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Superiority of high-load vs. low-load resistance training in military cadets

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Brief running head: High-load vs. low-load resistance training

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Abstract

Muscle strength and power are important determinants of soldiers' performance in modern warfare. Here, we compare the efficacy of 22 weeks of whole-body resistance training with high load (HL, 10 repetitions maximum/RM) and low loads (LL, 30RM) for developing maximal muscle strength and power, performance, and muscle mass in moderately trained cadets (20 ± 1 years, f; n=5, m; n=22). Outcome measures were assessed at baseline and at week 22, in addition to a mid-intervention assessment at week 10. Twenty-two weeks of HL led to greater increases in muscle strength (upper limb, *Δ* 10%, 95% CI [2.8, 17.1], p=0.01;lower limb, *Δ* 9.9%, CI [1.1, 18.6], p=0.029), jump height (*Δ* 5.5%, CI [1.4, 9.6], p=0.011), and upper-limb lean mass (*Δ* 5.2%, CI [1, 9.4], p=0.018) compared to LL. HL and LL led to similar changes in agility, muscle endurance performance, lower-limb muscle mass, and cross-sectional area in *m.vastus lateralis*. For all variables, training-associated changes occurred primarily during the initial ten weeks of the intervention, including the differential responses to HL and LL. In conclusion, while 22 weeks of HL led to greater increases in lower- and upper-limb muscle strength, power, and upper-limb lean mass than LL, the two load conditions led to similar improvements in agility performance and lower-limb muscle mass. Our results thus indicate that both loading regimes elicit multifaceted physiological improvements important for military readiness.

Key words

military environment, resistance-training modalities, prolonged exercise, cadets

INTRODUCTION

Soldiers need to exhibit high aerobic fitness, muscular strength, and mental capabilities to ensure optimal performance during demanding operations (38). Military training programs thus need to target a large range of demands (15,38). Unfortunately, prevailing programs often focus on aerobic endurance training, and thereby largely fail to develop muscle strength and power, which are recognized as increasingly important components of modern military practice and warfare (15,17). At present, the best-practice resistance-training plan in the military setting is challenging to prescribe, as physical endeavors such as field exercises and deployments often complicate day-to-day predictability and consistency (38).

Progressive high-load resistance training is the primary approach for developing muscle mass, maximal strength, and power (36). In the military environment, it tends to improve physical capabilities such as strength, speed, power, and agility, accompanied by increased lean body mass (11,16,20), all of which are all imperative for a soldier's military performance (15). However, the benefits of resistance training are not consistently seen in the military setting (31,42). This lack of consensus may be related to a simultaneous focus on aerobic training, as well as the nature of military-training regimes, which typically include exhausting field operations, leading to a complex range of concurrent physiological stressors that may compromise specific adaptations (25,31). While this complexity emphasizes the importance of incorporating resistance training into the annual training routines of soldiers, allowing maintenance of physical capacity throughout the year (17,20), it also emphasizes the need for identifying efficient resistance training modalities that can be performed during deployments.

In recent years, the high-load paradigm of resistance training (>65% 1 repetition maximum; 1RM (28)) has been challenged (29,32). Alternative approaches such as low-load training (30-50% 1RM) to failure (7) have been associated with similar muscular responses, including both maximal strength (7,40) and muscle hypertrophy (18,24,34,39,40). Still, the scientific standing remains equivocal, with other studies reporting favorable effects of high-load training for developing both maximal strength (4,18,23) and muscle mass (4). These discrepancies may be related to differences in study characteristics, such as the participants' training status and the study's duration, with studies typically being performed over a short time frame (range 6-13 weeks). In addition, comparisons of high- and low-load protocols have generally targeted the lower-body limbs, and although there is evidence to suggest that differential load conditions affect lower and upper body muscle groups somewhat similarly (34,40), this may be sensitive to the exercise performed (14), and there are studies indicating that lower and upper body muscle groups respond differently to changes in training volume (26,30). Our current insight is hence limited to a few studies, with unclear response patterns, restricted to shorter periods of training (<13 weeks). Intriguingly, low-load training promises to be particularly beneficial for military personnel, as it seems suitable for maintaining and developing physical capabilities and resilience in settings where heavy-loading exercise equipment or training facilities are unavailable.

The purpose of the present study was to compare the efficacy of 22 weeks of whole-body resistance training with high (10 repetitions maximum/RM, HL) and lower loads (30RM, LL) for improving maximal strength and power, performance, and muscle mass in moderately trained cadets undergoing military training. Secondary aims included comparing the efficacies of the two loading conditions between upper and lower limbs.

