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ORIGINAL ARTICLE

One, two, or three times a week? examining the optimal frequency for strength and muscle growth in accentuated eccentric exercise

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Abstract

Purpose This study examines the effects of performing accentuated eccentric loading (AEL) resistance exercise one, two, or three times per week, with equal session doses, in resistance-trained athletes.

Methods Twenty-three strength-trained athletes were allocated to one of three exercise groups: EX1 ($n=7$), EX2 ($n=9$), and EX3 ($n=7$). Participants engaged in AEL full squat training once (EX1), twice (EX2), or three times (EX3) per week for 12 weeks. Maximum concentric (CONM), isometric (ISOM), and eccentric strength (ECCM), and strength endurance (SE70), were assessed using the full squat. Muscular power was evaluated through squat jump (SJ) and countermovement jump (CMJ) tests. Muscle cross-sectional area (CSA) was measured via computed tomography, and muscle fiber type proportions by mATP-ase histochemistry.

Results Across all groups, ISOM (9.1 ± 8.5%), CONM (9.3 ± 5.7%), ECCM (14.0 ± 6.7%), and SE70 (28.6 ± 16.2%) increased significantly (all $P<0.001$). SJ improved by 7.3 ± 6.9% ($P<0.001$), and CMJ improved by 4.4 ± 6.0% ($P=0.003$). Quadriceps CSA increased by 3.6 ± 4.1% ($P<0.001$), and thigh CSA increased by 2.1 ± 2.9% ($P=0.005$). The only significant between-group difference was that EX3 exhibited a greater increase in CONM compared with EX1 ($P=0.03$).

Conclusion Training with AEL resistance exercise one, two, or three times per week for 12 weeks produced similar effects on maximum strength, power, and hypertrophy in resistance-trained athletes.

Keywords Accentuated eccentric loading · Resistance training · Training frequency · Strength · Muscle hypertrophy · Muscle fiber types · Resistance-trained participants

Abbreviations

ACSA	Anatomical cross-sectional area
AEL	Accentuated eccentric loading resistance exercise
AST	Average maximum strength of CONM + ECCM + ISOM
ANOVA	Analysis of variance
CMJ	Countermovement jump
CONM	Maximum concentric strength in the full squat lift
CSA	Cross-sectional area
CT	Computer tomography
DCER	Dynamic constant external resistance exercise
DEXA	Dual-energy X-ray absorptiometry
ECCM	Maximum eccentric strength in the full squat lift
ISOM	Maximum isometric strength in the full squat lift
MATPase	Myofibrillar adenosinetriphosphatase
MRI	Magnetic resonance imaging
SE70	Strength endurance at 70% load of the pre-CONM
SJ	Squat jump
TCSA	Thigh cross-sectional area
QCSA	Quadriceps cross-sectional area
1RM	One repetition maximum

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Introduction

Traditional resistance training with high external resistance is widely recognized as an effective method for increasing muscle mass and strength in athletes, thereby enhancing performance across various sports (Komi 2003). A critical factor in the development of maximum strength is the relative load used during training. Recent meta-analyses have demonstrated that higher relative loading results in superior strength gains compared with lower loading in resistance-trained participants (Lopez et al. 2021; Swinton et al. 2024). In traditional resistance training, often referred to as "dynamic constant external resistance" (DCER) training (Weir et al. 1993), the same external resistance is applied during both the eccentric and concentric phases of coupled contractions. Since skeletal muscles can generate greater forces during eccentric contractions compared with concentric contractions (Levin and Wyman 1927; Franchi et al. 2017), the load that can be applied in a lift is constrained by the force capacity during the concentric phase. In resistance-trained participants, the training load used, or the mean force generated, is typically 20–40% higher during maximum eccentric than concentric resistance training (Vikne et al. 2006; Coratella and Schena 2016). Consequently, during the eccentric phase of DCER exercises, muscles generate lower forces compared with their maximum capability during lengthening contractions, potentially not fully leveraging an additional training stimulus that may be achieved by applying greater loads during the eccentric phase.

The potential benefits of supramaximal resistance during the eccentric phase of coupled contractions, known as accentuated eccentric loading (AEL) (Wagle et al. 2017) were initially examined using isokinetic exercise equipment in previously untrained participants (Colliander and Tesch 1990; Lacerte et al. 1992). In resistance-trained participants this modality of training has shown either equivalent (Brandenburg and Docherty 2002; Barstow et al. 2003; Friedmann-Bette et al. 2010; Walker et al. 2016; Maroto-Izquierdo et al. 2017) or superior (Brandenburg and Docherty 2002; Walker et al. 2016; Douglas et al. 2018; Chakshuraksha and Apanukul 2021) increases in various measures of maximum voluntary strength compared with DCER exercise. AEL training has also resulted in either larger (Maroto-Izquierdo et al. 2017; Douglas et al. 2018) or similar (Friedmann-Bette et al. 2010; Maroto-Izquierdo et al. 2017) gains in muscular power and running speed relative to DCER exercise. Additionally, strength endurance, measured as the maximum number of repetitions until failure, has been shown to improve more following AEL than DCER training (Walker et al. 2016). In terms of muscle hypertrophy, AEL has led to greater (Maroto-Izquierdo et al. 2017), or equivalent (Brandenburg and Docherty 2002; Friedmann-Bette et al. 2010; Walker et al. 2016; Douglas et al. 2018) increases compared with DCER exercise. However, there is limited comparative information on single muscle cell adaptations to AEL versus DCER resistance exercise. To our knowledge, only one short-term has compared effects on muscle fiber type proportions, with Friedmann-Bette et al. (2010) detecting no systematic changes in proportions within either mode of training. Collectively, AEL exercise appears to offer additional benefits in strength, power, and hypertrophy compared with DCER in already trained individuals, suggesting it may be a valuable method for enhancing athletic performance.

Despite the potential advantages of AEL, the optimal frequency for implementing AEL sessions has not been empirically established for either untrained or resistance-trained individuals. Previous comparative studies of AEL and DCER exercise in trained individuals have typically used training frequencies of two (Barstow et al. 2003; Walker et al. 2016; Douglas et al. 2018), three (Brandenburg and Docherty 2002; Friedmann-Bette et al. 2010) or a combination of two and three sessions per week (Maroto-Izquierdo et al. 2017). These training frequencies also seem to be the most commonly used both in generic AEL and DCER exercise studies (Wernbom et al. 2007). Several studies have compared the effects of different training frequencies on DCER exercise with equal session doses (repetitions times number of sets) per muscle, but all have been conducted in previously untrained individuals, yielding mixed results. Most studies found no overall difference in strength gains when comparing training frequencies ranging from 0.5 to 5 times per week, when the session dose was constant (Graves et al. 1990; Pollock et al. 1993; Carroll et al. 1998; Burt et al. 2007; Serra et al. 2015, 2018; Barcelos et al. 2018; Van Vossel et al. 2023). However, two studies on DCER exercise (Braith et al. 1989; DeMichele et al. 1997) and one study using pure eccentric exercise (Sorichter et al. 1997) reported larger strength increases with more frequent sessions.

Only two studies have compared the specific muscle cross-sectional area (CSA) or volume response to different training frequencies. Barcelos et al. (2018) found no significant differences in vastus lateralis CSA gains between two, three, or five weekly sessions of leg extension exercise using ultrasound imaging. In contrast, a within-subject study using MRI-based muscle volume measurements reported significantly greater hypertrophy in three out of four muscle groups (quadriceps, biceps brachii, and triceps brachii) with three sessions per week compared with two (Van Vossel et al. 2023). Generally, for untrained participants, there seems to be an increased effect in strength and hypertrophy by increased weekly DCER training frequency when session doses are equal. However, AEL training imposes substantially greater eccentric loading than DCER, potentially leading to higher levels of fatigue and thus the need for longer recovery times (Bartolomei et al. 2019). Therefore, whether the optimal training frequency for AEL in resistance-trained participants matches that of DCER in untrained participants remains unclear.

The primary aim of the present study was to empirically examine and compare the effects of different frequencies of heavy AEL exercise, with equal session doses, on performance and hypertrophy in resistance-trained participants. We, therefore, conducted a 12-week intervention study of resistance-trained athletes to examine and compare the effects of 1, 2, and 3 weekly sessions of equal session dose of heavy AEL exercise on maximum strength, power, muscular endurance, muscle fiber type proportions, and anatomical muscle cross-sectional area.

Methods

Overview of the study

To compare the effects of different training frequencies of accentuated eccentric loading (AEL) exercise, resistance-trained participants were assigned to one of three groups: one (EX1), two (EX2), or three (EX3) sessions per week. To isolate the effects of training frequency and prevent the introduction of a confounding variable—session dose—each group exercised with equal session volume (sets multiplied by repetitions) and relative load over the 12-week period. This design leads to different total training volumes across groups, a natural consequence of differing training frequencies.

