

Adaptations in athletic performance and muscle architecture are not meaningfully conditioned by training free-weight versus machine-based exercises: Challenging a traditional assumption using the velocity-based method

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Abstract

Background: Although the superior effectiveness of free-weight over machine-based training has been a traditionally widespread assumption, longitudinal studies comparing these training modalities were scarce and heterogeneous.

Objective: This research used the velocity-based method to compare the effects of free-weight and machine-based resistance training on athletic performance and muscle architecture.

Methods: Thirty-four resistance-trained men participated in an 8-week resistance training program allocated into free-weight ($n=17$) or machine-based ($n=17$) groups. Training variables (intensity, intraset fatigue, and recovery) were identical for both groups, so they only differed in the use of a barbell or specific machines to execute the full squat, bench press, prone bench pull, and shoulder press exercises. The velocity-based method was implemented to accurately adjust the planned intensity. Analysis of covariance and effect size (ES) statistics were used to compare both training modalities on a comprehensive set of athletic and muscle architecture parameters.

Results: No between-group differences were found for any athletic ($p \geq 0.146$) and muscle architecture ($p \geq 0.184$) variable. Both training modalities significantly and similarly improved vertical jump (Free-weight: $ES \geq 0.45$, $p \leq 0.001$; Machine-based: $ES \geq 0.41$, $p \leq 0.001$) and lower limb anaerobic capacity (Free-weight: $ES \geq 0.39$, $p \leq 0.007$; Machine-based: $ES \geq 0.31$, $p \leq 0.003$). Additionally, the machine-based group meaningfully enhanced upper limb anaerobic power ($ES = 0.41$, $p = 0.021$), whereas the free-weight group significantly improved the change of direction ($ES = -0.54$, $p = 0.003$) and 2/6 balance conditions analyzed ($p \leq 0.012$). Changes in sprint capacity ($ES \geq -0.13$, $p \geq 0.274$), fascicle length, and pennation angle ($ES \leq 0.19$, $p \geq 0.129$) were not significant for either training modality.

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Conclusion: Adaptations in athletic performance and muscle architecture would not be meaningfully influenced by the resistance modality trained.

KEYWORDS

fascicle length, jump, pennation angle, sprint, training modality

1 | INTRODUCTION

Nowadays, resistance training is commonly incorporated as a complement to the field- or track-specific training of most sports disciplines because of its effectiveness to improve athletic capacities.^{1,2} Traditionally, practitioners have promoted the superior efficacy of free-weight over machine-based resistance training for increasing these positive adaptations. This assumption has mainly been supported by the higher acute activation produced by free-weight exercises in agonist/synergist and trunk muscles,^{3–5} which would theoretically maximize intermuscular coordination and athletic capacities.^{6,7}

Nevertheless, investigations comparing the long-term effects of these resistance training modalities are scarce and heterogeneous. There is evidence equally favoring free-weight^{8,9} and machine-based^{10,11} resistance training for improving jumping capacity, probably because they compared different exercises (e.g., squat vs. leg press) rather than different training modalities. Moreover, only one study has compared free-weight and machine-based training on horizontal displacement (e.g., sprint or change of direction)¹⁰ and balance capacities,¹² whereas no investigation to date has studied which modality would maximize upper limb athletic abilities. Similarly, there is reduced knowledge on whether the resistance training modality could meaningfully modulate muscle architectural adaptations, which in turn may influence both athletic capacities and risk of injury.¹³

Importantly, the comparison of athletic and structural adaptations produced by free-weight and machine-based resistance training would require the use of a reliable method to control the other training parameters capable of modulating long-term adaptations (e.g., intensity¹⁴ or intra-set volume¹⁵). Previous investigations comparing these training modalities have programmed the intensity by using fixed weights relative to a one-repetition maximum (1RM) measured at pre-training.^{12,16} Nevertheless, since the initial 1RM normally increases throughout the program,^{14,17} weights used to train at each target intensity would not accurately reflect it in most cases. On the other hand, a given number of maximum repetitions (e.g., 8RM) has traditionally been used to prescribe the intra-set volume when comparing free-weight and machine-based exercises.^{8,9,11} This *n*RM strategy would require the

athletes to reach muscle failure, which could be dangerous,¹⁸ inefficient, and even detrimental to neuromuscular performance.¹⁹ These disadvantages around intensity and intra-set volume programming could be solved by the velocity-based strategy. This methodology makes it possible to accurately program intensity by prescribing velocity values (instead of fixed weights), thus considering the subject's 1RM at each time point throughout an intervention.^{14,17} The intra-set volume, for its part, could be precisely prescribed through velocity-derived methodologies, such as the velocity loss,^{20,21} effort index,²² or level of effort.²³ Overall, the use of the velocity-based strategy would represent an important step forward to exhaustively isolate the main independent variable (training modality) by accurately matching the rest of the training parameters between both groups.

