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High-frequency resistance training improves maximal lower-limb strength more than low frequency

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Abstract

This study compared the effects of a weekly lower body resistance-training program divided into low frequency (LOW, one long session) versus high frequency (HIGH, four shorter sessions) in resistance-trained individuals. Twenty-two adults with more than 6 months resistance training experience were randomized to either the LOW or HIGH intervention group. Both groups completed an 8-week training program consisting of four multi-joint exercises targeting the hip and knee extensors. The program progressed from 12-repetition maximum (RM) to 6-RM, with 4–5 sets per exercise performed throughout the intervention. The four exercises were conducted either in one session or four sessions (one exercise per session) per week. 1-RM in the squat, muscle thickness of the vastus lateralis, muscle mass of the lower body (measured using bioelectrical impedance), and jump height were assessed pre- and post-intervention. The HIGH group demonstrated a statistically significant increase in 1-RM compared to the LOW group (7 kg, $p = 0.01$), while no statistically significant differences were found between the groups for the other outcomes ($p = 0.26$–0.63). Both interventions resulted in statistically significant increases in 1-RM squat (8 and 15 kg), muscle thickness (2.3 and 2.8 mm), and jump height (1.5 and 1.9 cm) from pre-to post-test. There were no statistical changes in lower-body muscle mass for either group ($p = 0.16$–0.86). In conclusion, a weekly training protocol of four multi-joint lower-limb exercises distributed over four sessions resulted in greater increases in maximal strength compared to one session in resistance-trained adults. Both frequencies were similarly effective in improving muscle hypertrophy and jump height.

KEYWORDS

hypertrophy, jump height, maximal strength, muscle mass, muscle thickness, power, strength training

Highlights

- Both high and low resistance training frequencies are viable options for increasing maximal strength, hypertrophy, and jump height.
- High resistance training frequency seems to favor lower limb muscle strength in trained adults.
- High and low resistance training frequencies lead to similar improvement in muscle hypertrophy and jump height in trained adults.

1 | INTRODUCTION

Training frequency, defined as the number of times a given muscle or a muscle group is trained per week (Grgic et al., 2018; Schoenfeld et al., 2016), is one of several variables that can be manipulated when designing resistance training programs (Bird et al., 2005; Kraemer et al., 2004). Practitioners approach training frequency differently, with some advocating to train the muscles with a low frequency (1–2 times per week) and a high training volume in each session while others preferring a higher frequency and less volume per session. It can be hypothesized that subjecting muscles to a high per-session training volume may increase energy utilization and fatigue, consequently reducing the training quality compared to shorter and more frequent sessions (Hartman et al., 2007; Schoenfeld, 2020). In practice, this would mean that a low frequency approach would lead to fewer kilograms lifted over a given time period (e.g., weekly) due to reduced loading or performing fewer repetitions. Conversely, shorter sessions spread over several days per week conceivably would lead to more intense bouts and increased loading (Schoenfeld, 2020). Over time (e.g., > 4 weeks), this may be beneficial for increasing muscle strength, muscle mass, and muscle power.

Most of the previous studies that have compared different training frequencies with an equal number of sets per week reported no statistical or magnitude differences in strength and hypertrophy between the intervention groups (Arazi et al., 2011; Benton et al., 2011; Brigatto et al., 2019; Candow et al., 2007; Hamarsland et al., 2022; Johnsen et al., 2021; Neves et al., 2022; Ochi et al., 2018; Saric et al., 2019; Yue et al., 2018). Consequently, meta-analyses and systematic reviews have concluded that weekly training frequency can be based on personal preference provided that weekly training volume is equated (Cuthbert et al., 2021; Grgic et al., 2019; Schoenfeld et al., 2019). However, the null findings may be explained by the design of the training programs in the studies. Some interventions have compared relatively similar frequencies (e.g., 2 vs. 3 sessions per week), raising the possibility that the conditions were not sufficiently different to identify statistical differences between groups (Benton et al., 2011; Brigatto et al., 2019; Candow et al., 2007). Others have implemented a low weekly training volume for the specific muscle groups (Hamarsland et al., 2022; Johnsen et al., 2021; Neves et al., 2022; Ochi et al., 2018; Yue et al., 2018), which minimizes accumulated fatigue in the low frequency groups and thus potentially undermines the rationale for employing a high training frequency approach. Finally, it has been suggested that a training schedule consisting of more complex exercises (i.e., multi-joint) would benefit from a higher training frequency due to greater motor learning and a faster recovery, compared to single-joint exercises (Grgic et al., 2018; Soares et al., 2015). Based on the presented arguments, further research is needed to better elucidate the effects of higher training frequencies, specifically those encompassing four or more weekly sessions, particularly in interventions that employ multi-joint exercises (Grgic et al., 2018, 2019).

Two previous studies have reported that a higher training frequency (five sessions per week) may be more favorable than a low training frequency (one session per week) with volumes equated between conditions (Yoshida et al., 2022; Zaroni et al., 2019). Yoshida et al. (2022) reported that a high training frequency was more effective in increasing strength than a low frequency in resistance-trained men; however, no statistical differences were observed in muscle thicknesses between the groups. Importantly the training was composed solely of eccentric actions; hence, it is difficult to generalize these findings to traditional dynamic resistance training protocols (Yoshida et al., 2022). Alternatively, Zaroni et al. (2019) conducted an 8-week intervention consisting of combined concentric–eccentric actions to investigate the effects of varying resistance-training frequencies in resistance-trained men. The two groups were trained 5 days per week with one group performing a total-body program (one exercise for each muscle group per session) and the other group performing a split-body program (five exercises for the same muscle group per session). The weekly training volume for each muscle was 15 sets at 10–12-RM. Results showed that spreading the weekly training volume over five sessions led to greater increases in muscle thickness of the elbow flexors and vastus lateralis, but not the triceps brachii, when compared to performing a split-body routine. There were no between-group differences in muscle strength (1-RM bench press, squat, and seated row) (Zaroni et al., 2019). Of note, the intensity (10–12-RM) had a lack of specificity regarding adaptions for strength and power and there was no progression in volume or intensity throughout the intervention. Finally, neither study (Yoshida et al., 2022; Zaroni et al., 2019) assessed muscular power.