Before the exercise intervention, the recovery of voluntary muscular force and power was monitored at intervals ranging from 15 min to 72 h after a single AEL training session. The details of these assessments and their results are provided in Online Resource 1, with the main findings summarized in the 'Results' section. At the beginning of the study, cross-sectional images of the thighs were acquired using computed tomography (CT), and muscle biopsies from the m. vastus lateralis were collected the following day. During the second week, baseline assessments were conducted for maximum isometric (ISOM), concentric (CONM), and eccentric (ECCM) strength, strength endurance (SE70), as well as squat jump (SJ) and countermovement jump (CMJ) performance, with measurements taken twice, except for the SE70. Participants then completed two 6-week training periods with a one-week hiatus between them, under supervision. All training sessions were conducted using an in-house custom-designed squat apparatus dedicated specifically for AEL exercise as described further below. Throughout the exercise period, weekly assessments of ISOM, SJ, and CMJ were performed to monitor changes in strength and power. Post-training tests were conducted following the same procedures as pre-tests. The study was approved by The Regional Ethics Committee for Medical Research (ID205/97) and conducted in accordance with the Helsinki Declaration and in a lawful manner. Due to the passing of the project leader, the data were anonymized before being stored. All participants provided written, informed consent for their participation in the study.

Participants

Thirty-two healthy, resistance-trained men were recruited from the Norwegian School of Sports Sciences and the Norwegian Olympic Sports Centre, Oslo. All participants had engaged in regular full squat training for at least the past year. Moreover, the minimum strength-to-body-mass ratio required for participation was 1.5 times the body mass in the full squat. None had systematically trained AEL squats in the previous six months. Two participants withdrew before randomization, leaving 30 participants who were randomly allocated to one of three training groups: EX1 ($n=10$), EX2 ($n=12$), and EX3 ($n=8$). During the study, one participant requested to switch from EX2 to EX1 before the intervention began. Additionally, two participants in EX1 withdrew during pre-testing, and two new participants were recruited to replace them (EX1, $n=11$; EX2, $n=11$; EX3, $n=8$). As a result, the study was not fully randomized. During the study, seven participants dropped out for various reasons: two due to injuries unrelated to the study, one due to recurring back problems, one because of influenza that caused a two-week break in training, and three due to scheduling conflicts. Consequently, 23 participants completed the study (EX1, $n=7$; EX2, $n=9$; EX3, $n=7$). The participants included recreational resistance-trained individuals (15), track and field power athletes (4) and athletes of alpine ski racing (1), badminton (1), rowing (1) and Greco-Roman wrestling (1). The participants' age and anthropometric details are reported in Table 1. The mean 1RM full squat strength to body mass ratio was 1.77 ± 0.15 (mean $\pm$ SD) before the intervention. A schematic overview of the study design and participants is given in Fig. 1.

Accentuated eccentric loading exercise equipment

For exercising the AEL squat, a custom-made exercise squat device was constructed in-house and used in the experiment (Fig. 2). The participants stood upright with a 20 kg Olympic barbell on the shoulders that was connected to a double-wagon sledge by steel wires via castors in the floor and ceiling (Fig. 2a). The two separable wagons (Fig. 2; markings "1" and "2") moved vertically along two steel rails. During the upright starting position and the downward eccentric

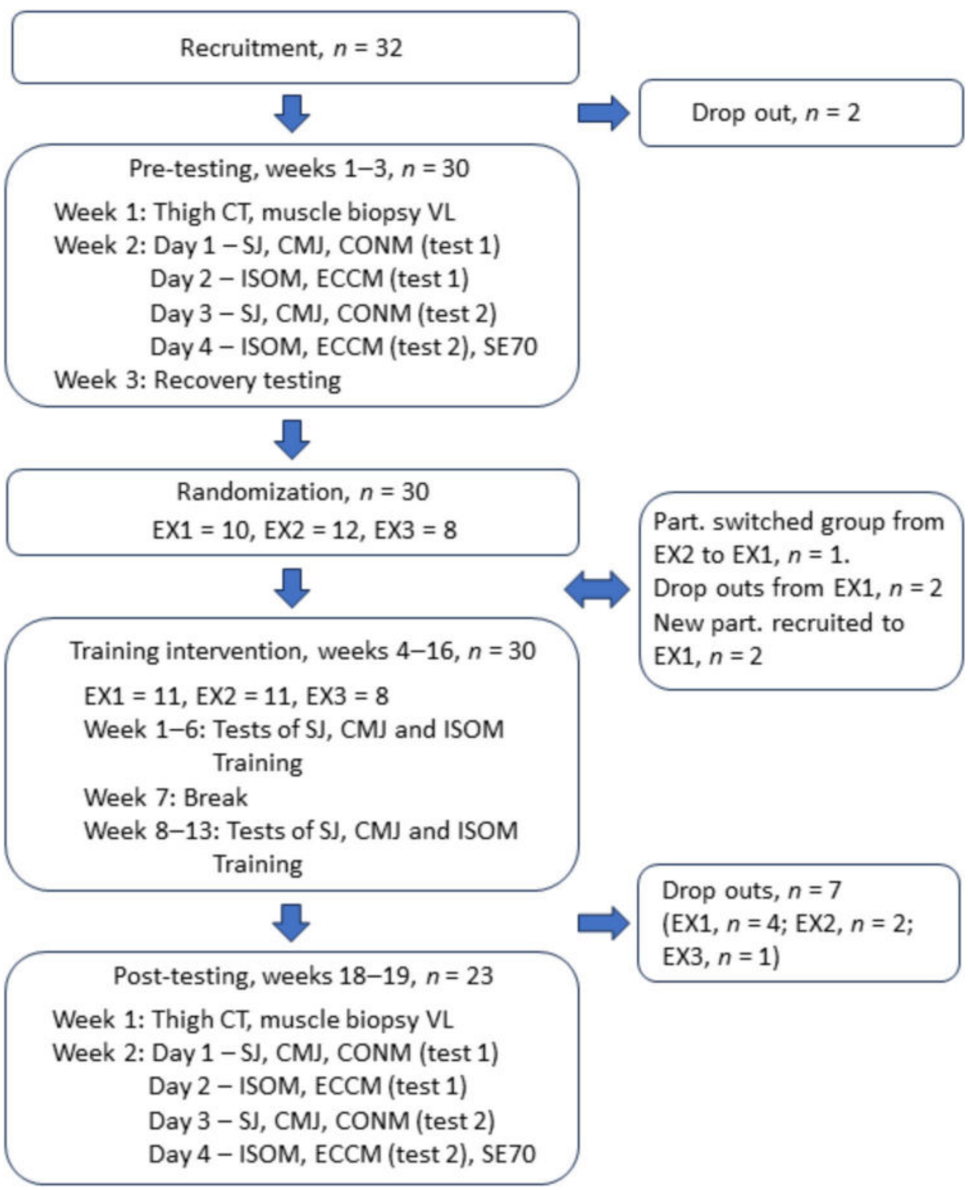
Table 1 Participant characteristics. The table displays age (yrs), standing height (cm), bodyweight (kg) and body mass index (kg/m^2) in EX1, EX2, EX3 and in all participants (EX1/2/3). Data are means (± SD)

	EX1 (n=7)	EX2 (n=9)	EX3 (n=7)	EX1/2/3 (n=23)
Age (yrs)	30.3 (10.2)	27.7 (4.6)	31.5 (7.1)	29.6 (7.2)
Height (cm)	183.1 (4.7)	185.3 (4.7)‡	177.7 (6.9)	182.3 (6.2)
Bodyweight (kg),				
pre	88.6 (7.7)	93.5 (13.8)	89.4 (14.3)	90.8 (12.1)
post	89.9 (8.4)*	95.9 (13.5)*	90.9 (13.8)*	92.6 (12.1)**
BMI (kg/m^2),				
pre	26.4 (1.9)	27.1 (2.9)	28.3 (4.5)	27.3 (3.2)
Post	26.8 (2.1) *	27.8 (2.8) *	28.8 (4.3)*	27.8 (3.1)**

Statistically significantly different from pre *; $P<0.05$, **; $P<0.001$. Statistically significant from EX3‡; $P=0.05$

phase of the squat, the lower wagon ("2") was attached to the upper wagon ("1") by spring hooks (Figs. 2a and b). At a pre-adjusted position, corresponding to the participant's deepest position in the full squat, the lower wagon automatically detached from the upper wagon (Fig. 2c). The participants then performed the concentric, upward phase of the squat with only the upper wagon connected to the barbell, resulting in a lighter load compared with the eccentric phase (Fig. 2d). Simultaneously, the lower wagon was raised semi-automatically to the starting position by a pneumatic piston connected to an air compressor (Fig. 2a marking "3"). After detachment of the lower wagon, a supervisor activated the piston, which lifted the lower wagon to the pre-adjusted position where it automatically reattached to the upper wagon via spring hooks. The entire process of raising and reattaching the lower wagon took approximately two seconds. The

Fig. 1 Overview of the study design and participants in the study. The study timeline starts at the top of the figure and the direction is indicated by blue arrows. *CMJ* countermovement jump, *CONM* concentric squat, *CT* computer tomography, *ECCM* eccentric squat, *EX1…3* experimental groups one to three, I*SOM* isometric squat, *n* number of participants, *SE70* squat strength endurance, *SJ* squat jump, *VL* vastus lateralis