Considering all the above, the current research conducted a velocity-based intervention to compare the effects of free-weight and machine-based resistance training on athletic performance and muscle architecture. We hypothesized that the free-weight and machine-based training modalities would produce similar adaptations in athletic capacities and muscle architecture.

2 | MATERIALS AND METHODS

2.1 | Subjects

Thirty-four resistance-trained men volunteered to take part in this study. Inclusion criteria were: i) having at least 2 years experience training free-weight and machine-based modalities, ii) not taking drugs or dietary supplements known to influence physical performance throughout the study; iii) not having physical limitations, disease, or health problems that could affect the testing or training sessions; and iv) not conducting any other resistance exercise during the time this research lasted. To assign the subjects to each training modality in a counterbalanced way, their relative strength (1RM divided by body mass, $1RM_{Rel}$) in eight exercises (4 exercises $\times$ 2 modalities, described later in detail) was measured during the initial evaluation. Thereafter, subjects were randomly allocated into the free-weight group ($n=17$, age = 22.2 ± 2.1 years, height = 178.6 ± 4.8 cm, body mass = 77.9 ± 9.2 kg, mean

$1RM_{Rel} = 1.17 \pm 0.34$) or machine-based group ($n = 17$, age = 20.6 ± 2.0 years, height = 176.9 ± 5.6 cm, body mass = 76.2 ± 10.0 kg, mean $1RM_{Rel} = 1.16 \pm 0.34$). One subject from each group dropped out during the training program for personal reasons not related to the training program. Compliance with the training program was $\geq 95.8\%$ (23/24 sessions) for the rest of the subjects. The study was conducted according to the Declaration of Helsinki and approved by the Ethics Commission of the Local University (ID: 3592/2021). All subjects signed a written consent form after being informed of the purpose and experimental procedures.

2.2 | Study design

After a familiarization period, the free-weight and machine-based groups trained 3 sessions per week for 8 weeks, using the full squat (SQ), bench press (BP), prone bench pull (PBP), and seated shoulder press (SP) exercises. All training variables (intensity, intraset volume, number of sets, interset, and between-sessions recoveries) were identical for both groups. Therefore, they only differed in the use of a barbell or specific machines for performing the SQ, BP, PBP, and SP exercises. Velocity was measured to accurately adjust the planned intensity for each training modality. The changes generated by both groups were examined using a comprehensive set of athletic and ultrasound evaluations measured before (T1) and after (T2) the training program. Additionally, the changes in relative strength for the eight exercises (4 exercises $\times$ 2 modalities) were evaluated.

Before the initial evaluation, all subjects completed a 2-week familiarization period. During six sessions, they practiced all the athletic tests and were instructed in the lifting technique of both modalities of resistance exercises, focusing on performing the concentric phase at maximal intended velocity while completing the full range of motion.

2.3 | Testing procedures

2.3.1 | Muscle architecture

The B-mode option of an ultrasound device (Versana Premier™, GE Healthcare, Chicago, IL, USA) was used to measure vastus lateralis pennation angle (VL_{PA}) and fascicle length (VL_{FL}). Subjects rested supine on an examination bed with their knees fully extended (0° flexion).²⁴ After a time interval of 20 min to allow fluid shift stabilization, a trained operator acquired longitudinal images at 50% of the trochanter-mid patella distance of the right leg

using a linear-array probe (38 mm field of view).²⁵ An adequate quantity of transmission gel (Kefus, Alicante, Spain) was applied to reduce the pressure exerted on the skin and improve the acoustic contact. For increasing consistency, the probe position at the exact point at which each participant's image was taken at T1 was registered on a transparent acetate sheet to be traced back onto the participant's skin at T2. Moreover, frequencies (range 10–13 MHz) and depths (range 5–8 cm) of the images were individually configured for each participant and held constant at both time points.

Regarding the analysis, VL_{PA} (angle at the intersection between the fascicle and deep aponeurosis) and VL_{FL} (length of the fascicle from the superior to deep aponeurosis) were analyzed using the public domain software ImageJ (version 1.53a, National Institute of Health, USA). Parameters were measured from the visible portion of two fascicles within the same image and the extrapolation method was used when a portion of the fascicle extended outside of the probe field of view.²⁶ The average value obtained from the two fascicles was considered for further analysis, measuring a third one when the coefficient of variation (CV) was higher than 5%.²⁰

2.3.2 | Functional capacities

Sprint and vertical jump tests

Sprint times were measured using photocell timing gates (Chronojump Boscossystem, Barcelona, Spain) placed at 0 and 20 m. Two maximal 20-m sprints, separated by a 3-min rest, were performed on a running track. The shortest time resulting from both sprints was saved for further analysis. For consistency, the leg forward by each subject at the start line (1-m behind the first timing gate) was registered at T1 and replicated at T2. Following 5 min of rest and the instructions detailed elsewhere,²⁷ subjects performed five maximal countermovement jumps (CMJ) and squat jumps (SJ) separated by 1 min of recovery (and 5 min of rest between types of jump). The highest and lowest values recorded in each jump test were removed, and the resulting average was kept for analysis. Both the CMJ and SJ were evaluated using an infrared timing system (Optojump System, Microgate, Bolzano, Italy).

