$ for ANOVA main effects and interactions.

%1RM. The individual MV associated with the 70%1RM determined in the pretest session was used for loading prescription. When the MV was outside a range of ±0.03 $m \cdot s^{-1}$, an adjustment of ±2 kg was established, until MV was inside the mentioned MV range.

Statistical Analysis

Descriptive data are reported as mean (SD). Data normality and randomness were verified using the Shapiro–Wilks test and Wald–Wolfowitz runs test, respectively ($P > .05$). A 3-factor mixed analysis of variance test was used to examine the effects of "time" (within-subject factor: pretest vs posttest), "evaluation condition" (within-subject factor: FW vs SM), and "training group" (between-subjects factor: FW vs SM) on LVP parameters (L_0, v_0, A_{line}) and $BP_{Failure}$. A 2-factor mixed analysis of variance test was used to determine the effects of "time" and "training group" on VL_{CSA} and PM_{CSA}. The factor sex was not considered in the analyses of variance because it failed to reveal any significant interaction effect for any dependent variable. Paired samples *t* tests and Hedges *g* effect size (ES) along with 95% CIs were used to explore the magnitude of the changes (pre–post) separately for the FW and SM training groups. The ES was also used to compare the magnitude of the changes between the FW and SM training groups using the pooled pretest SDs.[27] ES magnitudes were classified as: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–2.00), and extremely large (>2.00).[28] All analyses were conducted using SPSS software (version 23.0, SPSS Inc). Statistical significance was accepted at an alpha level of .05.

Results

The main effect of "time" was significant for all variables (with the only exception of SQ v_0; $P = .124$) derived from the SQ (Table 2), and BP (Table 3), LVPs, and $BP_{Failure}$ due to higher values observed at posttest compared with pretest. The "time" × "training group" interaction was significant for BP v_0 ($P = .043$) due to greater improvements for the SM training group. For the remaining variables, this interaction did not reach significance, suggesting overall comparable changes from pretesting to posttesting for both groups.

However, the "time" × "evaluation condition" × "training group" interaction was significant for SQ and BP L_0 and A_{line}, indicating that the FW training group improved more using the FW evaluation condition while the SM training group improved more using the SM evaluation condition, reflecting the specificity of training for enhancing the maximum capacities of producing force and power. The magnitude of the ES comparing the pre–post changes in SQ parameters between training groups was always small (ES = 0.24–0.49), except for the trivial ES found for SQ v_0 (Figure 2). Regarding the BP, ESs were always trivial (ES = 0.01–0.17), with the exceptions of the small ESs found for BP v_0 (ES = 0.48) in favor of the SM group and $BP_{Failure}$ (ES = 0.54) in favor of the FW group (Figure 3).

The main effect of "time" was significant for both VL_{CSA} and PM_{CSA} due to a greater CSA at posttest compared to pretest, but the "time" × "training group" interaction did not reach significance, suggesting comparable increments in CSA for both training groups (Figure 4). The magnitude of the ES comparing the pre–post changes in VL_{CSA} between the FW and SM training groups was trivial (ES = 0.03), while a small ES (ES = 0.30) in favor of the SM training group was observed for the PM_{CSA}.

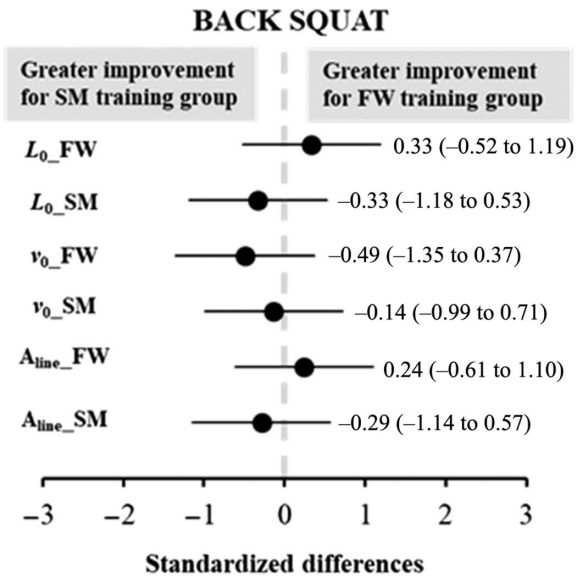

Figure 2 — Standardized differences with 95% CIs for the changes in back-squat load–velocity-profile parameters between the FW and SM training groups. A_{line} indicates area under the load–velocity relationship line; FW, free-weight evaluation condition; L_0, load-axis intercept; SM, Smith-machine evaluation condition; v_0, velocity-axis intercept.