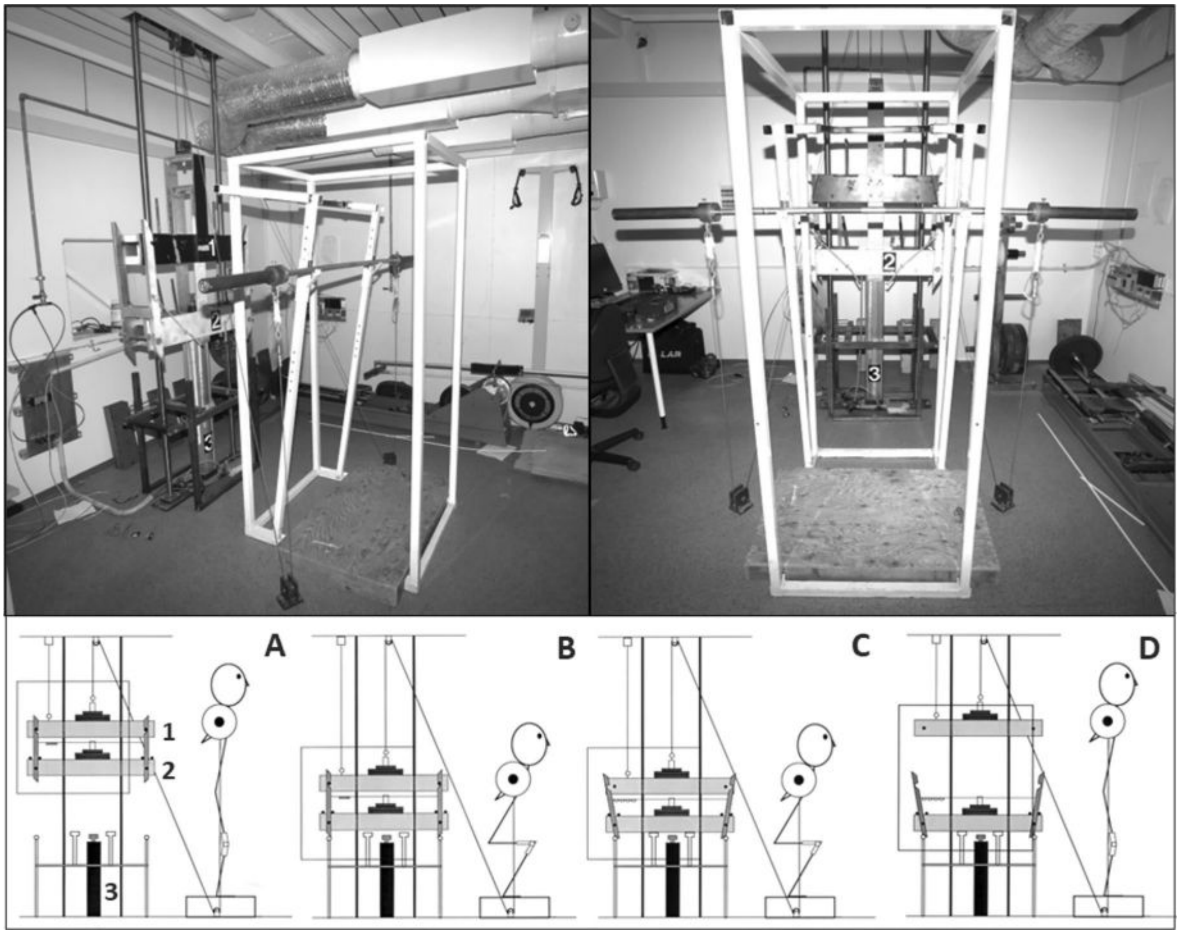


Fig. 2 The custom-made, two-wagon squat apparatus for exercising the accentuated eccentric overload squat in the study. In the starting position **a** both separable wagons (1 and 2) are connected to each other by hooks and to the Olympic bar by steel wires. At the start of the eccentric phase the participant lowers to the bottom position **b** with eccentric overload. At the bottom position, the lower wagon (2) uncouples from the upper wagon (1) and the participant rises to the standing position **c** and **d** with a reduced external load during the concentric phase. A pneumatic piston (3) raises the lower wagon which reattach to the upper wagon. See main text for a detailed description. Photos are published with the kind permission of Sindre Madsgaard, Norwegian Olympic Sports Centre

exercise equipment was individually adjusted to ensure that the full movement path of the squat mirrored that of the concentric strength test. The base load for the concentric phase comprised the barbell (20 kg) and the upper wagon (35 kg), totalling 55 kg. Additional weight for the concentric phase was placed on the barbell with minimum increments of 2.5 kg (2×1.25 kg). The eccentric phase included the weight of the lower wagon (40 kg) and any additional load using 2.5 kg increments.

Resistance exercise intervention

The training intervention consisted of two 6-week periods with a 1-week break in between, totalling 12 weeks of AEL resistance training. All training sessions were completed individually with the supervision of certified exercise physiologists with several years' of experience with resistance exercise. The training session volume (five sets of four repetitions) and the relative resistance (percentage of pre-concentric maximum strength, CONM) for both the eccentric and concentric phases were consistent across all groups. Participants in EX1 completed one session per week, EX2 two sessions per week, and EX3 three sessions per week, resulting in 12, 24, and 36 AEL sessions, respectively. Each session started with a general warm-up of individual choice, followed by two warm-up sets of 8–12 repetitions using 40–50% of the pre-CONM of ordinary squat lifts. Thereafter the participants completed 1–2 sets of specific warm-up squat lifts in the AEL exercise device using 70–90% of the CONM in the eccentric phase and 50% in the concentric phase. To allow for familiarization with the AEL training, the participants initially used a sub-maximal load the first week of training, specifically 1.1 times the pre-CONM in the eccentric phase of the lift and 50% in the concentric phase.

During the eccentric phase of the squat, the participants were instructed to use 3–4 s and to uphold a constant lowering velocity and to use their normal squat lifting velocity during the concentric phase. Throughout the 12 weeks, all groups performed five sets of four repetitions per session to ensure sufficient training volume for strength development (Ralston et al. 2017). The rest periods between sets were 3–5 min. Throughout the intervention period, the eccentric training load was increased progressively on a weekly basis by approximately 2.5% of the pre-CONM when a participant successfully completed all repetitions in all sets. Thus, within a given week, participants in groups EX2 and EX3 performed their consecutive training sessions using the same absolute training load. The exception was during training weeks 6 and 7, where the eccentric load remained constant due to the 1-week break. The concentric load was consistently maintained at 50% of the pre-CONM throughout the study. In groups EX2 and EX3, participants were asked to incorporate at least 48 h of rest period between successive squat sessions. Nevertheless, in a few cases, some participants had a shorter rest duration to fulfil the prescribed training schedule for the week. Aside from the three participants who were excluded due to missed sessions or scheduling conflicts, all remaining participants completed their assigned exercise sessions. The participants were instructed to refrain from other quadriceps-dominant leg exercises (e.g., standard back squats, leg extensions, leg presses, lunges, hack squats, front squats, and variations of deadlifts) but were otherwise asked to maintain their regular resistance exercise routine and daily activities. The activities outside the study were not monitored by the researchers.

Performance tests

All performance tests were variations of the squat movement and were conducted twice, both before and after the 12-week exercise intervention. The best performance from each test was used for analysis. The squat jump (SJ), countermovement jump (CMJ), and maximum concentric strength (CONM) in the full squat were assessed on the first and third days, while maximum isometric (ISOM) and eccentric squat (ECCM) strength were evaluated on the second and fourth days. Within each day, the outcome tests were separated by approximately 15 min of rest. Each trial of maximum strength was separated by a 3–5-min pause to ensure recovery—a consistent practice used for all strength tests (CONM, ISOM, ECCM) throughout the study. The jump-trials were typically separated by 30–60 s between jumps. The test–retest coefficient of variation (% CV) between the two baseline tests days was 3.0% for CONM, 4.2% for ECCM, and 5.8% for ISOM. The mean test–retest variability was 4.3% for the SJ and 4.2% for the CMJ. An overview of the tests and the testing order is illustrated in Fig. 1. Strength endurance (SE70) was tested once, using a load based on the best pre-test CONM result, and this test followed the completion of the other tests. The participants wore ordinary training clothing according to their preference. Participants used knee sleeves and powerlifting belts (100 mm width, 13 mm thickness) during both training and strength tests, but knee wraps were prohibited. The participants were verbally encouraged to exert maximum effort in all tests. To ensure safety, participants were safeguarded by one to three experienced spotters during the tests of CONM and ECCM. All performance tests conducted before, during, and after the intervention were supervised and assessed by two exercise physiologists with extensive experience in the testing procedures. All tests requiring external loads were performed using calibrated Olympic barbells and weights (Eleiko Group AB, Halmstad, Sweden). A triaxial force platform (AMTI, Watertown, MA, USA) connected to a personal computer was used to assess performance in the ISOM, ECCM, SJ, and CMJ tests, with a sampling rate of 500 Hz. A custom-designed analysis program, written in ASYST (Asyst Tech, Fremont, CA, USA), calculated the forces and generated force–time plots to visualize performance during the tests. Force data were converted to kilograms (kg) and rounded to the nearest 0.1 kg. The platform's reliability was tested using Eleiko calibrated weights, with known masses ranging from 10 to 400 kg, and the maximum error was ± 0.25% or 10 g of their face value, as per the manufacturer. The coefficient of variation measured on several occasions ranged between 0.01% and 0.1%.