Change of direction

The Zig-zag test based on four 5-m sections marked with cones set at 100° angles was used to examine the change of direction (COD) capacity. This test was chosen due to how it required the subjects to quickly accelerate and decelerate while maintaining balance. Moreover, its simplicity would minimize the learning effects.²⁸ The shortest time of two maximal attempts, separated by a 5-min rest, was

used for further analysis. The time was registered by photocell timing gates (Chronojump Boscosystem, Barcelona, Spain) placed 5 meters before and after the first and last cone, respectively. Before each trial, the leg forward by each subject at the start line (0.3-m behind the first timing gate) was registered at T1 and replicated at T2.

Anaerobic capacity and power

The Wingate test was included for examining the changes in upper- (ArmWGT) and lower limb (LegWGT) anaerobic performance.²⁹ Both Wingate tests were executed in a mechanically braked cycle ergometer (Monark 874 E, Monark, Vansbro, Sweden) adapted with a crank-based power meter (Rotor 2INpower, Rotor Bike Components).³⁰ To allow comfortable pedaling with the arms during the ArmWGT, the Monark cycle ergometer was elevated using a special table with different heights, and the pedals were replaced by specific handles. The saddle and handlebar positions of the cycle ergometer during the LegWGT, as well as the height of the table during the ArmWGT, were individually adjusted to anthropometric characteristics at T1 and identically reproduced at T2. The subjects performed the Wingate tests using the load (in kilograms) corresponding to 7.5% (LegWGT) or 5.0% (ArmWGT) of their body mass.³¹ When the researcher shouted “Go,” the participants performed a 20-sec all-out effort. The highest value (in watts, W) through the test was used for determining anaerobic power (Peak), whereas anaerobic capacity (Mean) was estimated by using the average value throughout the 20 sec as detailed elsewhere.³²

Balance

Balance was examined during both standing and single-leg static positions. Both legs had to be shoulder-width apart and with 0° rotation for the standing condition. During the single-leg conditions, only one leg provided support at the center of the force platform (C-Force, Innervations, West Perth, Australia), whereas the other one had to be kept parallel to the trunk at a 90° knee flexion angle. Once the standing and single-leg positions (dominant and non-dominant leg, in that order) were completed (Stable condition), they were repeated using a thermoplastic elastomer pad (50 × 39 × 6.5 cm) located between the subject's feet and the force platform (Unstable condition).³³ During all tests, subjects were required to be barefoot, keep their eyes open, place their hands on their hips and remain as still as possible for 30 sec (standing condition) and 20 sec (single-leg condition). If a trial failed to meet these technical requirements, it was stopped and repeated after a 1-min rest. The average sway velocity (deg/sec) calculated as total sway (summed angular displacement of the center of mass) divided by the test duration was used for examining changes in balance capacity.

Relative strength and load-velocity relationships

Regardless of the modality trained, subjects completed a velocity-monitored loading test up to the 1RM in the free-weight and machine-based variants of SQ, BP, PBP, and SP exercises. This was intended to reduce the effect of the specificity principle when comparing training modalities. The mean propulsive velocity of all repetitions was monitored by using a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain),³⁴ which was carefully installed to favor the vertical displacement of the measuring cable during each exercise. A detailed description of the 1RM testing protocol and the position of the velocity transducer was provided elsewhere.³⁵ The 1RM_{Rel} resulting from each of the eight loading tests was obtained. Moreover, velocity was used to describe the individual load-velocity relationship for each subject, which was subsequently applied to adjust intensity during the training intervention.

Resistance training program

Both groups completed an 8-week resistance training program only differing in the modality used to perform the four exercises: free-weight (SQ_{Free}, BP_{Free}, PBP_{Free}, and SP_{Free}) or machine-based (SQ_{Machine}, BP_{Machine}, PBP_{Machine}, and SP_{Machine}). The free-weight group performed the four exercises using a 20-kg bar, at which extra load was added by sliding calibrated weight discs (Eleiko, Sport AB, Halmstad, Sweden). The machine-based group performed each exercise by using a specific machine that mimicked the trajectory achieved with free weights. Except for the hack used in the SQ_{Machine}, which was loaded using calibrated discs, the weight stacks already installed in the machines were used for adding extra load to this modality. A comprehensive technical description and graphical representation of each exercise were provided elsewhere.³⁵