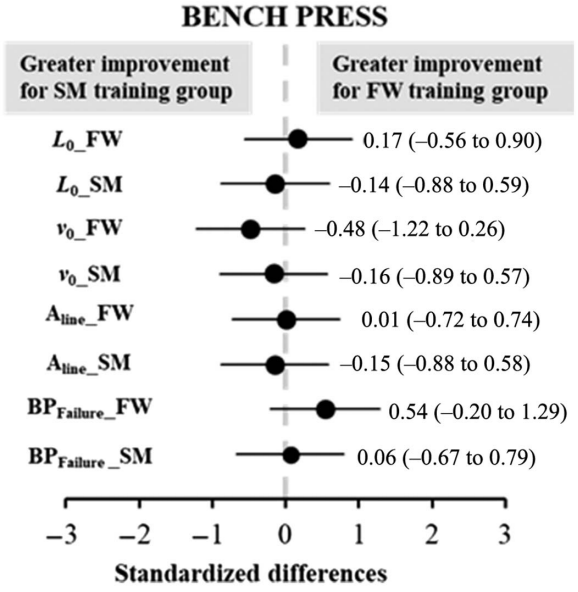

Figure 3 — Standardized differences with 95% CIs for the changes in BP load–velocity-profile parameters and $BP_{Failure}$ between the FW and SM training groups. A_{line} indicates area under the load–velocity relationship line; $BP_{Failure}$, bench-press repetitions until failure with the same absolute load; FW, free-weight evaluation condition; SM, Smith-machine evaluation condition; L_0, load-axis intercept; v_0, velocity-axis intercept.

Discussion

This study compared the chronic effects of training the same exercises (SQ and BP) with (SM) or without (FW) restricting the displacement of the barbell to the vertical direction. The main findings suggest that, while both training groups (FW and SM)

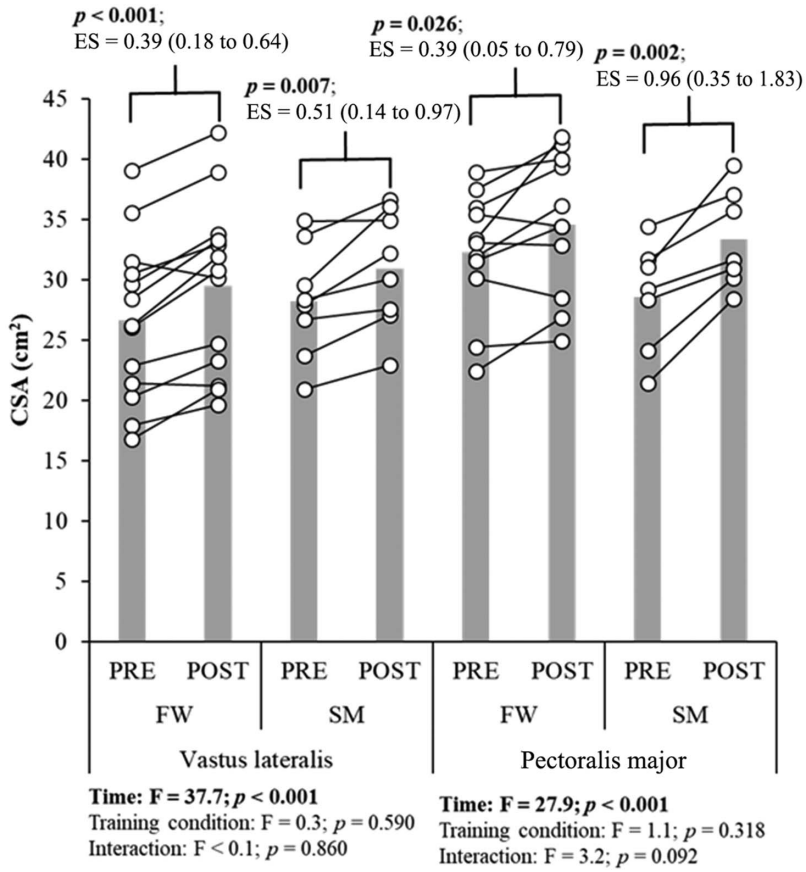

Figure 4 — Mean and individual pre to post changes produced by both training groups on vastus lateralis and pectoralis major CSA. Two-way ANOVA results (*F* score and *P* value) are depicted below each figure separately for the vastus lateralis and pectoralis major muscles. *P* values and ES with 95% CIs revealing within-group pre–post differences are depicted at the top of the figure. ANOVA indicates analysis of variance; CSA, cross-sectional area; ES, effect size; FW, free-weight evaluation condition.

improved all the variables evaluated except for SQ v_0, the changes in L_0 and A_{line} appear to be significantly influenced by the specificity between the training and testing conditions. However, although the strength-endurance capacity ($BP_{Failure}$), VL_{CSA}, and PM_{CSA} showed comparable improvements in both training groups, v_0 may have a greater improvement in the SM modality. While athletes should train under conditions similar to their competitive environment, the general population, unconcerned with the specificity of strength adaptations, can choose a training modality based on personal preference, as overall gains in strength, and muscle CSA, are expected to be similar.