The maximum concentric strength (CONM) was measured as the one-repetition maximum (1RM) in the full squat, following the standardized competition rules of the International Powerlifting Federation (IPF 2015). Briefly, the participants began the test in an upright stance with their feet spaced 30–50 cm apart, holding a loaded Olympic barbell at the top of their shoulders, resting at the base of the neck. From this position, they flexed their knee and hip joints, lowering themselves until the top surface of the thighs at the hip joint descended below the top of the knees, and then returned to a fully upright position. Before attempting their 1RM, the participants completed a standard warm-up, lifting 50–60 kg for 10–12 repetitions, followed by three to four sets with progressively heavier weights and fewer repetitions. The sensitivity of the test was set at 2.5 kg, meaning that increments in load were made in no less than 2.5 kg. Normally, the participants performed three to four lifts to establish their 1RM.

Maximum eccentric squat strength (ECCM) was assessed by determining the maximum load (kg) that participants could lower with controlled, constant velocity, during the eccentric phase of a full squat. The eccentric phase required the participants to take at least 3.5 s to descend from an upright standing position to the deepest squat position, as defined in the CONM test. During the descent, participants held a loaded Olympic barbell, with time and ground force measured on the force platform. To qualify as a successful lift, the mean ground force during the descent had to be at or above 95% of the added external mass. While brief fluctuations around the 95% criterion were acceptable, the force could not drop below this level and remain so for the remainder of the lift. The warm-up for the ECCM included 2–3 sets of standard squats using gradually increasing weights followed by a specific eccentric warm-up that began at 90% of the 1RM, with participants performing one to two repetitions. Weights were then gradually increased in steps of 2.5 kg increments until the maximum eccentric strength was established. Typically, participants performed three to five single lifts to determine their maximum eccentric strength.

Maximum isometric squat strength (ISOM) was measured using a force platform combined with an Olympic barbell secured in a custom-designed adjustable rack. The rack was mounted to the floor on each side of the platform, allowing the barbell height and foot position to be individually adjusted for each participant. These adjustments were tailored to match the participant's deepest squat position from the CONM test (position-matched) and were consistently used for all subsequent tests. The warm-up for the ISOM test began with participants pressing against the bar with approximately 50% of their maximum force for 3–5 s, followed by 2–3 additional contractions with increasing effort, each separated by 30–60 s of rest. During the strength test, participants performed a ramped contraction with increasing effort over 2–3 s, followed by 2–3 s of sustained maximal effort against the bar. Maximum isometric strength was defined as the peak force measured vertical to the platform. Participants completed three to four maximum effort contractions for the ISOM testing.

Strength endurance (SE70) was assessed by determining the maximum number of full squat repetitions participants could complete using a load equivalent to 70% of their pre-test CONM. The same absolute load, rounded to the nearest 2.5 kg, was used for both pre-test and post-test sessions. Only repetitions that met the CONM criteria were counted as successful. To standardize the pacing between repetitions, participants were allowed to take only a single breath while standing upright before initiating the next lift. Prior to testing, participants were instructed on the performance criteria and practiced the lifting rhythm and technique with a light load for 5–10 repetitions. During the test, one investigator provided safety support behind the participant, while another monitored lifting technique and informed the participant of the number of valid repetitions completed. Participants were allowed to make multiple attempts if needed. Due to muscular pain experienced during the final ECC test, two participants (one from EX2 and one from EX3) opted out of the SE70 post-test. Consequently, the SE70 results are based on data from eight participants in EX2 and six participants in EX3.

Vertical squat jump (SJ) and countermovement jump (CMJ) were performed on a force platform to assess muscular power, following the standardized procedures described by Komi and Bosco (1978). The height of the rise of the centre of gravity during the jumps was calculated from the force–time data collected by the platform. For the SJ, participants began from a static position with a knee angle of approximately 90°. The CMJ started from a standing, erect posture, initiated by a downward movement into a knee angle of about 90° before jumping. To ensure consistency, participants were instructed to keep their hands on their hips throughout both types of jumps, preventing the use of arm swing to assist the movement. Participants typically completed 4–6 attempts for each jump test to achieve their maximum performance.

Weekly monitoring of performance

To monitor weekly progress in strength and muscular power during the training period, ISOM, SJ and CMJ performance were assessed prior to the first/only training session each training week using the same procedures as during the pre- and post-tests. After a general and specific warm-up, the participants first performed 3–5 maximum effort SJs and CMJs. Following the jumps, participants performed two warm-up contractions in the ISOM test rack with gradually increasing effort and then executed 2–3 maximum effort ISOMs. The data were expressed relative to the baseline values for these tests with the best result from each test used for analysis. One participant from the EX2 group experienced back pain during ISOM in week 10 and did not want to perform this test for the remaining weeks. His data series for ISOM are, therefore, not included in the analyses.

Anatomical muscle cross-sectional area

The anatomical cross-sectional area (ACSA) of the quadriceps muscles (QCSA) and whole thighs (TCSA) of both legs were measured using computed tomography (CT; X-vision/EX, Toshiba). The participants rested in the supine position on the motorized table with the lower extremities securely strapped to prevent movements during scanning. A frontal scout image was first taken of the lower femur to position the participant within the gantry. The cross-sectional image (120 peak kilovolts, 300 milliampere seconds, 15 mm slice thickness) was captured at a location standardized to each participant's height. Specifically, the scan was taken 20 cm above the lower part of the condylus medialis of the femur for individuals with a height of 180 cm. For persons of different height (h in cm), the scan site was taken $\frac{h \times 20}{180}$ cm above the knee joint. By this correction, the scan was taken at the same relative position for all participants. The CT images were imported to ImageJ (1.54d, Rasband, W.S., U. S. National Institute of Health, Bethesda, MD, USA) software for offline analysis. An investigator blinded to the time point of the scan, group assignment and identity of the participants conducted the analysis. Calibration of the images was performed using a known mm scale bar displayed on the image. The muscle margins were carefully traced, and the software automatically calculated the cross-sectional areas. To assess the whole TCSA, the outer border of all the leg muscles was circumscribed. For the QCSA, the collective muscle bellies of the vastii muscles and the rectus femoris (m. rectus femoris) were outlined. The areas corresponding to the femur and intermuscular fat tissue were traced separately and subtracted from the total muscle group area. All measurements were completed three separate, non-consecutively times, and the mean value of these measurements were used for further analysis. The average ACSA (cm^2) of both thighs and the quadriceps muscles of both legs was calculated and used further in the analysis. The test–retest coefficient of variation for the measurements was 0.56% for QCSA and 0.35% for the TCSA. One participant from the EX2 group did not attend the post-intervention CT scan, and his data were excluded from the analyses.

Muscle biopsy sampling

The participant lay supine at rest on a standard height-adjusted treatment table and the skin was shaved and washed with isopropanol (70%). Thereafter local anaesthesia (Xylocaine 10 g L^{-1}) was given first in the skin and thereafter in the fascia and muscle in the right vastus lateralis muscle, 15 cm above the upper border of the patellae. After about 10 min after the injection, the area was first washed with chlorhexidine and a ~ 15 mm incision was made in the skin and muscle fascia. Several muscle samples were taken using a modified Bergstrøm-type percutaneous biopsy needle without suction (Bergstrom 1962). The muscle biopsies were immediately frozen in Isopentane, precooled to their freezing point (–160° C) by liquid nitrogen, and then temporarily stored on dry ice (–78.5° C) for a few hours before being transferred to and stored in a cryofreezer at –80° C until later analyses. The incision site was carefully closed with surgical strips. The post-exercise biopsies of each participant were taken randomly either 1 cm distally or proximally to the first biopsy site.

Histochemistry and image analysis

Muscle samples were warmed to –20°C in a cryostat (HM 560M, Microm International, Walldorf, Germany), oriented and mounted on metal discs using an embedding medium (Tissue-Tek O.C.T. Compund, Sakura, Tokyo, Japan). Serial cross-sections of 10 µm thickness were cut in the cryostat and put on glass microscope slides (Superfrost plus, Menzel, Braunschweig, Germany). Myofibrillar ATP-ase histochemistry was completed (Brooke and Kaiser 1970) to differentiate the muscle fibre types. Muscle fibres were classified as type 1, 2C, 2A, 2AX and 2X according to their stability to the acidic and alkaline preincubations (Andersen and Aagaard 2000). Type 1 fibers were stable at pH 4.37 and 4.6 but labile at pH 10.3, while 2A muscle fibers were stable at pH 10.3 but labile at pH 4.37 and 4.6. Muscle fibers that were stable at both pH 10.3 and 4.6 but labile at 4.37, were classified as 2AX or 2X depending on the staining intensity at pH 4.6. 2C-fibers were stable at all three preincubations. Glass slides of pre- and post-exercise muscle samples of each participant were stained simultaneously to minimize possible risks of different staining intensities between assays. Slides were magnified in a microscope (BX50WI, Olympus, Tokyo, Japan) using a 10X water immersion objective (UMPLFL10XW, Olympus, Tokyo, Japan) and photographed using a digital camera (Coolpix 995, Nikon, Tokyo, Japan) connected to the microscope. A composite photomontage of the images of each preparation (preincubation pH 4.37, 4.6 and 10.3) were assembled in Photoshop. On average 508 ± 155 fibers were classified before and 527 ± 145 after the experiment of each participant. One participant in the EX1 group had only 193 fibers available for post-test analysis but was still included in the overall analysis. The analysis was conducted by an investigator who was blinded to the identity of the participants, time point, and group assignments. Due to the poor integrity of the cell boundary in several muscle samples, the cell cross-sectional areas were not measured in this study. Additionally, the participants exhibited negligible proportions of the type 2C and 2X fibers. Specifically, 11 participants had less than 0.5% of type 2C fibers, and eight participants had less than 0.5% of type 2X fibers. Therefore, for statistical analysis, type 2X fibers and 2AX fibers were combined into a single group termed 2AX/X. The type 2C fibers were split equally between type 1 and type 2A fibers. Consequently, the fiber type analysis consisted of type 1, type 2A, and type 2AX/X fibers.