The frequency (3 sessions per week), number of sets (3 per exercise), interset recoveries (4 min), between-sessions rest (48 h), intraset volume (half of the possible repetitions), and intensity (65 to 85% 1RM, linear programming) were identical for both training modalities. To increase the accuracy on each target intensity, the velocity attained in the first two repetitions (usually the fastest) of each exercise was measured at the first session of each intensity: session 1 (65% 1RM), session 6 (70% 1RM), session 11 (75% 1RM), session 15 (80% 1RM), and session 20 (85% 1RM). In these velocity-controlled sessions, the absolute load (in kilograms) was individually adjusted to match the mean propulsive velocity associated with the planned intensity for that day ($\pm 0.03 \text{ m} \cdot \text{s}^{-1}$), according to the individual load-velocity relationship determined at T1. Once the specific absolute load was adjusted, it was used in subsequent sessions programmed with the same intensity.²⁷ In turn, the intraset volume of all training sets corresponded to half of the total

repetitions possible at each intensity, which would result in a velocity loss of $\sim 20\%$.²³ This level of intra-set fatigue has shown to be an effective and efficient stimulus to improve athletic adaptations.¹⁹ Subjects were required to complete the concentric phase of each repetition at maximal intended velocity and using the full range of motion.

2.4 | Statistical analyses

Normality and homoscedasticity were verified with Shapiro–Wilk and Levene's tests, respectively. A 2×2 factorial analysis of covariance (ANCOVA), controlled by the score of each dependent variable at T1 (covariate), was conducted to examine between-group differences. Bonferroni's post hoc adjustment was used when significant differences were detected. Significance was accepted at $p \leq 0.05$. The effect size (ES) was obtained from mean T1–T2 differences and corrected for small sample bias (Hedges'g).³⁶ Percentage of change (Δ) was calculated as $((\text{mean T2} - \text{mean T1}) / \text{mean T1}) \times 100$. For the sprint, COD, and balance tests, the lower the ES and Δ the greater the improvement in these outcomes. To analyze the within-image reproducibility of muscle architecture, the CV was obtained as $(\text{between-fascicles SD} / \text{mean}) \times 100$. Statistical analyses were performed using the SPSS software (version 26.0, IBM Corp), and figures

were designed using the GraphPad Prism software (version 6.0, GraphPad Software Inc).

3 | RESULTS

3.1 | Strength changes

No significant group $\times$ time interaction was found for any of the eight exercises ($p \geq 0.119$, F -value ≤ 2.817). The two groups significantly ($p < 0.001$) increased the 1RM_{Rel} in both modalities of SQ (mean Δ , free-weight group = 13.5%; machine-based group = 13.4%), BP (mean Δ , free-weight group = 9.2%; machine-based group = 8.5%), PBP (mean Δ , free-weight group = 8.4%; machine-based group = 8.6%), and SP (mean Δ , free-weight group = 12.7%; machine-based group = 11.6%) exercises.

3.2 | Sprint, change of direction and vertical jump

No significant group $\times$ time interaction was found for any of these variables ($p \geq 0.180$, F -value ≤ 1.894) (Figure 1). Both training modalities significantly ($p < 0.001$) improved CMJ (Free-weight: mean change = 2.8 cm [1.4 to 4.2 cm], $\Delta = 7.4\%$ [3.5 to 11.3%]; Machine-based: 2.5 cm