Given the paucity of scientific evidence on the topic, the aim of the present study was to compare the effects of a progressive, volume-equated resistance training program employing multi-joint exercises for the hip and knee extensors, with training carried out either once per week (all exercises in one session) or divided over four (one exercise per session) weekly sessions on muscular adaptations. Secondarily, we also assessed lower body muscle mass and jump height. Based on previous research (Paz-Franco et al., 2017; Yoshida et al., 2022; Zaroni et al., 2019), we hypothesized that the higher frequency group would be able to train with a progressively higher load (i.e., lift more weights throughout the intervention) and consequently increase their maximal strength and muscle thickness more than the lower frequency group.

2 | MATERIALS AND METHODS

2.1 | Design

A randomized parallel design was employed to compare the effects of lower body resistance training for resistance-trained adults using a low (LOW) versus high training frequency (HIGH), including one long or four shorter training sessions per week, respectively. Both groups performed the same exercises (back squat, dead lift, split squat, and Bulgarian squat) with the same number of sets and repetitions per week over an 8-week period. LOW performed all exercises in one session while HIGH performed one exercise in each session. Pre- and post-intervention assessments included one repetition maximum (1-RM) in the squat, countermovement jump height (CMJ), lower body muscle mass assessed with bioelectrical impedance, and muscle thickness of the vastus lateralis assessed with ultrasound.

2.2 | Participants

Eligible participants had to be between 18 and 30 years old, had to be conducting resistance training weekly for the last 6 months, be familiar with the exercises in the training program, and be free of injury or pain that could impair the performance during training or testing. Further, the women and men had to be able to lift more than 80% and 100% of their body weight in the back squat, respectively (Santos Junior et al., 2021). The participants were recruited through social media, posters, and direct personal contact. A priori sample size calculation was performed in SPSS (IBM Corp. Released 2021. IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp) based on the changes observed for 1-RM squat (mean ± standard deviation (SD); 19.5 ± 9.3 versus 9.9 ± 6.6 kg) and muscle thickness of the vastus lateralis (mean ± SD; 4.6 ± 2.1 vs. 2.49 ± 1.5 cm), in the study by Zaroni et al. (2019). The alpha level was set to 0.05 and the power to 0.8. The calculation estimated a requirement of 12–13 participants in each intervention group (24–26 in total). A total number of 27 resistance-trained adults volunteered to participate in the study and underwent the pre-intervention test. All participants were informed orally and in writing about the study's potential risks and benefits, and they provided written consent before being enrolled in the study. The study was conducted in accordance with the ethical guidelines set by the Western Norway University of Applied Sciences and the national legislation. The data collection and management were evaluated by the Norwegian Center for Research Data (ref. 630494).

After the pre-intervention test, participants were stratified based on sex and then randomly allocated to different intervention groups using an online random number generator (randomizer.org). During the intervention, five participants withdrew due to personal reasons ($n = 1$), not enough time ($n = 2$), and injury not related to the intervention ($n = 2$). Consequently, 22 participants completed the study. The descriptive information for the total sample and the two groups are presented in Table 1.

2.3 | Procedure

One week prior to experimental testing, the participants completed a familiarization test for the 1-RM squat. The experimental testing comprised two separate days with a 48–72-h interval between each session. During the first session, measurements were taken in the following order: (i) muscle mass, (ii) muscle thickness, and (iii) jump height; the second session consisted of assessing 1-RM squat performance.

2.3.1 | Muscle mass

Muscle mass was measured using the Tanita MC780 multifrequency segmental body composition analyzer, with participants arriving in the morning after a 12-h fast and refraining from showering or intense exercise. Participants wore only shorts and a sports bra (for women) and stood barefoot on the scale, with age, sex, and height entered into the software. The scale estimated muscle mass (in kilograms) for different body segments, with the combined value for the lower body used in the analysis. Previous studies have shown that bioelectrical impedance assessment is both reliable and valid for measuring muscle mass (Vasold et al., 2019; Verney et al., 2015).

TABLE 1 Description of intervention groups.

	Total	LOW	HIGH
Sex (F/M)	15/7	8/3	7/4
Age (years)	21.6 ± 1.5	21.6 ± 1.8	21.5 ± 1.1
Height (cm)	172 ± 11	171 ± 8	173 ± 13
Weight (kg)	72.2 ± 11.0	72.1 ± 10.0	72.3 ± 12.4
1-RM pre (kg)	85.9 ± 27.2	85.0 ± 23.2	86.8 ± 32.0

Note: Data are presented as mean ± standard deviation.

Abbreviations: cm, centimeters; F, female; HIGH, four sessions per week; kg, kilograms; LOW, one session per week; M, male; Total, groups combined.

2.3.2 | Muscle thickness

Muscle thickness of the vastus lateralis was measured by b-mode ultrasound imaging using a 6-cm probe and a scanning frequency of 2–12 MHz (Echo Blaster 64/128, LogiScan 64/128, and ClasUs series Ultrasound systems; Echo Wave 2 Software; Telemed, Latvia). Participants laid supine on a massage bench with images captured at 50% of the distance between the lateral epicondyle and the greater trochanter. The assessment position in the pre-intervention test was transferred to transparent plastic sheets for each individual, which were used in the posttest to ensure consistent image capture (de Boer et al., 2008). Five transverse images were taken at the same site. The image with the highest and lowest value was discarded. The average measurement of the three remaining images was used in the analysis. All images were analyzed at the same time, by the same researcher, who was blinded to the group allocation. The intraclass correlation between the different images was 0.993, and the coefficient of variance was 2.3%. Previous studies have shown that ultrasound has a good between-session reliability for measuring muscle thickness of the quadriceps (Barotsis et al., 2020; Takahashi et al., 2021).