Data handling and statistical analysis

In addition to the measured outcome variables, a variable termed average squat strength (AST) was introduced, representing the mean value of the three maximum strength tests (CONM, ISOM, and ECCM). Specific quadriceps strength (kg/cm^2) was determined as the ratio of AST to QCSA, while normalized concentric squat strength was calculated as CONM divided by body mass. For all statistical tests, normality of distribution was assessed using the Shapiro–Wilk test and graphical representations (q-q plots), while homogeneity of variance was assessed with Levene's test.

First, we compared the group of dropouts ($n=9$) to the participants who completed the study ($n=23$) regarding descriptive and outcome variables at baseline, using two-sided, independent samples *t*-tests. Non-normally distributed outcome data were analysed using the Mann–Whitney *U* test. When the assumption of homogeneity of variance was violated, the Welch *t*-test was applied. Muscle fiber types were not analysed in the dropout group.

For baseline differences between the three intervention groups (EX1, EX2, EX3), one-way ANOVA with Tukey–Kramer post hoc test was used due to the unbalanced number of participants. If the variance was unequal between groups, the Welch ANOVA with Games-Howell post hoc tests were used.

To examine and compare within-group changes from baseline to post-test between the different intervention groups (EX1, EX2, and EX3), a two-way mixed-model ANOVA was used. Significant interactions of time and groups were followed up by comparing and testing change scores from pre to post tests.

The effect of the AEL intervention on the normalized concentric squat strength ratio was examined across groups pooled (EX1/2/3) only, and two-sided, paired samples *t*-test was used accordingly.

To examine relationships between changes in the weekly monitoring tests (SJ, CMJ and ISOM) with changes in performance and muscle area after training, the relative difference expressed as percentages from baseline to the mean of three consecutive weeks of the monitoring tests (weeks 1–3, 4–6, 7–9 and 10–12) across all groups were correlated with the relative difference from baseline to post-intervention for the performance tests and muscle area using two-sided Spearman's rank-order correlation. Possible relationships between the relative changes in performance and muscle morphological variables across all groups pooled were examined using the same procedures as noted above. All statistical analysis and graphs were completed in SPSS 29.0 (IBM, Armonk, NY, USA) and Prism 9.4.1 (GraphPad Software, Boston, MA, USA) respectively. Unless otherwise stated, the data are given as means ± SD. Statistical significance was set at $P \leq 0.05$.

Results

Baseline

At baseline, no differences for any variable were found between the dropouts ($n=9$) and the participants that completed the study ($n=23$, all p-values ≥ 0.15). Except for a significant difference in standing height between EX2 and EX3 ($p=0.03$), there were no statistical differences between the three completing intervention groups EX1, EX2 and EX3 (all p-values > 0.33) at baseline (Table 1). These results suggest that the study was well balanced, and further that dropouts have not introduced a bias. Before the intervention started, all participants completed an examination of performance recovery from an acute session of heavy AEL exercise, monitored over a 72-h period to assess whether higher frequencies of AEL exercise could be tolerated in the chronic intervention study (Online Resource 1). After 48 h of rest, performance in SJ, CMJ, and ISOM was restored to pre-session values, indicating that incomplete recovery did not influence the findings in the study.

Progression of strength and power during the intervention period

As visualized in Fig. 3c there was a progressive mean increase in isometric squat strength (ISOM) across all exercise groups combined throughout the training period. In contrast, only small changes were observed in the SJ and CMJ across groups (Figs. 3a and b). For the individual groups, both EX1 and EX2 displayed gradual increases in SJ performance compared with the baseline values. On the other hand, EX3 demonstrated fluctuations around the baseline value throughout the training period, with no consistent trend observed. For CMJ, only group EX2 seemed to display consistent improvements, while the results of EX1 and EX3 remained relatively stable.

Weekly relative changes from baseline in the monitoring variables correlated with post-test changes in the same variables. Generally, these correlations increased in strength as the intervention progressed. Specifically, the weekly changes in SJ correlated significantly with post-test changes in SJ during weeks 4–6, weeks 7–9, and weeks 10–12 ($P \leq 0.01$). Similarly, the weekly changes in CMJ correlated with post-test CMJ changes for all four periods examined ($P \leq 0.01$). For isometric squat strength, weekly relative changes correlated also with post-test changes during all four periods ($P \leq 0.01$). However, no significant correlations were found between isometric strength changes and other performance or morphological variables. See the Online Resource 2 for all correlations.

Effects of training on physical performance

All pre- and post-data on strength, power and strength endurance data are given in Table 2. The relative mean and individual changes are given in Fig. 3. Across all groups combined (EX1/2/3) the normalized squat strength (CONM to body mass) increased from a baseline value of 1.77 ± 0.15 to 1.90 ± 0.19 ($P < 0.001$) after training. However, few significant differences between groups were found. Across all

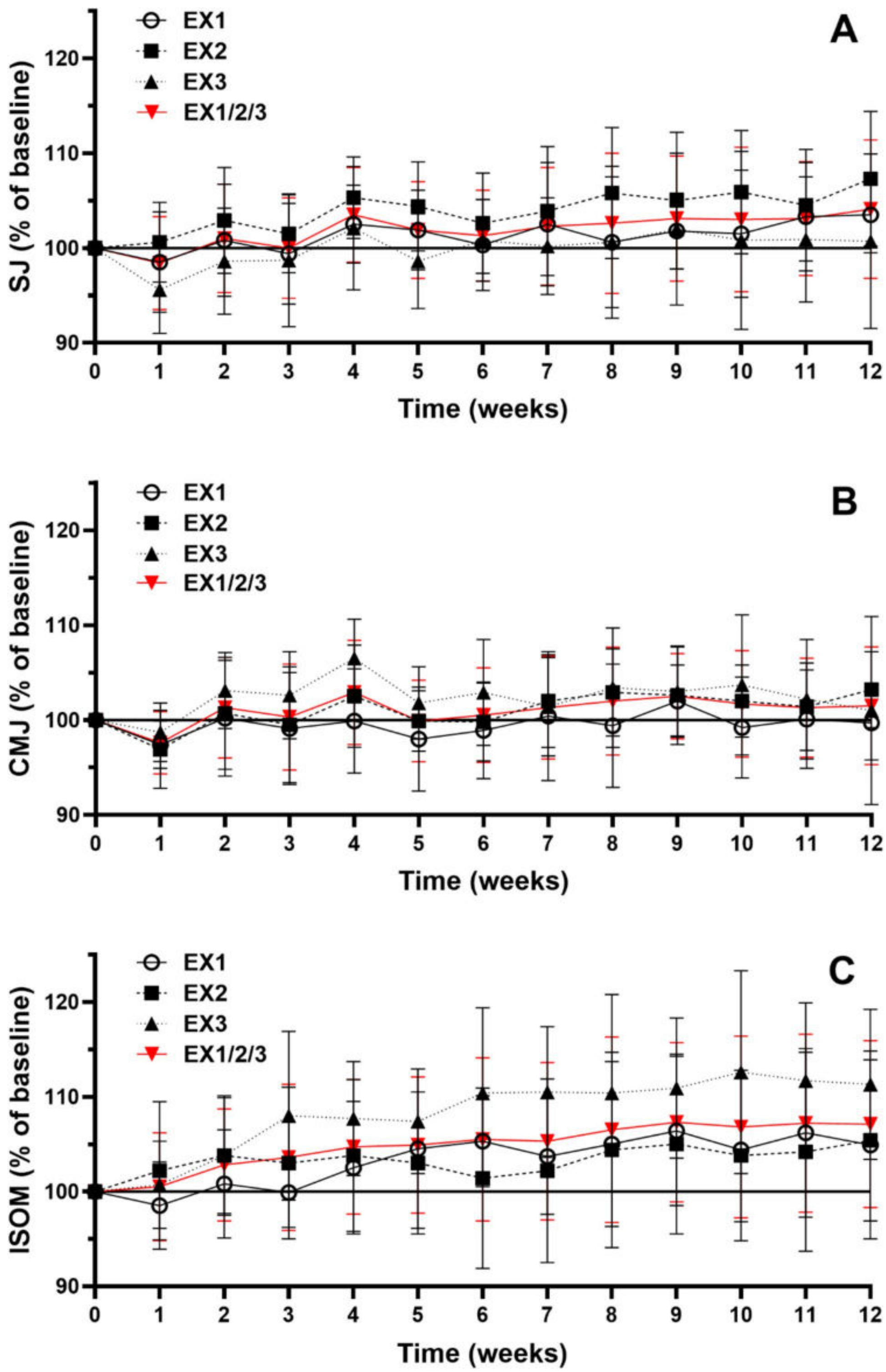


Fig. 3 Weekly tests of performance in squat jump (SJ; A), countermovement jump (CMJ; B) and maximum isometric squat (ISOM; C) during the 12-week exercise period for EX1 ($n=7$), EX2 ($n=9$ except ISOM, $n=8$) and EX3 ($n=7$) and for all groups pooled (EX1/2/3, $n=22$–23). EX1 is depicted by open circles and connected by solid lines, EX2 is shown by filled boxes and connected by dashed lines, and EX3 is indicated by filled triangles connected by dotted lines. The pooled EX1/2/3 is represented by red, filled triangles, connected by red, solid lines. The X-axes are time (in weeks) and Y-axes are relative performance (percent of baseline). Data are means (± SD)

outcome variables in the study, only one significant interaction between time and intervention was found, an interaction between intervention and time for CONM ($P=0.035$). Follow-up tests revealed that the increase in CONM strength was 13.9 ± 13.2 kg greater in the EX3 group compared with the EX1 group ($P=0.03$). There were no other statistically significant differences between the different exercise groups in physical performance (all P-values > 0.09).