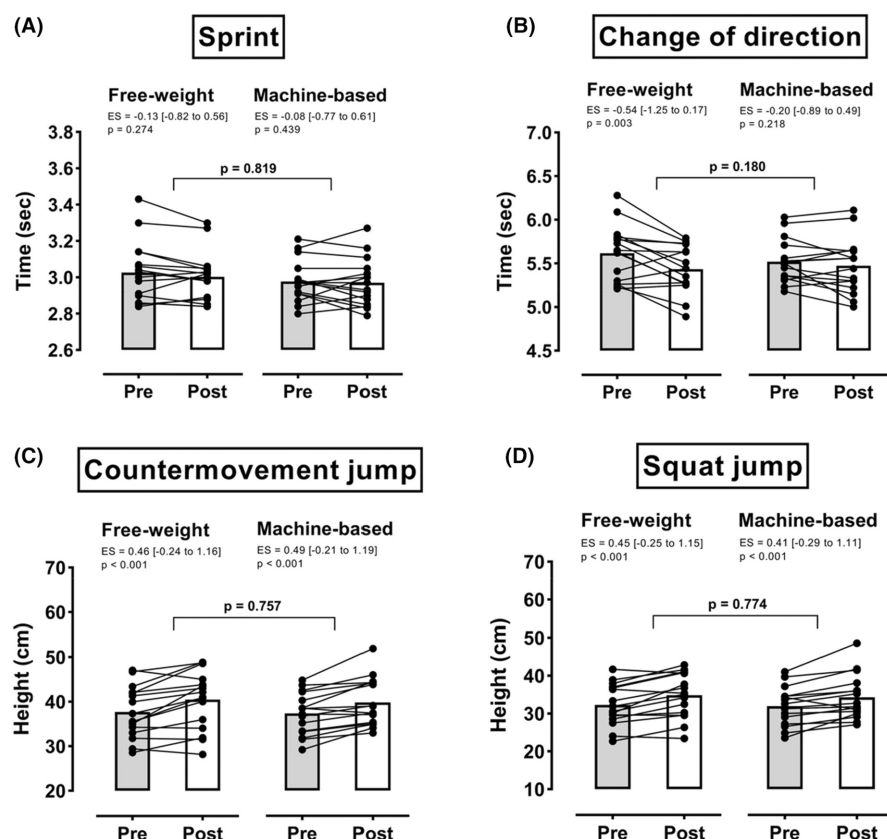


FIGURE 1 Mean and individual changes produced by free-weight ($n = 16$) and machine-based ($n = 16$) modalities in the sprint (Panel A), change of direction (Panel B), countermovement jump (Panel C), and squat jump (Panel D). ES [95% CI]: Effect size (Hedges'g) with 95% confidence interval. For the sprint and change of direction, the lower the ES the greater the improvement in these outcomes. The p -value below the ES indicates the within-group effect (pre-post). The p -value above the bracket linking the two groups indicates the group $\times$ time interaction.

[1.4 to 3.6 cm], $\Delta=6.7\%$ [3.9 to 9.5%]) and SJ (Free-weight: 2.6 cm [1.4 to 3.8 cm], $\Delta=8.0\%$ [4.2 to 11.9%]; Machine-based: 2.3 cm [1.1 to 3.5 cm], $\Delta=7.2\%$ [3.2 to 11.1%]). Additionally, the free-weight group significantly enhanced COD (-0.17 sec [-0.28 to -0.06 sec], $\Delta=-3.0\%$ [-4.9 to 1.1%], $p=0.003$) capacity. Changes in sprint performance were not significant for either modality (Free-weight: -0.02 sec [-0.05 to 0.01 sec], $\Delta=-0.7\%$ [-1.6 to 0.3%], $p=0.274$; Machine-based: -0.01 sec [-0.05 to 0.03 sec], $\Delta=-0.3\%$ [-1.5 to 1.0%], $p=0.439$).

3.3 | Anaerobic performance

No significant group $\times$ time interaction was found for any upper ($p \geq 0.457$, F -value ≤ 0.570) or lower limb ($p \geq 0.146$, F -value ≤ 2.242) anaerobic variable (Figure 2). Both training modalities significantly improved lower limb anaerobic capacity (Free-weight: 40.9 W [28.3 to 53.5 W], $\Delta=5.8\%$ [3.9 to 7.7%], $p < 0.001$); Machine-based: 27.3 W [16.0 to 38.6 W], $\Delta=3.9\%$ [2.2 to 5.5%], $p < 0.001$). Similarly, lower limb anaerobic power was significantly enhanced by the free-weight (66.4 W [31.3 to 101.5 W], $\Delta=5.7\%$ [2.2 to 9.1%], $p=0.007$) and machine-based (80.5 W [28.1 to 132.9 W], $\Delta=7.2\%$ [2.5 to 11.8%], $p=0.003$) groups. Moreover, the machine-based group significantly increased upper limb

anaerobic power (43.1 W [20.8 to 65.4 W], $\Delta=8.0\%$ [3.5 to 12.4%], $p=0.021$).

3.4 | Balance capacity

No significant group $\times$ time interaction was found for any balance condition ($p \geq 0.201$, F -value ≤ 1.562) (Figure 3). Whereas changes achieved by the machine-based group were not significant ($p \geq 0.083$), the free-weight group significantly enhanced Standing_{Unstable} (-0.07 deg/sec [-0.11 to -0.03 deg/sec], $\Delta=-14.6\%$ [-23.8 to -5.4%], $p=0.012$) and Dominant_{Stable} (-0.15 deg/sec [-0.32 to 0.02 deg/sec], $\Delta=-12.5\%$ [-25.1 to 0.1%], $p=0.011$) conditions. In general, balance improvements achieved by the free-weight group (mean Δ , standing conditions = -10.7% , single-leg conditions = -6.7%) were higher than those generated by the machine-based group (mean Δ , standing conditions = -4.8% , single-leg conditions = -4.6%).

3.5 | Muscle architecture

The CV resulting from muscle architecture analysis were: VL_{FL} (T1, min-max = 0.1 – 2.7% ; T2, min-max = 0.0 – 1.8%), VL_{PA} (T1, min-max = 0.1 – 3.8% ; T2, min-max = 0.0 – 3.7%). When comparing between-groups differences, no significant