2.3.3 | Jump height

The countermovement jump test was conducted on a MuscleLab Force Plate Model 2 (Ergotest Technology AS). The software program (MuscleLab Software v8.13; Ergotest Technology AS) calculated jump height using impulse (force *x* time). The measurement is based on the impulse-momentum theorem which uses the accumulation of force over the time period of the eccentric–concentric movement to calculate the jump height (McMahon et al., 2018). The participants were instructed to perform an explosive eccentric–concentric movement while keeping their hands on their hips. Participants completed a minimum of three jumps, with additional jumps performed until jump height declined if the last jump was the highest. A one-minute rest period was provided between each attempt, with the best attempt used in the analysis. The intraclass correlation between the different attempts was 0.969, and the coefficient of variance was 5.9%. Further, the force plate had demonstrated good test–retest reliability for measuring the countermovement jump (Lombard et al., 2017).

2.3.4 | 1-RM squat

All maximal dynamic strength testing was performed using a Smith machine (Pivot 680L, Pivot Fitness, Tianjin, China). The participants completed a familiarization session 1 week before the pre-intervention test to standardize performance and ensure proper technique. Before the test, the participants performed a warm-up protocol consisting of 10 squat jumps, three repetitions with the barbell (20 kg), and one repetition at 40%, 60%, 80%, 100%, and 120% of their own body weight. During the 1-RM assessment, each participant started in an erect position and descended until their femurs were parallel to the floor. The test leader then gave a signal, and the participant ascended to the starting position. If the lift was successful, the load was increased by 2.5–5 kg. The testing continued either until failure or when the test leader and the participant mutually agreed that a higher load could not be lifted with proper technique. The 1-RM was achieved in one to four attempts, and a minimum of 3 minutes rest was given between each attempt. To ensure consistency between tests, the same researcher supervised the testing for all participants. The intraclass correlation between the familiarization and the pre-intervention test was 0.979, and the coefficient of variance was 5.5%.

2.4 | Intervention

The intervention consisted of four exercises that were conducted either in one session per week (all exercises in the following order: squat, dead lift, split, and Bulgarian squat) or across four sessions per week (one exercise per session) over an 8-week period. The exercises and details of the study are presented in Figure 1.

Participants completed a five-minute general warm-up on a stationary bike and a specific warm-up of exercises at 50% of the expected training load before each session. Load and volume progressively increased from 12-RM to 6-RM and from 4 to 5 sets per exercise, respectively, with a self-determined but controlled tempo and 2-min rest intervals from week 1 to 4 and 3-min rest intervals from week 5 to 8 (Figure 1). All sessions were directly supervised by the same instructor. If the participants could not attend a given session, they were encouraged to perform the session later, manually log the session, and send the log to the instructor by email. The instructor ensured proper technique and adherence to the program's prescribed load. If participants completed all prescribed repetitions with a proper technique, they were instructed to increase the load in the next set. For the LOW group, a minimum of 5 days rest was required between the sessions, while for the HIGH group, no more than 2 consecutive sessions were allowed before a day of rest. Normal activity and nutrition habits were encouraged, but lower body training outside of the intervention was prohibited.

2.5 | Statistical analysis

Due to the randomization, no systematic differences were assumed between groups at baseline. All variables were inspected for normality and were found suitable for mixed models' analysis. Each outcome variable (1-RM strength, muscle thickness, muscle mass, and jump height) was analyzed separately, with the effect of intervention and the time point included as fixed effects with the following time points: baseline, HIGH after 8 weeks, and LOW after 8 weeks. To account for repeated measures, the participants' ID was set as random effect.

Week 1-2	Week 3-4	Week 5-6	Week 7-8
12-RM	10-RM	8-RM	6-RM
4 sets per exercise	4 sets per exercise	5 sets per exercise	5 sets per exercise
2 minutes rest between sets		3 minutes rest between sets	

FIGURE 1 An overview of the training intervention.