The hypothesis regarding greater gains when training and testing conditions align was confirmed for L_0 and A_{line} parameters. These findings align with previous studies.[14,15,19,20] However, a strength of our study lies in the utilization of VBT with the same exercises for the first time. This is an important consideration because minor variations in exercises can impact training adaptations despite targeting similar muscle groups,[29] while real-time monitoring of lifting velocity ensures precise adherence to prescribed exercise intensity (%1RM) and effort levels.[16] Therefore, while individuals pursuing health-related goals may choose based on their preferences, athletes focusing on performance goals, such as powerlifters, should train under the condition they aim to improve (ie, FW training to maximize gains in FW 1RM).

The outcomes of our study indicate that the training regimen may not be optimal for enhancing SQ v_0, while BP v_0 appears to exhibit greater improvements within the SM group. Wirth et al[30] reported significant enhancements in SJ and CMJ after training until failure for 8 weeks, with FW SQ, but not with leg press. These disparities may be attributed more to the biomechanical similarities of the FW SQ to the tested exercises (SJ and CMJ), than to the exclusive use of FW or machines. However, other studies have demonstrated improvements in SJ, CMJ, and velocity with light loads in various exercises, after training at 65% to 85% 1RM for 8 weeks with various exercises, without revealing significant between-groups differences.[19,20] Nevertheless, none of the previously mentioned studies prescribed a resistance training program focused on improving velocity with light loads. Furthermore, a possible increase in body mass due to muscle mass gain could have influenced the lack of improvement in SQ v_0. Although acknowledging that SQ v_0 did not reach statistically significant pre–post changes, v_0 in both exercises (SQ and BP) and both evaluation conditions (FW and SM) seem to enhance more with a SM, as indicated by the ESs (Figures 2 and 3).

Strength-endurance ($BP_{Failure}$) demonstrated comparable improvements in both groups. Schwanbeck et al[31] found a greater 6 to 10 RM improvement in SM BP in the SM training group after 8 weeks of training, while no other between-groups differences were found for strength endurance. However, the ambiguity of

intensity and test description (ie, a range of 6–10RM) makes their results difficult to interpret. Saeterbakken et al[32] reported greater enhancements in 10RM in the SM training group after 6 weeks of training. Participants from Saeterbakken et al[32] study terminated sets closer to failure, which could explain the differences compared with our results. Completing sets close to failure on a SM potentially allows for 1 to 2 extra repetitions due to its stability, which may boost strength-endurance. Nevertheless, this advantage may not manifest after training far from failure.

An 8-week resistance training program differing only on the degree of restriction seems to yield similar increments in VL_{CSA} and PM_{CSA}, as evidenced by this and previous research.[14,15,19,20] Similarly, biceps and quadriceps muscle thickness did not differ between groups in the Schwanbeck et al[31] study. It is important to note that our training program was not specialized to maximize hypertrophy, as training sets terminated far from failure.

Although this study addresses several important gaps in the literature it is not without limitations. First, while training 2 exercises for 8 weeks was sufficient for increasing strength and muscle mass, it is unclear whether a longer duration or a more diverse exercise regimen could lead to different adaptations between FW and SM exercises. Second, we do not have information regarding the intersession reliability of the operator when using ultrasound for CSA measurements. Third, the sample size for PM_{CSA} analysis was limited as it was conducted exclusively on men. Fourth, our analysis was restricted to VL_{CSA}, while including the entire quadriceps CSA might have provided more comprehensive insights into overall quadriceps structural changes. Finally, we did not evaluate any athletic skill due to logistical difficulties. Future research should explore the effects of resistance training programs using FW and SM on athletic skills to provide more comprehensive insights for exercise prescription (eg, unloaded jumps, sprints, or changes of direction).

Practical Applications

This study underscores the importance of tailoring the restriction of the barbell displacement based on individual goals and preferences. While athletes aiming for specific performance gains may benefit from training in the condition they seek to improve, individuals pursuing general health goals can opt for the modality that enhances adherence to the exercise program.

Conclusions

This study sheds light on the impact of free-weights versus Smith-machine exercises on strength gains and muscle hypertrophy. Our findings confirm that strength and power improvements were specific to the evaluation modality. However, the Smith machine appears to elicit greater improvements in velocity-axis intercept compared with free weights. Additionally, the changes in strength-endurance and hypertrophy outcomes were comparable between groups.

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