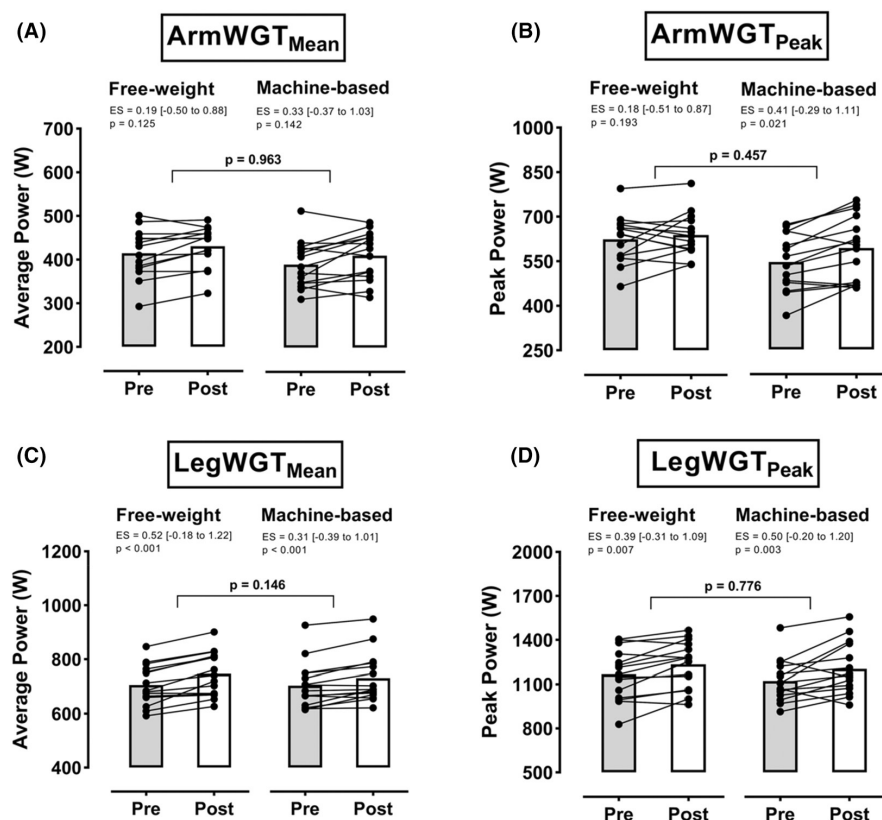


FIGURE 2 Mean and individual changes produced by free-weight ($n=16$) and machine-based ($n=16$) modalities in upper (Panels A-B) and lower limb (Panels C-D) anaerobic capacity and power. ES [95% CI]: Effect size (Hedges'g) with 95% confidence interval. The p -value below the ES indicates the within-group effect (pre-post). The p -value above the bracket linking the two groups indicates the group $\times$ time interaction.