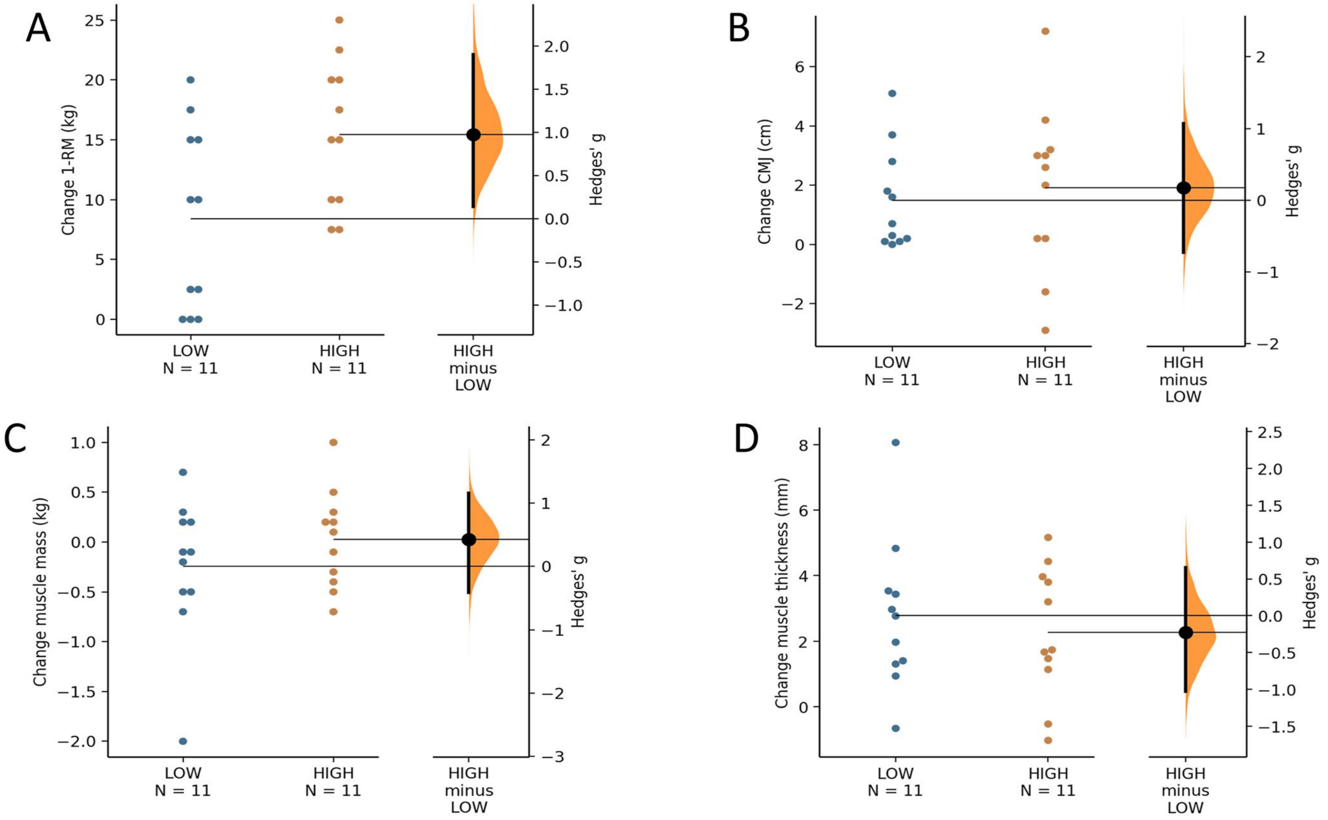

FIGURE 2 Estimation plot showing individual changes within- (from pre to post) and effect size between the groups in 1-RM squat (A), CMJ (B), muscle mass (C), and muscle thickness (D).

Effect size (ES) is reported as Hedges' *g* to account for the small sample size. The ES between pre and post was based on the mean difference (post-pre) and the pooled standard deviation of the difference. The ES between the group differences was based on the mean difference between the groups and the pooled standard deviation. An ES < 0.2 was considered trivial, 0.2–<0.5 small, 0.5– <0.8 medium, and ≥0.8 large (Cohen, 1988). Values are presented as mean (95% confidence interval), and *p*-values<0.05 were considered statistically significant. All analyses were performed using STATA/IC 16.0 for Windows (StataCorp LP). Figure 2 was created using an online software program (estimationstats.com).

TABLE 2 Changes within and between groups from baseline to 8 weeks.

	Baseline	Within groups 8 weeks		Between groups
	Mean (95% CI)	LOW Mean (95% CI)	HIGH Mean (95% CI)	Difference Mean (95% CI)
1-RM squat (kg)	85.9 (74.4, 97.4)	94.3 (82.5, 106.1)**	101.4 (85.6, 113.2)**	7.1 (0.0, 12.6)**
Muscle mass (kg)	17.1 (15.5, 18.7)	16.9 (15.2, 18.5)	17.1 (15.5, 18.8)	0.3 (−0.2, 0.8)
Muscle thickness VL (mm)	24.3 (22.8, 25.8)	27.1 (25.4, 28.8)**	26.6 (24.9, 28.3)**	−0.5 (−2.1, 1.2)
CMJ (cm)	23.4 (21.0, 25.8)	24.8 (22.3, 27.4)*	25.3 (22.7, 27.9)**	0.5 (−1.4, 2.3)

Abbreviations: CI, confidence interval; cm, centimeter; kg, kilogram; mm, millimeter; RM, repetition maximum; VL, vastus lateralis.
*$p < 0.05$, and **$p < 0.01$.

3 | RESULTS

All of the 88 long sessions were completed while 351 out of the 352 short sessions were completed, with 94% of all sessions directly supervised by an instructor.

The results are presented in Table 2. Both groups increased their performance in 1-RM squat from pre-to post-test (HIGH: 15 (10, 20) kg, ES = 2.34 and LOW: 8 (3, 13) kg, ES = 1.00). The between-group analyses showed that HIGH increased their 1-RM squat to a greater extent than LOW ($p = 0.01$, ES = 0.98, Figure 2A).

Neither group increased their lower body muscle mass ($p = 0.16$–0.86 and ES = 0.05–0.31). However, both groups displayed increases in vastus lateralis muscle thickness (HIGH: 2.3 (0.9, 3.7) mm, ES = 1.04 and LOW: 2.8 (1.2, 4.0) mm, ES = 1.11). There were no statistical between-group differences for either muscle mass ($p = 0.26$, ES = 0.43, Figure 2C) or muscle thickness ($p = 0.57$, ES = 0.22, Figure 2D).

Both groups increased their jump performance from pre-to post-test (HIGH: 1.9 (0, 3.8) cm, ES = 0.63 and LOW: 1.5 (0.3, 2.7) cm, ES = 0.80), with no statistical difference between the groups ($p = 0.63$, ES = 0.17, Figure 2B).

There was no statistical difference between the groups in the total weight lifted during the intervention (LOW: 53,159 (46,968 and 59,350) kg and HIGH: 62,559 (48,835 and 76,282) kg and $p = 0.18$), although the difference was of a medium magnitude (ES = 0.57). There was a pattern of a greater increase in the training load for the HIGH group compared to the LOW group from week one to week eight in all exercises, although it only reached statistical significance in the Bulgarian squat (Squat 24.1 (4.4) versus 19.5 (2.8), $p = 0.07$, and ES = 0.81; dead lift 19.3 (5.0) versus 15.5 (2.2), $p = 0.14$, and ES = 0.63; split 14.1 (3.1) versus 10.9 (1.6), $p = 0.05$, and ES = 0.85; Bulgarian squat 12.9 (1.6) versus 9.1 (1.9), $p = 0.03$, and ES = 1.37 for HIGH versus. LOW, respectively).