The main effect for time (EX1/2/3) was significant for all measures of maximum strength, power and muscular endurance (all P-values < 0.01). Simple main effects of time showed that all separate groups increased the

Table 2 Performance tests. Pre- and post-intervention performance tests, the absolute difference (Δ) and corresponding p-values for the differences. EX1, $n=7$, EX2, $n=9$, EX3, $n=7$ and all groups collapsed, $n=23$, except SE70; EX 2, $n=8$, EX3, $n=6$. All data are means (±SD) except *P*-values

	EX1	EX2	EX3	All groups
CONM (kg)				
pre	158.2 (16.8)	164.2 (37.2)	161.1 (26.6)	161.4 (27.9)
post	167.1 (18.3)	178.1 (39.4)	183.9 (34.9)	176.5 (32.2)
Δ Abs	8.9 (6.6)	13.9 (9.0)	22.9 (119)	15.1 (10.3)
P-value	0.012	0.002	0.002	<0.001
ECCM (kg)				
pre	187.1 (18.7)	187.2 (41.1)	193.6 (35.0)	189.1 (32.4)
post	204.3 (25.6)	216.1 (50.7)	227.1 (44.5)	215.9 (41.7)
Δ Abs	17.1 (12.5)	28.9 (14.3)	33.6 (13.8)	26.7 (14.3)
P-value	0.011	<0.001	<0.001	<0.001
ISOM (kg)				
pre	160.0 (34.2)	173.5 (35.9)	175.1 (25.9)	169.9 (31.9)
post	177.5 (52.4)	183.5 (36.5)	196.7 (34.2)	185.7 (40.2)
Δ Abs	17.5 (22.0)	10.0 (12.0)	21.6 (14.3)	15.8 (15.9)
P-value	0.08	0.038	0.007	<0.001
AST (kg)				
pre	168.4 (22.5)	175.0 (36.2)	176.6 (28.1)	173.5 (29.0)
post	183.0 (30.6)	192.5 (40.8)	202.6 (36.5)	192.7 (35.8)
Δ Abs	14.5 (10.8)	17.6 (7.5)	26.0 (11.0)	19.2 (10.4)
P-value	0.012	<0.001	<0.001	<0.001
SE70 (no.)				
pre	14.6 (1.3)	14.2 (1.9)	12.8 (3.0)	13.9 (2.1)
post	17.7 (2.6)	18 (2.4)	18.0 (6.7)	17.9 (3.9)
Δ Abs	3.1 (1.7)	3.9 (1.6)	5.2 (4.3)	4.0 (2.6)
P-value	0.003	<0.001	0.031	<0.001
SJ (cm)				
pre	38.0 (5.1)	39.4 (5.8)	37.8 (7.3)	38.4 (5.9)
post	40.9 (4.8)	42.3 (5.2)	39.8 (8.0)	41.1 (5.9)
Δ Abs	3.0 (2.1)	2.9 (2.6)	2.0 (3.0)	2.7 (2.4)
P-value	0.009	0.009	0.123	<0.001
CMJ (cm)				
pre	41.9 (4.9)	42.6 (6.3)	39.3 (7.9)	41.4 (6.3)
post	43.5 (4.9)	43.8 (5.4)	41.6 (8.9)	43.1 (6.3)
Δ Abs	1.6 (2.5)	1.2 (2.0)	2.4 (2.9)	1.7 (2.3)
P-value	0.142	0.105	0.071	0.003

CONM and ECCM and the compound variable average of all strength tests (AST) significantly, while only EX1 and EX3 increased ISOM. The jump height increased significantly for groups EX1 and EX2 at the SJ test, while only EX3 showed significant improvements in the CMJ.

Across all participants (EX1/2/3) the changes in CONM and ECCM from pre to post-intervention correlated with changes in each other ($r=0.84$, $P<0.01$) and with SE70 ($r=0.45$ and $r=0.46$, $P<0.05$) for the CONM and ECCM, respectively. The changes in the SJ and CMJ correlated significantly with each other only ($r=0.62$, $P<0.01$). On the other hand, the changes in ISOM did not correlate with the changes in any other performance variable (Table 3). Figure 4 presents the individual responses of all participants across nine distinct tests over a 12-week training period. Except for the SE70 and ECCM tests, all outcome variables displayed some negative or non-changing values for the differences. Likewise, several large positive responses were observed across the tests, and this heterogeneity in responses was consistent across the three training groups. Further analysis of individual responses revealed no systematic patterns: negative outcomes were not confined to a few 'non-responders', nor were large positive responses limited to a small subset of 'high responders'. Furthermore, while a strong positive or negative response in one test correlated with certain other tests as shown above, no consistent pattern was observed across all tests.

Effect of training on muscle ACSA, specific strength and fiber type proportions

The absolute values for muscle ACSAs are presented in Table 4 and the relative mean and individual changes in Fig. 3. No significant interactions between time and intervention were found in the outcomes of muscle area nor fiber type proportions (all p-values > 0.24). The main effect for time across groups (EX1/2/3) was significant for the mean QCSA and TCSA and increased respectively by 3.5 ± 4.0 cm^2 and 3.8 ± 5.3 cm^2 (both P–values <0.01). Simple main effects of time for changes in QCSA were significant for groups EX2 ($P=0.005$) and EX3 ($P=0.03$), while for TCSA only EX2 displayed a significant increase ($P=0.01$). EX1 did not increase the ACSA of the quadriceps nor the whole thigh significantly.

There was a main effect of time for specific quadriceps strength (AST:QCSA ratio) which increased significantly for all groups combined (EX1/2/3) from a baseline value of 1.73 ± 0.18 kg/cm^2 to 1.85 ± 0.24 kg/cm^2 ($P<0.001$) after training. The increase was statistically significant for each group examined separately ($P \leq 0.02$).

The data on muscle fiber type proportions are displayed in Table 5 and individual and mean changes (percentage points) in Fig. 4. Overall, there was a main effect of time for the type 2A fiber proportions ($P=0.01$) in that across all groups, an increase by 5.9 ± 10.5 percentage points was found from pre to post test. No significant main effects

Table 3 Relationships between changes in performance variables. Relationship between relative changes in performance variables after the intervention across all groups. All correlations are calculated using Spearman's rank-order correlation. All data series are $n=23$ except SE70; $n=21$. All correlations are $n=21$–23

	SJ	CMJ	ISOM	CONM	ECCM	SE70
SJ	1	0.62**	– 0.09	– 0.01	– 0.07	0.38
CMJ	0.62**	1	– 0.02	0.23	– 0.04	0.32
ISOM	– 0.09	– 0.02	1	0.14	– 0.02	– 0.01
CONM	– 0.01	0.23	0.14	1	0.84**	0.45*
ECCM	– 0.07	– 0.04	– 0.02	0.84**	1	0.46*
SE70	0.38	0.32	– 0.01	0.45*	0.46*	1