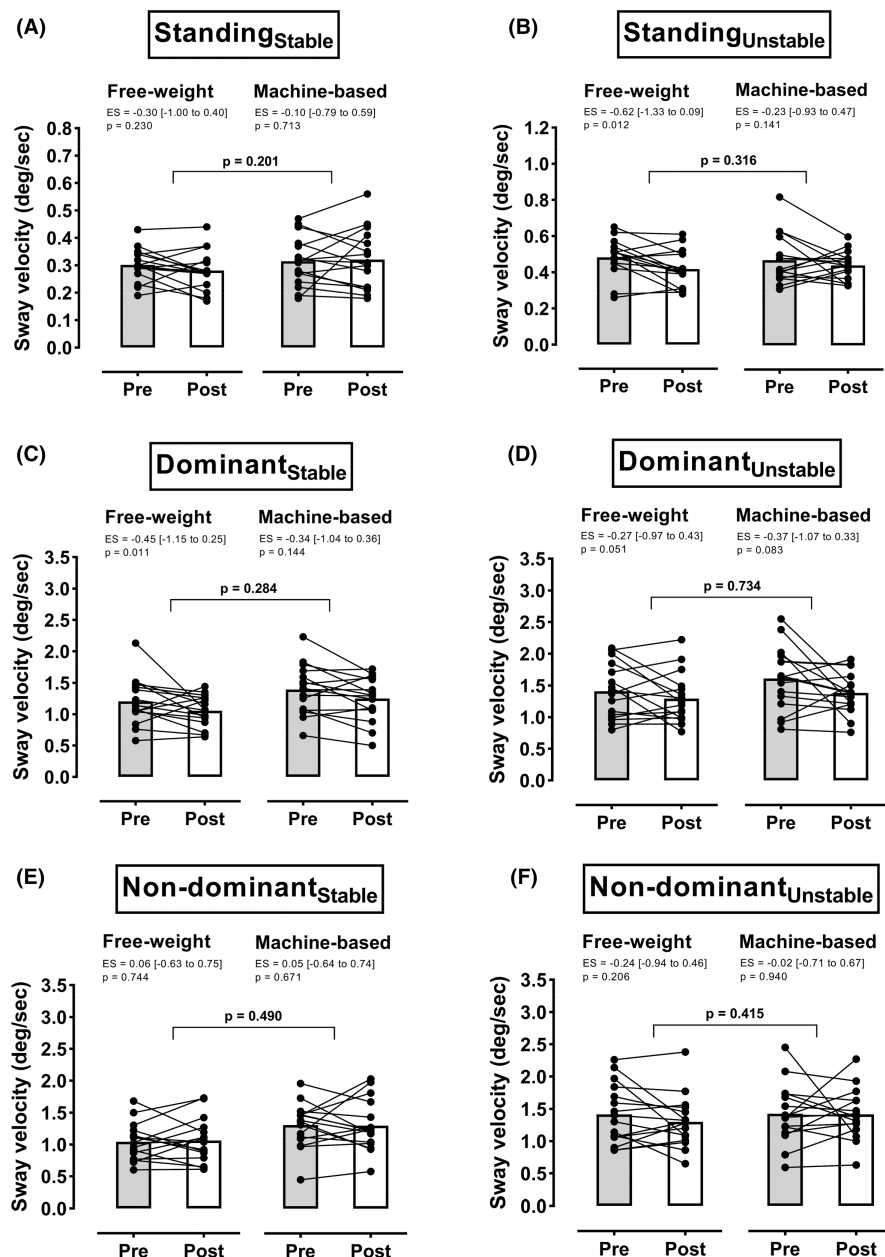


FIGURE 3 Mean and individual changes produced by free-weight ($n=16$) and machine-based ($n=16$) modalities in standing (Panels A-B) and single-leg (Panels C-F) balance conditions. ES [95% CI]: Effect size (Hedges'g) with 95% confidence interval. The lower the ES the greater the improvement in this outcome. The p -value below the ES indicates the within-group effect (pre-post). The p -value above the bracket linking the two groups indicates the group $\times$ time interaction.

group $\times$ time interaction was found for either VL_{FL} ($p=0.922$, F -value=0.010) or VL_{PA} ($p=0.184$, F -value=1.863) (Figure 4). Changes produced by both training modalities on VL_{FL} (Free-weight: 0.09 cm [-0.25 to 0.43 cm], $\Delta=1.3\%$ [-4.2 to 6.8%], $p=0.386$, Machine-based: 0.16 cm [-0.14 to 0.46 cm], $\Delta=2.5\%$ [-2.4 to 7.3%], $p=0.466$) and VL_{PA} (Free-weight: 0.70° [-0.63 to 2.03°], $\Delta=3.0\%$ [-3.0 to 8.9%], $p=0.129$, Machine-based: -0.12° [-0.95 to 0.71°], $\Delta=-0.5\%$ [-4.1 to 3.0%], $p=0.717$) were not significant.

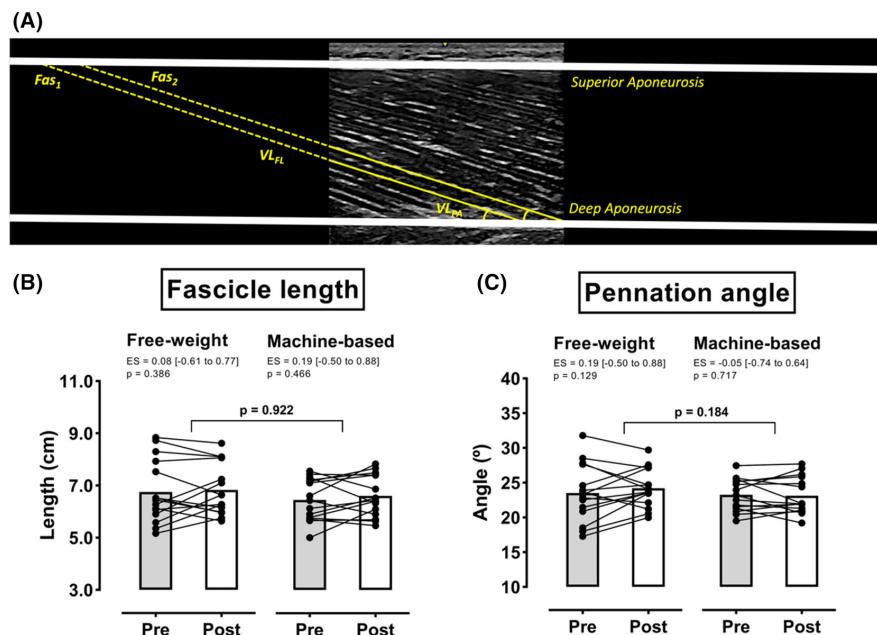
4 | DISCUSSION

The lack of between-group differences and the similar levels of change in most of the variables examined suggest

that adaptations in athletic performance and muscle architecture would not be meaningfully influenced by the resistance modality trained. Based on these results, athletes incorporating resistance training as a complement to their field- or track-specific training could use free-weight or machine-based exercises depending on their possibilities or preferences.