4 | DISCUSSION

The main finding of the present study was that, in accordance with our hypothesis, dividing the same training schedule for the hip and knee extensors into four weekly sessions led to a greater improvement in maximal strength compared to performing all exercises in one weekly session. However, there were no statistical between-group differences for vastus lateralis muscle thickness, lower limb muscle mass, or jump height. Of note, both interventions led to an increase in muscle thickness and jump height, but not muscle mass.

Previous research links maximal strength gains to training volume (Grgic et al., 2018). Although results were not statistically significant, our high-frequency group lifted 18% more weight over the study period, potentially explaining the difference in maximal strength between groups. Based on the progression in the training load, there seemed to be a general tendency for a greater increase in the HIGH group. Further, the trend became more evident throughout the training program and reached statistical significance only in the last exercise of the program. This could imply that dividing the training into several sessions is of more importance in programs composed of higher training volumes, and thus, the accumulation of fatigue is greater. Furthermore, the difference in strength between the groups could also be related to the specificity of the training and testing. It has been argued that for more complex movements such as multi-joint exercises, performing the movements several times per week may be favorable for motor learning (e.g., timing of muscle recruitment and muscle coordination) and consequently lead to improved performance compared to a lower training frequency when the testing is similar to the training (Carroll et al., 2001; Grgic et al., 2018). This argument is supported by the lack of between-group differences in hypertrophy, which suggests alterations in neural adaptions as the main cause of the difference in maximal strength. However, it should be noted that the squat, which constituted the 1-RM test, was only performed once per week in both groups. Thus, the performance of the other exercises (i.e., split squat, Bulgarian squat, and dead lift), all targeting the hip and knee extensors, throughout the week seemingly conferred a transfer in strength adaptations to the testing modality.

The lack of statistical difference between the groups in hypertrophy may be a consequence of similarities in training volume (i.e., total weight lifted). Previous studies have suggested that there is a dose–response relationship between training volume and increases in muscle mass, provided all other training variables are held constant (up to at least 10 sets for a given muscle per week)

(Schoenfeld et al., 2017, 2018). Although we observed an 18% nonsignificant difference in total weight lifted, this may not have been enough to cause differences between the groups. Also, the total number of weekly sets per muscle ranged from 16 to 20, which is above the dose–response relationship volume suggested in previous studies (Schoenfeld et al., 2017, 2018). Consequently, the training stimuli might have been very good in both groups, independently of the load lifted. Of interest, neither group increased lower body muscle mass. The muscle mass was assessed via multi-frequency bioelectrical impedance, which measures the whole leg, that is, not specifically the muscles targeted in the present training program. Therefore, the impedance scale measurements may not have been sensitive enough to detect a change in the hypertrophy of the hip and knee extensors.

The present study is one of several studies to compare higher (≥ four sessions per week) versus lower (≤ three sessions per week) training frequencies with training volume (i.e., number of sets) equated between the groups (Benton et al., 2011; Hamarsland et al., 2022; Johnsen et al., 2021; Saric et al., 2019; Yoshida et al., 2022; Yue et al., 2018; Zaroni et al., 2019). However, this study is somewhat unique due to the large difference between the frequencies, a progressive training program consisting of multi-joint exercises, a relatively high weekly training volume, and a population consisting of resistance-trained adults. These features render the findings practically relevant for the general population of resistance-trained adults engaging in resistance training.

Two previous studies have compared large differences in training frequency (1 vs. 5 sessions per week), reporting the higher frequency condition to be superior for maximal strength (Yoshida et al., 2022) and hypertrophy (Zaroni et al., 2019). Yoshida et al. (2022) investigated the effects of a relatively low training volume consisting of five weekly sets of eccentric-only contractions in a single-joint movement (biceps curl) apportioned into either one or five weekly sessions among untrained students. Similar to our findings, Yoshida et al. (2022) reported that spreading out the sets across several weekly sessions was superior for maximal strength but not for muscle thickness compared to one session per week. Alternatively, Zaroni et al. (2019) conducted an 8-week intervention consisting of multi-joint exercises with a larger training volume (15 sets per week) in resistance-trained men. The protocol did not include progression of either volume or intensity throughout the training period. In contrast to our study, the results showed the higher frequency protocol to be advantageous for enhancing muscle thickness of the elbow flexors and the vastus lateralis but not for maximal strength. Importantly, and unlike our study, Zaroni et al. (2019) reported that the high frequency group lifted significantly more load than the low frequency group (22.3% and ES = 1.13). This could explain the different findings in muscle thickness between our studies.

Our findings did not reveal any changes in jump height between the groups. However, both groups improved their performance from baseline. In contrast, Paz-Franco (Paz-Franco et al., 2017) reported that performing a resistance training program twice per week led to increased jump height compared to performing one session per week or one session every other week. Importantly, that protocol did not equate training volume (Paz-Franco et al., 2017), and thus, the greater work performed by the high frequency group could explain the between-group differences. Furthermore, differences in methodology could also explain the discrepant findings. For example, the Paz-Franco study (Paz-Franco et al., 2017) emphasized maximal speed mobilization in the concentric phase while our study required participants to perform repetitions at a self-determined but controlled tempo. In addition, Paz-Franco et al. (2017) examined professional athletes while our population consisted of resistance-trained individuals.