**, $P<0.01$

*, $P<0.05$

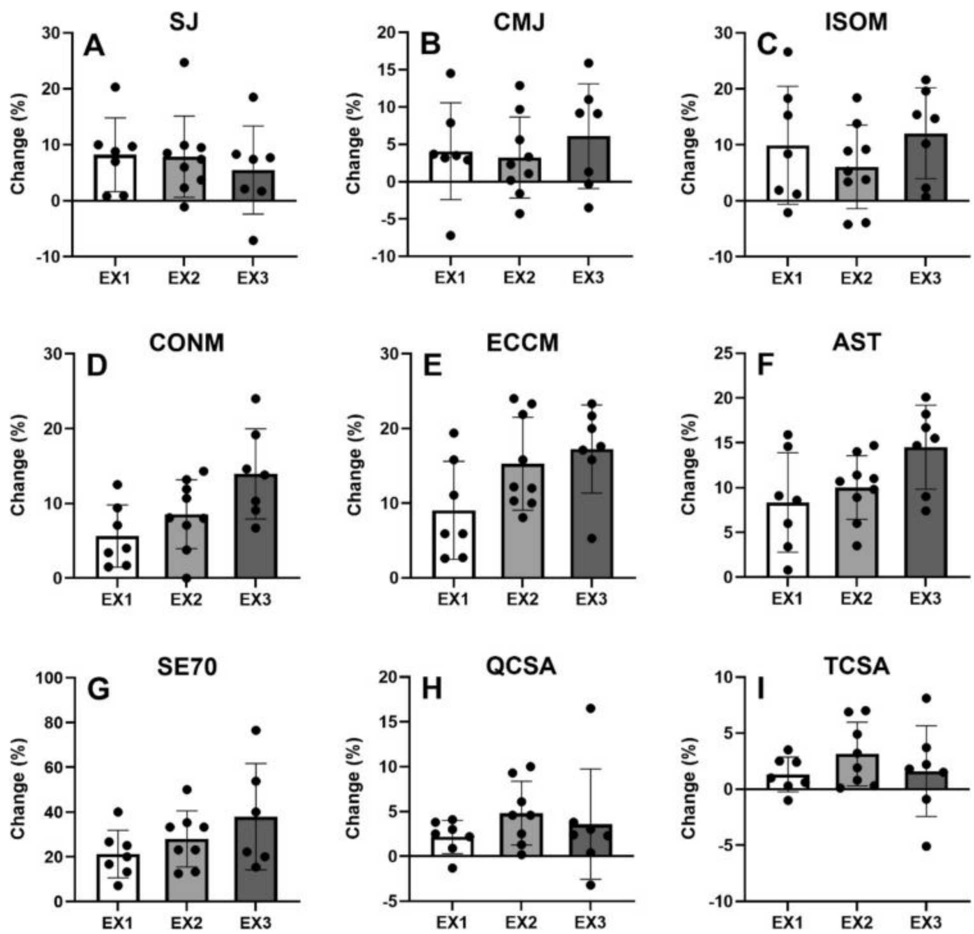


Fig. 4 Relative changes (%) in performance tests (*AST* average squat strength, *CMJ* countermovement jump, *CONM* concentric strength, *ECCM* eccentric strength, *ISOM* isometric strength, *SE70* strength endurance, *SJ*—squat jump) and anatomical muscle cross-sectional area (*QCSA* quadriceps cross-sectional area, *TCSA* thigh cross-sectional area) after training once (EX1), twice (EX2) and trice (EX3) a week for 12 weeks. The X-axes depict the different groups; EX1 is shown by unfilled bars, EX2 is indicated by grey bars and EX3 is shown by dark grey bars. The Y-axes are relative changes (%). Bars are mean and error bars are ± SD. Filled circles are the individual changes

after intervention were found for type 1 or the type 2AX/X fibers. Significant simple main effects of time for the proportion of type 2A fibers were found for the EX1 and EX3 groups (both P -values = 0.04). The absolute changes in QCSA, ACSA and muscle fiber type proportions did not correlate significantly with the changes in any of the performance variables (Table 6).

Discussion

We examined the effect of exercising accentuated eccentric loading (AEL) one, two or three days per week with equal session dose in resistance-trained athletes. The participating athletes displayed an overall mean of 161 ± 28 kg in the

Table 4 Muscle cross-sectional area

Group	Pre (SD)	Post (SD)	Δ Abs (SD)	*P*-value
Quadriceps CSA (cm^2)				
EX1	100.9 (7.3)	103.0 (6.2)	2.1 (1.9)	0.19
EX2	101.7 (13.7)	106.3 (11.8)	4.6 (3.1)	0.005
EX3	98.3 (11.4)	101.9 (14.3)	3.7 (6.3)	0.03
All groups	100.4 (10.6)	103.9 (10.7)	3.5 (4.0)	< 0.001
Thigh CSA (cm^2)				
EX1	187.6 (9.7)	190.1 (9.4)	2.4 (2.9)	0.26
EX2	187.8 (27.1)	193.3 (24.7)	5.5 (4.8)	0.011
EX3	186.2 (20.1)	189.5 (24.2)	3.2 (7.8)	0.14
All groups	187.3 (19.3)	191.0 (19.5)	3.8 (5.3)	0.005

Anatomical muscle cross-sectional area (cm^2) of the m. quadriceps femoris and the whole thigh before and after the training period, the absolute difference (Δ) and the *P*-values of the differences. EX1, $n=7$, EX2, $n=8$, EX3, $n=7$, all groups, $n=22$. All data are means (± SD) except *P*-values. *P*-values indicate within-group significance levels between pre-and post-tests

Table 5 Muscle fiber type proportions

Group	Fiber type	Pre (SD)	Post (SD)	Δ %-points (SD)	*P*
EX1	1	54.8 (7.8)	46.2 (12.3)	– 8.6 (17.2)	0.24
	2A	38.0 (8.0)	46.7 (9.6)	8.7 (16.1)	0.2
	2AX/X	7.2 (6.3)	7.1 (7.8)	– 0.1 (2.5)	0.9
EX2	1	48.4 (8.2)	49.1 (11.8)	0.6 (10.0)	0.86
	2A	42.4 (7.1)	43.8 (7.9)	1.3 (9.0)	0.67
	2AX/X	9.1 (6.6)	7.2 (7.1)	– 2.0 (4.1)	0.19
EX3	1	49.7 (11.9)	42.2 (10.6)	– 7.5 (5.8)	0.014
	2A	40.2 (9.2)	49.1 (11.1)	8.8 (2.2)	< 0.001
	2AX/X	10.1 (9.0)	8.7 (8.5)	– 1.4 (6.6)	0.61
All	1	50.7 (9.2)	46.1 (11.2)	– 4.6 (11.8)	0.08
	2A	40.4 (7.7)	46.3 (9.1)	5.9 (10.5)	0.016
	2AX/X	8.9 (6.9)	7.6 (7.3)	– 1.2 (4.4)	0.21

Muscle fiber type proportions (% (± SD) in the vastus lateralis in EX1 ($n=7$), EX2 ($n=9$), EX3 ($n=7$) and all groups pooled ($n=23$) before and after the training intervention, the differences (percentage points ± SD) and the *P*-values for the differences

full IPF-standardized raw squat (CONM range 130–230 kg) at a mean body weight of 91 kg (range 72–121 kg) at baseline, giving a mean CONM/body mass ratio of 1.77 ± 0.15. At the end of the training period the average squat strength (AST) had increased by around 11%, while the quadriceps muscle cross-section area (QCSA) had risen by 3.6% for all groups pooled. Despite a three-fold difference in training frequency and total training volume between the exercise groups, only marginal differences among groups were found for any of the measured outcome variables. The present study is likely the first to examine the effects of varying frequencies of AEL exercise with equal session dose in resistance-trained athletes.

Table 6 Relationships between changes in performance and muscle morphology

	Type 1	Type 2A	Type 2AX/X	QCSA	TCSA
SJ	0.29	– 0.15	– 0.38	0.25	0.18
CMJ	0.13	– 0.02	– 0.3	0.13	0.11
ISOM	– 0.28	0.19	0.24	– 0.18	– 0.18
CONM	– 0.06	0.24	– 0.14	0.32	0.37
ECCM	0.01	0.24	– 0.32	0.2	0.24
SE70	0.01	0.06	– 0.12	0.35	0.23

Relationship between changes in performance and morphological variables across all study participants. All relationships are calculated using Spearman's rank-order correlation. All data series are $n=23$ except SE70, $n=21$, QCSA and TCSA, $n=22$. All correlations $n=20$–23. No significant correlations were found

Physical performance

Over the course of three months, the AEL training resulted in gradual mean increases in the weekly monitoring variables of ISOM and jump height (SJ and CMJ) across all groups combined. No clear plateau was observed in strength or jump performance, suggesting the absence of a ceiling effect during the training period. At post-test, all physical performance variables displayed significant increases across all groups collapsed, thus the AEL exercise was effective in enhancing performance in maximum strength, power and strength endurance in already strength-trained participants. The relative mean increases in the outcome variable were generally less than what seen in previously untrained participants, which is typical for already resistance-trained populations following both AEL (Brandenburg and Docherty 2002; Walker et al. 2016; Maroto-Izquierdo et al. 2017; Douglas et al. 2018) and DCER resistance-training (Ahtiainen et al. 2003; Helland et al. 2017; Lopez et al. 2021) of similar duration. However, although the mean 9.3% relative increase in CONM across groups appears limited on a relative perspective, it corresponds to a significant absolute gain of 15.1 kg, resulting in a raw full squat averaging 177 kg at post-test, which is a notable improvement, especially for already resistance-trained participants.

Although three maximum AEL sessions per week appeared to be tolerated over the course of the intervention, we found no overall study dose–response effects, despite the large difference between groups in the total number of training sessions and thereby total training dose across the 12 weeks of intervention. Only one statistically significant beneficial surplus effect from increasing the frequency from one to two or three sessions per week was observed. Specifically, the CONM increased significantly more in participants who trained three times per week compared with those who trained once per week. Given the range of performance variables measured, this single between-group difference might also be attributed to the effects of repeated statistical testing. Consequently, on an overall basis, our findings do align with several previous studies on DCER training in untrained participants, which reported comparable strength increases when training one to three times per week with equal session doses (Graves et al. 1990; Pollock et al. 1993; Carroll et al. 1998; Burt et al. 2007; Serra et al. 2015, 2018; Barcelos et al. 2018; Van Vossel et al. 2023). This finding is on the other hand somewhat in contrast to the training frequencies normally used by elite strength athletes. For example, elite Olympic weightlifters often train the leg extensors 6–7 days a week (Crewther and Christian 2010; Storey and Smith 2012). Similarly, a survey of Norwegian powerlifters found that 90% of the athletes trained the squat three or more times weekly (Shaw et al. 2022). These examples highlight the prevalence of high-frequency training among elite strength athletes. In contrast, our data suggest that a weekly frequency between one to three sessions of intense AEL exercise yield similar improvements in muscular power, maximum strength, or strength endurance when the session doses are equal.