Results showed significant effectiveness of both training modalities to improve most of the capacities measured. For instance, free-weight and machine-based modalities similarly improved jump height (mean $\Delta=7.7\%$ vs. 7.0%, Figure 1C,D). Probably, the biomechanics similarities between SQ_{Free} - $SQ_{Machine}$ and vertical jump (force applied in the vertical axis to the body) could have favored the transference of the strength gains generated by both SQ

FIGURE 4 Analysis of vastus lateralis fascicle length (VL_{FL}) and pennation angle (VL_{PA}) from the visible part of two fascicles (Fas_1 and Fas_2) (Panel A). Mean and individual changes produced by free-weight ($n=16$) and machine-based ($n=16$) modalities on fascicle length (Panel B) and pennation angle (Panel C). ES [95% CI]: Effect size (Hedges'g) with 95% confidence interval. The p -value below the ES indicates the within-group effect (pre-post). The p -value above the bracket linking the two groups indicates the group $\times$ time interaction.



modalities. Indeed, the fact that previous machine-based groups based their routine on training the leg press or knee extension exercises (extremely different from the vertical jump biomechanics) would explain the lower effectiveness traditionally found for this modality.^{8,9}

Similar to jumping, lower limb anaerobic capacity and power were significantly increased by free-weight (mean $\Delta=5.8\%$) and machine-based (mean $\Delta=5.6\%$) modalities (Figure 2C,D). Whereas improvements in anaerobic power would come from enhancements in the rate of force development,³⁷ changes in anaerobic capacity could be mainly related to the enhancements in $1RM_{Rel}$ of SQ_{Free} and $SQ_{Machine}$ exercises achieved by the free-weight (mean $\Delta=13.5\%$) and machine-based (mean $\Delta=13.4\%$) groups. As the athletes increased their $1RM_{Rel}$, the absolute load used during the Wingate test would represent a lower intensity, thus allowing them to produce a higher velocity (i.e., cadence) and, so, a greater amount of muscle power. In contrast, although the two groups significantly increased their $1RM_{Rel}$ on both modalities of BP, PBP, and SP exercises (mean Δ , free-weight group = 10.1%; machine-based group = 9.6%), the transference to upper limb anaerobic performance was more subdued (Figure 2A,B). This fact could have been caused by the lower familiarization of the subjects to pedal with their hands. To the best of our knowledge, this is the first attempt to elucidate the efficacy of free-weight and machine-based training modalities on upper limb athletic adaptations. Although future studies should extend this comparison by using other athletic tests, results found in ArmWGT could be directly applicable to those sports highly conditioned by cyclic upper limb movements such as handbike, rowing or swimming.

Regarding the sprint capacity, adaptations produced by both training modalities were not significant (Figure 1A). This lower transference, which would agree with a previous study comparing SQ_{Free} and $SQ_{Machine}$,¹⁰ could be explained by the higher technical complexity of the sprint action³⁸ together with its lower biomechanics likeness to both modalities of the SQ trained. Nevertheless, we observed a subtle superiority of the free-weight group to enhance COD capacity (Figure 1B), which could be related in turn to the higher adaptations on balance achieved by this modality (Figure 3). Specifically, these meaningful increases in static balance could also have resulted in higher dynamic stability, thus enhancing the subject's capacity to quickly accelerate and decelerate.³⁹

Finally, changes in muscle architecture were small for both modalities ($\Delta \leq 3.0\%$, Figure 4B,C). Although different factors could be behind these results (e.g., adaptations are usually specific to the thigh region measured), the previous subject's experience and the low intraset fatigue incurred throughout the intervention could explain the subdued adaptations found for VL_{FL} and VL_{PA} , respectively. In particular, the considerable experience of the subjects in performing both modalities of the SQ at full range of motion could have attenuated the longitudinal fascicle growth that usually occurs when training at lengths to which the muscle is not accustomed.⁴⁰ On the other hand, the low levels of intraset fatigue incurred by both modalities, which in turn have been demonstrated to generate noteworthy strength gains without considerable hypertrophy,²¹ could explain the reduced incorporation of sarcomeres in parallel (iVL_{PA}).

Despite the important step forward this study made in comparing the free-weight and machine-based training

modalities, it is not exempt from limitations. Firstly, since architectural adaptations have shown to be inhomogeneous within the same muscle,⁴¹ our structural-related findings would not be extrapolated to other thigh regions. Secondly, despite the novel results derived from the ArmWGT, other specific tests should be included to continue comparing upper limb athletic adaptations produced by both training modalities. Finally, it would be of great practical value that future studies extend the knowledge on the topic by including female and untrained participants, a longer training time and other lower limb exercises (e.g., hip thrust).

5 | PERSPECTIVES

The superior effectiveness of free-weight over machine-based resistance training has been a traditionally widespread belief among practitioners.⁷ To comprehensively examine this assumption, we compared these training modalities on five athletic capacities (sprint, COD, vertical jump, balance, upper and lower limb anaerobic performance), two muscle architecture parameters (VL_{FL} and VL_{PA}) and eight maximum strength tests (4 exercises $\times$ 2 modalities). Thus, contrary to this traditional free-weight superiority and in line with a recent systematic review on the topic,⁴² we found that adaptations in athletic performance and muscle architecture were not meaningfully influenced by the resistance modality trained. Based on these results, athletes incorporating resistance training as a complement to their field- or track-specific training could use free-weight or machine-based exercises depending on their possibilities or preferences.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests. No funding was received for this research.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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