The present study has some limitations that must be addressed. The training intervention consisted of multi-joint exercises for both the hip and knee extensors. However, muscle thickness was only measured in the vastus lateralis and only at the midpoint of the muscle. The fact that several of the trained muscles were not measured may have masked potential differences. Moreover, a compelling body of research indicates muscle hypertrophy in a nonuniform manner (Wak et al., 2013), and thus, we may have neglected to detect hypertrophic changes along the length of the vastus lateralis. Also, muscle mass was measured using a bioelectrical impedance scale. The scale analyses the entire lower body and may not be sensitive enough to detect changes in smaller muscles or muscle groups. Of note, the validity of these scales is highly dependent on similar standardizations between the test and retest (e.g., hydration level). Although the participants were instructed and encouraged to follow the standardizations for the Tanita scale, we cannot guarantee they were upheld. Further, participants' relative 1-RM strength in the squat at baseline was 108% of body weight for the women and 131% for the men. This has been suggested to correspond to advanced level for both sexes (Santos Junior et al., 2021). Consequently, the findings of the present study cannot necessarily be generalized to those with lower or higher levels of training experience. Of note, previous studies have suggested that individuals with little training experience respond well to all training programs (Lera Orsatti et al., 2014; Mclester Jr et al., 2000; Ribeiro et al., 2015) and therefore are of less interest when examining different training frequencies. In addition, based on the a priori sample size calculation, the study was somewhat underpowered due to dropouts. Although effect sizes were added to the findings to open for interpretation beyond the *p*-value, future research should replicate our study with a higher sample size. Finally, although the participants were encouraged to continue with their customary nutritional habits, this was not controlled. Consequently, dietary alterations may have confounded the results. However, the random assignment of participants to the different intervention groups should conceivably have accounted for any such discrepancies between the groups.

In conclusion, over a period of 8 weeks, distributing a weekly training schedule consisting of multi-joint exercises for the hip and knee extensors over four sessions resulted in greater increases in maximal strength compared to one weekly session in trained adults. Further, both strategies resulted in hypertrophy of the exercised muscles and increased jump height, with similar improvements between groups.

4.1 | Practical applications

The results of the present study imply that resistance-trained individuals focusing on increasing their maximal leg strength should distribute their weekly training volume to several shorter sessions. However, it is important to emphasize that fewer sessions with greater volume may also be a viable strategy to increase maximal strength, albeit with somewhat compromised results. Further, if hypertrophy or jump height is the desired outcome, different training frequencies seem to be similarly effective. Importantly, these recommendations are specific to the conditions investigated in this intervention; the findings cannot necessarily be generalized to interventions focusing on different outcomes (e.g., muscular power) or performing a different training program (e.g., different frequencies and training volume).

AUTHOR CONTRIBUTIONS

Helene Pedersen and Vidar Andersen came up with the original idea and wrote the first draft. Pål Frøyen Vereide and Nicolay Stien collected the data and Vegard Moe Iversen performed the statistical analyses. All authors helped in developing the methodology, contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST STATEMENT

Brad J. Schoenfeld serves on the scientific advisory board of Tonal Corporation, a manufacturer of fitness equipment. The other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets analyzed during the current study are not publicly available due to the content of the agreement between the participants and the responsible institution. However, they are available from the corresponding author on reasonable request.

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REFERENCES

Arazi, Hamid, Abbas Asadi, Paulo Gentil, Rodrigo Ramírez-Campillo, Pooria Jahangiri, Adel Ghorbani, Anthony C. Hackney and Hassane Zouhal. 2011. "Effects of 8 Weeks Equal-Volume Resistance Training with Different Workout Frequency on Maximal Strength, Endurance and Body Composition." *International Journal of Sports Science and Engineering* 5(2): 112–8.

Barotsis, Nikolaos, Panagiotis Tsiganos, Zinon Kokkalis, George Panayiotakis, and Elias Panagiotopoulos. 2020. "Reliability of Muscle Thickness Measurements in Ultrasonography." *International Journal of Rehabilitation Research* 43(2): 123–8. https://doi.org/10.1097/mrr.0000000000000390.

Benton, Melissa J., Mark J. Kasper, Scot A. Raab, Green T. Waggener, and Pamela D. Swan. 2011. "Short-term Effects of Resistance Training Frequency on Body Composition and Strength in Middle-Aged Women." *The Journal of Strength & Conditioning Research* 25(11): 3142–9. https://doi.org/10.1519/jsc.0b013e31820f505f.

Bird, Stephen P., Kyle M. Tarpenning, and Frank E. Marino. 2005. "Designing Resistance Training Programmes to Enhance Muscular Fitness: A Review of the Acute Programme Variables." *Sports Medicine* 35(10): 841–51. https://doi.org/10.2165/00007256-200535100-00002.

Brigatto, Felipe A., Tiago V. Braz, Thamires Cristina da Costa Zanini, Moisés D. Germano, Marcelo S. Aoki, Brad J. Schoenfeld, Paulo H. Marchetti, and Charles R. Lopes. 2019. "Effect of Resistance Training Frequency on Neuromuscular Performance and Muscle Morphology after 8 Weeks in Trained Men." *The Journal of Strength & Conditioning Research* 33(8): 2104–16. https://doi.org/10.1519/jsc.0000000000002563.

Candow, Darren G., and Darren G. Burke. 2007. "Effect of Short-Term Equal-Volume Resistance Training with Different Workout Frequency on Muscle Mass and Strength in Untrained Men and Women." *The Journal of Strength & Conditioning Research* 21(1): 204–7. https://doi.org/10.1519/00124278-200702000-00037.

Carroll, Timothy J., Stephan Riek, and Richard G. Carson. 2001. "Neural Adaptations to Resistance Training: Implications for Movement Control." *Sports Medicine* 31(12): 829–40. https://doi.org/10.2165/00007256-200131120-00001.

Cohen, Jacob. 1988. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed., 567. Hillsdale, N.J.: L. Erlbaum Associates. xxi.