Several factors could explain this discrepancy compared with the training schedules of elite strength athletes. In contrast to the present study where each training session was equally intense, the training in elite athletes is normally periodized and may involve lifts that require less than maximal loads for the leg extensors, and which may thus benefit recovery between sessions (Storey and Smith 2012). In addition, although the participants in the study were resistance-trained, they were most likely not directly comparable to elite strength athletes for strength development. Additionally, it is possible that the 12-week study period may have been too short to induce systematic differences between the training groups. As seen in Fig. 4, the large heterogeneity in the outcome effects, combined with the moderate group sizes ($n = 7$–9) may also have rendered the study statistically underpowered to detect true differences between the groups. For the outcomes of SJ, CMJ and ISOM the study design by using a weekly assessment of jump height and ISOM may have introduced training effects in these variables, diminishing potential group differences. Although the total volume of these tests was marginal compared with the AEL training, we cannot rule out the possibility that the weekly tests biased the outcomes due to the specificity of training effects (Rasch and Morehouse 1957; Morrissey et al. 1995).

Muscle hypertrophy

For muscle hypertrophy, there was a 3.6% significant increase in QCSA across all groups pooled over the 12-week training period. This aligns with previous studies on AEL exercise in resistance-trained participants, which used MRI imaging to assess hypertrophy and similarly reported small increases in muscle ACSA (Brandenburg and Docherty 2002). However, the hypertrophy observed in the present study appears relatively large when compared with the marginal gains reported after a full year of training in elite weightlifters (Hakkinen et al. 1987), highlighting the diminishing returns for increasingly trained participants. Although there was no significant effect of training frequency on hypertrophic adaptations, the EX1 group did not exhibit significant increases in either QCSA or TCSA. This might suggest that training once per week may have been insufficient to optimize hypertrophy following AEL exercise. However, increasing the frequency to three sessions per week did not lead to significantly greater hypertrophic gains either, implying that three heavy AEL sessions per week may have exceeded the optimal training stimulus, potentially reaching a ceiling effect in these trained participants.

The lack of a clear frequency effect in our study is consistent with the mixed findings after DCER resistance training with equal session doses. For instance, Barcelos et al. (2018) found no significant differences in vastus lateralis CSA gains when training two, three, or five times per week. In contrast, Van Vossel et al. (2023) using a within-subject design, reported consistently greater muscle volume gains when training three times per week compared with two times per week. Additionally, a meta-analysis by Schoenfeld et al. (2019) found that, in previously untrained individuals, training two to three times per week resulted in greater hypertrophic gains than training once per week at an equivalent session volume. However, it should be noted that 10 of the 12 studies included in this meta-analysis were conducted on older, untrained adults (mean age range: 65–78 yr), limiting the generalizability of these findings to the trained participants in our study. The mean gains in the different strength tests (+9% to +14%) for our participants exceeded the hypertrophic increase in quadriceps ACSA (+3.6%), as further reflected by a significant improvement in specific quadriceps strength (AST:QCSA ratio) from 1.73 to 1.85 kg/cm^2. These results indicate that the major determinant of muscle strength development in the present study might be of neural origins, although it is possible that changes in muscle architecture may have explained some of the increases in strength (Aagaard 2003; Folland and Williams 2007). Additionally, we found no significant relationships between changes in neither muscle ACSA or fiber type proportions with changes in performance outcomes, further indicating that muscle hypertrophy and fiber type transformations have limited explanatory power for performance increases in the present study.

Muscle fiber type proportions

At baseline, the mean proportions of type 1, 2A, and 2AX/X muscle fibers were 51%, 40%, and 9%, respectively, consistent with previously published data from larger populations (Simoneau and Bouchard 1989). After the training period, the proportion of type 2A fibers in the vastus lateralis muscle increased significantly by 6 percent points across all participants. This change is comparable to findings from studies on DCER resistance training of similar duration (Andersen and Aagaard 2000; Terzis et al. 2008). In contrast, Friedmann-Bette et al. (2010) did not observe significant changes in fiber type proportions following AEL training. However, this discrepancy may be due to their shorter intervention period (6 wk), which could have been insufficient to elicit measurable shifts in fiber type composition. Generally, patterns of increased physical activity are associated with a downregulation of type 2X gene expression (Andersen and Gruschy-Knudsen 2018) and a shift toward slower fiber types (Blaauw et al. 2013). Conversely, detraining and inactivity typically lead to a shift toward a higher proportion of faster fiber types (Vikne et al. 2020). In alignment with the heterogeneity of training responses in the performance and hypertrophy variables, the changes in muscle fiber proportions varied considerable between individuals (Fig. 5). While part of this variability likely reflects true biological differences, a significant portion may stem from the inherent variability of the muscle biopsy technique itself (Lexell et al. 1985). Within-group increases in type 2A fiber proportions were significant in groups EX1 and EX3, but there were no significant differences between groups in mean fiber type changes, suggesting comparable training effects across conditions. Our findings align with those of Carroll et al. (1998) who reported no differences in relative MHC proportion changes between groups performing DCER training twice or three times per week. We, therefore, believe the lack of transformation towards the type 2A fibers in EX2 is likely due to random variation rather than being a true absence of an effect.

Since we observed only minor differences in strength, hypertrophy, and power between training with AEL one to three times per week at an equal session dose, a key implication is that athletes have considerable flexibility in structuring their resistance training programs. When the primary goal is to maximize muscle mass, strength, and power, training with AEL two to three times per week per muscle group may be advantageous. Conversely, during periods where other training modalities take priority, a single weekly session of AEL is likely sufficient to maintain strength and power performance.

Methodological limitations

Several methodological limitations should be considered when interpreting the results. First, as outlined in the methods section, the study did not control for or monitor additional sports training outside of the intervention. Specifically, some participants may have engaged in sports training that heavily involved the leg extensors, which could have influenced the outcomes. Second, the study did not systematically assess participants' prior leg extensor training frequency. As a result, it is possible that some participants increased or decreased their training frequency during the study, which could have introduced additional variability in the outcomes. During the intervention, several participants dropped out of the study, and a total of 23 completed the study (EX1 = 7, EX2 = 9 and EX3 = 7). The reduced number of participants that finalized the study may have reduced the statistical power and the ability to detect meaningful differences between groups. Furthermore, the randomization process was compromised due to one participant switching groups and two new participants being added to one group. This deviation from a fully randomized design may have impacted the study's internal validity.

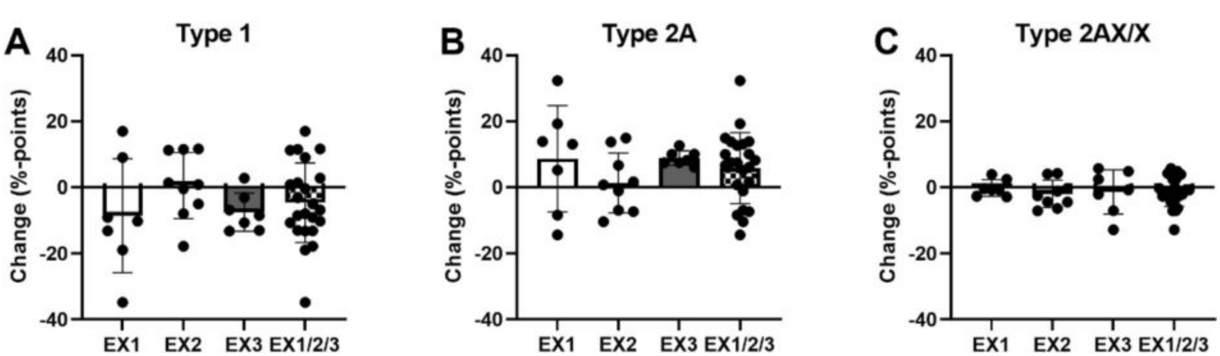


Fig. 5 Relative changes (percentage points) in fiber type proportions after training. The X-axes denote the different groups; EX1 is shown by unfilled bars, EX2 is indicated by grey bars and EX3 is shown by dark grey bars. All groups combined (EX1/2/3) is denoted by a checkerboard bar. The Y-axes are relative changes in percentage points. Bars are means ± SD and the individual changes are represented by the filled circles

Conclusion

In conclusion, twelve weeks of accentuated eccentric resistance training led to notable improvements in maximum strength, power, and muscle cross-sectional area in already well-trained athletes. These improvements were observed regardless of whether the athletes trained once, twice, or three times per week using the same session dose. These findings highlight a potential versatility in training frequency for athletes utilizing AEL exercise.

Author contributions

PER conceived the research idea. PER, HV, VJ and JIM designed the study. PER and VJ designed and built the exercise apparatus. PER, HV, JIM and AV conducted the examinations. PER and HV conducted the intervention. PER, HV and JIM analysed the data. HV wrote the manuscript. All authors reviewed and approved the paper except PER, in which a close family member read and approved the manuscript in his place.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon request for academic and research purposes.

Declarations

Conflict of interest The authors declare that they have no conflict of interest related to the present study. This study was funded by the Norwegian Olympic Sports Center, Oslo, Norway.

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