Cuthbert, Matthew, G. Gregory Haff, Shawn M. Arent, Nicholas Ripley, John J. McMahon, Martin Evans, and Paul Comfort. 2021. "Effects of Variations in Resistance Training Frequency on Strength Development in Well-Trained Populations and Implications for In-Season Athlete Training: A Systematic Review and Meta-Analysis." *Sports Medicine* 51(9): 1967–82. https://doi.org/10.1007/s40279-021-01460-7.

de Boer, Maarten D., Olivier R. Seynnes, Pietro E. di Prampero, Rado Pišot, Igor B. Mekjavić, Gianni Biolo, and Marco V. Narici. 2008. "Effect of 5 Weeks Horizontal Bed Rest on Human Muscle Thickness and Architecture of Weight Bearing and Non-Weight Bearing Muscles." *European Journal of Applied Physiology* 104(2): 401–7. https://doi.org/10.1007/s00421-008-0703-0.

Grgic, Jozo, Brad J. Schoenfeld, Timothy B. Davies, Bruno Lazinica, James W. Krieger, and Zeljko Pedisic. 2018. "Effect of Resistance Training Frequency on Gains in Muscular Strength: A Systematic Review and Meta-Analysis." *Sports Medicine* 48(5): 1207–20. https://doi.org/10.1007/s40279-018-0872-x.

Grgic, Jozo, Brad J. Schoenfeld, and Christopher Latella. 2019. "Resistance Training Frequency and Skeletal Muscle Hypertrophy: A Review of Available Evidence." *Journal of Science and Medicine in Sport* 22(3): 361–70. https://doi.org/10.1016/j.jsams.2018.09.223.

Hamarsland, Håvard, Hermann Moen, Ole Johannes Skaar, Preben Wahlstrøm Jorang, Håvard Saeterøy Rødahl, and Bent R. Rønnestad. 2022. "Equal-Volume Strength Training with Different Training Frequencies Induces Similar Muscle Hypertrophy and Strength Improvement in Trained Participants." *Frontiers in Physiology* 12: 2374. https://doi.org/10.3389/fphys.2021.789403.

Hartman, Michael J., Brandon Clark, Debra A. Bemben, J. Lon Kilgore, and Michael G. Bemben. 2007. "Comparisons Between Twice-Daily and Once-Daily Training Sessions in Male Weight Lifters." *International Journal of Sports Physiology and Performance* 2(2): 159–69. https://doi.org/10.1123/ijspp.2.2.159.

Johnsen, Emil, and Roland van den Tillaar. 2021. “Effects of Training Frequency on Muscular Strength for Trained Men under Volume Matched Conditions.” *PeerJ* 9: e10781. https://doi.org/10.7717/peerj.10781.

Kraemer, William J., and Nicholas A. Ratamess. 2004. “Fundamentals of Resistance Training: Progression and Exercise Prescription.” *Medicine & Science in Sports & Exercise* 36(4): 674–88. https://doi.org/10.1249/01.mss.0000121945.36635.61.

Lera Orsatti, Fábio, Eliana A. Nahas, Nailza Maestá, Jorge Nahas Neto, Cláudio Lera Orsatti, Guilherme Vannucchi Portari, and Roberto C. Burini. 2014. “Effects of Resistance Training Frequency on Body Composition and Metabolics and Inflammatory Markers in Overweight Postmenopausal Women.” *The Journal of Sports Medicine and Physical Fitness* 54(3): 317–25.

Lombard, Wayne, Sorrel Reid, Keagan Pearson, and Michael Lambert. 2017. “Reliability of Metrics Associated with a Counter-Movement Jump Performed on a Force Plate.” *Measurement in Physical Education and Exercise Science* 21(4): 235–43. https://doi.org/10.1080/1091367x.2017.1354215.

Mclester Jr, John R., P. Bishop, and Me Guilliams. 2000. “Comparison of 1 Day and 3 Days Per Week of Equal-Volume Resistance Training in Experienced Subjects.” *The Journal of Strength & Conditioning Research* 14(3): 273–81. https://doi.org/10.1519/1533-4287(2000)014<0273:codadp>2.0.co;2.

McMahon, John J., Timothy J. Suchomel, Jason P. Lake, and Paul Comfort. 2018. “Understanding the Key Phases of the Countermovement Jump Force-Time Curve.” *Strength and Conditioning Journal* 40(4): 96–106. https://doi.org/10.1519/ssc.0000000000000375.

Neves, Ricardo P., Felipe C. Vechin, Emerson L. Teixeira, Demostenys D. da Silva, Carlos Ugrinowitsch, Hamilton Roschel, André Y. Aihara, and Valmor Tricoli. 2022. “Effect of Different Training Frequencies on Maximal Strength Performance and Muscle Hypertrophy in Trained Individuals—A Within-Subject Design.” *PLoS One* 17(10): e0276154. https://doi.org/10.1371/journal.pone.0276154.

Ochi, Eisuke, Masataka Maruo, Yosuke Tsuchiya, Naokata Ishii, Koji Miura, and Kazushige Sasaki. 2018. “Higher Training Frequency is Important for Gaining Muscular Strength Under Volume-Matched Training.” *Frontiers in Physiology* 9: 744. https://doi.org/10.3389/fphys.2018.00744.

Paz-Franco, Adrián, Ezequiel Rey, and Roberto Barcala-Furelos. 2017. “Effects of 3 Different Resistance Training Frequencies on Jump, Sprint, and Repeated Sprint Ability Performances in Professional Futsal Players.” *The Journal of Strength & Conditioning Research* 31(12): 3343–50. https://doi.org/10.1519/jsc.0000000000001766.

Ribeiro, Alex, Nelson Carneiro, Matheus Nascimento, Luís Gobbo, Brad J. Schoenfeld, Abdallah Achour Júnior, Sebastião Gobbi, Arli Oliveira, and Edilson Cyrino. 2015. “Effects of Different Resistance Training Frequencies on Flexibility in Older Women.” *Clinical Interventions in Aging* 10: 531–8. https://doi.org/10.2147/cia.s77433.

Santos Junior, Evaldo Rui T., Belmiro F. de Salles, Ingrid Dias, Alex S. Ribeiro, Roberto Simão, and Jeffrey M. Willardson. 2021. “Classification and Determination Model of Resistance Training Status.” *Strength and Conditioning Journal* 43(5): 77–86. https://doi.org/10.1519/ssc.0000000000000627.

Saric, Juraj, Domagoj Lisica, Ivan Orlic, Jozo Grgic, James W. Krieger, Sasa Vuk, and Brad J. Schoenfeld. 2019. “Resistance Training Frequencies of 3 and 6 Times Per Week Produce Similar Muscular Adaptations in Resistance-Trained Men.” *The Journal of Strength & Conditioning Research* 33(1): S122–9. https://doi.org/10.1519/jsc.0000000000002909.

Schoenfeld, Brad, and Jozo Grgic. 2018. “Evidence-Based Guidelines for Resistance Training Volume to Maximize Muscle Hypertrophy.” *Strength and Conditioning Journal* 40(4): 107–12. https://doi.org/10.1519/ssc.0000000000000363.

Schoenfeld, Brad Jon. 2020. *Science and Development of Muscle Hypertrophy*. Human Kinetics.

Schoenfeld, Brad Jon, Jozo Grgic, and James Krieger. 2019. “How Many Times Per Week Should a Muscle Be Trained to Maximize Muscle Hypertrophy? A Systematic Review and Meta-Analysis of Studies Examining the Effects of Resistance Training Frequency.” *Journal of Sports Science* 37(11): 1286–95. https://doi.org/10.1080/02640414.2018.1555906.

Schoenfeld, Brad J., Dan Ogborn, and James W. Krieger. 2016. “Effects of Resistance Training Frequency on Measures of Muscle Hypertrophy: A Systematic Review and Meta-Analysis.” *Sports Medicine* 46(11): 1689–97. https://doi.org/10.1007/s40279-016-0543-8.

Schoenfeld, Brad J., Dan Ogborn, and James W. Krieger. 2017. “Dose-Response Relationship Between Weekly Resistance Training Volume and Increases in Muscle Mass: A Systematic Review and Meta-Analysis.” *Journal of Sports Science* 35(11): 1073–82. https://doi.org/10.1080/02640414.2016.1210197.

Soares, Saulo, João B. Ferreira-Junior, Maria C. Pereira, Vitor A. Cleto, Rafael P. Castanheira, Eduardo L. Cadore, Lee E. Brown, Paulo Gentil, Michael G. Bemben, and Martim Bottaro. 2015. “Dissociated Time Course of Muscle Damage Recovery Between Single- and Multi-Joint Exercises in Highly Resistance-Trained Men.” *The Journal of Strength & Conditioning Research* 29(9): 2594–9. https://doi.org/10.1519/jsc.0000000000000899.

Takahashi, Yosuke, Yuji Fujino, Kohei Miura, Ayumi Toida, Tadamitsu Matsuda, and Shigeru Makita. 2021. “Intra- and Inter-Rater Reliability of Rectus Femoris Muscle Thickness Measured Using Ultrasonography in Healthy Individuals.” *Ultrasound J* 13(1): 21. https://doi.org/10.1186/s13089-021-00224-8.

Vasold, Kerri L., Andrew C. Parks, Deanna M. L. Phelan, Matthew B. Pontifex, and James M. Pivarnik. 2019. “Reliability and Validity of Commercially Available Low-Cost Bioelectrical Impedance Analysis.” *International Journal of Sport Nutrition and Exercise Metabolism* 29(4): 406–10. https://doi.org/10.1123/ijsnem.2018-0283.

Verney, Julien, Chloé Schwartz, Saliha Amiche, Bruno Pereira, and David Thivel. 2015. “Comparisons of a Multi-Frequency Bioelectrical Impedance Analysis to the Dual-Energy X-Ray Absorptiometry Scan in Healthy Young Adults Depending on their Physical Activity Level.” *Journal of Human Kinetics* 47(1): 73–80. https://doi.org/10.1515/hukin-2015-0063.

Wakahara, Taku, Atsuki Fukutani, Yasuo Kawakami, and Toshimasa Yanai. 2013. “Nonuniform Muscle Hypertrophy: its Relation to Muscle Activation in Training Session.” *Medicine & Science in Sports & Exercise* 45(11): 2158–65. https://doi.org/10.1249/mss.0b013e3182995349.

Yoshida, Riku, Shigeru Sato, Kazuki Kasahara, Yuta Murakami, Fu Murakoshi, Kodai Aizawa, Ryoma Koizumi, Kazunori Nosaka, and Masatoshi Nakamura. 2022. “Greater Effects by Performing a Small Number of Eccentric Contractions Daily than a Larger Number of them once a Week.” *Scandinavian Journal of Medicine & Science in Sports* 32(11): 1602–14. https://doi.org/10.1111/sms.14220.

Yue, Fu Leon, Bettina Karsten, Eneko Larumbe-Zabala, Marcos Seijo, and Fernando Naclerio. 2018. “Comparison of 2 Weekly-Equalized Volume Resistance-Training Routines Using Different Frequencies on Body Composition and Performance in Trained Males.” *Applied Physiology Nutrition and Metabolism* 43(5): 475–81. https://doi.org/10.1139/apnm-2017-0575.

Zaroni, Rafael S., Felipe A. Brigatto, Brad J. Schoenfeld, Tiago V. Braz, Júlio C. Benvenutti, Moisés D. Germano, Paulo H. Marchetti, Marcelo S. Aoki, and Charles R. Lopes. 2019. “High Resistance-Training Frequency Enhances Muscle Thickness in Resistance-Trained Men.” *The Journal of Strength & Conditioning Research* 33(1): S140–51. https://doi.org/10.1519/jsc.0000000000002643.