METHODS

Experimental Approach to the Problem

The study was conducted using a randomized, repeated-measures, between-subject, parallel design. The resistance-training intervention lasted for 22 weeks (Figure 1A; September-March), whereby testing of maximal muscle strength, speed, muscle endurance performance and muscle mass were performed at three time points (Weeks 0, 10 and 22). At each of the time points, testing was organized into three test blocks, conducted at three separate days. Test day 1 included blood sampling and whole-body dual-energy X-ray absorptiometry (DXA-scan) followed by counter movement jump (CMJ), maximal isometric half squat (MIHS), one repetition maximum in three exercises, and a muscle endurance performance test. Test day 2 included an agility test. Test day 3 included muscle biopsy sampling (m. vastus lateralis; >48h after test day 2). One week prior to testing at week 0 (baseline), all participants conducted a familiarization session containing the entire battery of physical tests to reduce possible learning effects. All cadets tested approximately at the same time of the day (± 1-2h) to control for circadian variations. All tests were supervised by the same trained test personnel. All test sessions were monitored by personnel not otherwise involved in the study, meaning that all test personnel were blinded for training load allocation. Participants were instructed to refrain from performing any additional resistance-type training for the duration of the study. During week nine, participants conducted a 4-day weight-controlled dietary registration.

(Include Figure 1 here)

Subjects

Twenty-seven cadets (20 ± 1 years, 75.5 ± 12.9 kg, 182 ± 9 cm) from the 2nd year of the Norwegian Defense Cyber Academy volunteered for the study. Prior to enrollment, the cadets had conducted two weekly exercise training sessions throughout the last year as part of their Cyber Academy training program, consisting of exercises such as circuit training exercises, calisthenics, and high-intensity interval training. Cadets that had conducted systematic heavy resistance training (>2 sessions/week) during the last six months leading up to the study were not eligible for participation. The participants did not have any existing musculoskeletal injuries, were non-smokers, and did not report any use of anabolic steroids. Participants were pair-matched based on initial strength performance and then randomly allocated to either a heavy-load group (HL, male: 12, female: 2, 10RM) or a low-load group (LL; male: 10, female: 3, 30RM). The study was performed according to the ethical standards established by the Helsinki Declaration of 1975 and was pre-registered in a Norwegian public database (Norwegian Center for Research, project number 43901/3), and approved by the local Ethics Committee at Inland Norway University of Applied Sciences. All participants gave their informed consent before enrollment in the study. Baseline characteristics are shown in Table 1.

(Include Table 1 here)

Procedures

Resistance training

The resistance training intervention lasted for 22 weeks, and was conducted in two phases, separated by an obligatory three-week military leave. It was initiated by a 10-week period

(September to December), followed by a 9-week period from January to March. The training protocol consisted of three sets (2-3 min inter-set rest) of seven exercises per session, performed two days a week during the first 10 weeks (total 20 sessions) and increased to three days a week every other week during the last nine weeks (total 17 sessions). Every set was performed to concentric failure, i.e. the inability to perform another concentric repetition with proper form. Participants were instructed to continuously increase their RM load throughout the intervention period to ensure that they reached the state of failure towards the end of each series (39). Exercises were performed in the following order: squat, leg press, leg curl, bench press, standing rowing, seated pull-down, seated biceps curl. At the start of each resistance training session, participants performed a ~10 min general warm-up using a cycle ergometer (self-selected intensity). This was followed by specific warm-up during the first lower- (squat) and upper-body (bench press) exercise, consisting of 10 repetitions at ~30-50% of 1RM. During each exercise session, training loads and numbers of repetitions were registered for each exercise. The training sessions were supervised by experienced strength coaches to ensure proper technique and training progression. After each exercise session, participants consumed a standardized drink (30 g chocolate Whey protein powder, Proteinfabrikken, Norway) to ensure adequate protein intake for resistance-trained persons (1.3-1.8 $g \cdot kg^{-1} \cdot d^{-1}$).

Dietary intake and reporting of other training

To assess total energy intake and macronutrient intake, a 4-day (3 weekdays + 1 weekend day) weight-controlled self-reported food diary was conducted at week nine (Figure 1A). Participants were instructed to record all food items and respective portion sizes consumed during the designated time frame using a digital food weighing scale and a dietary journal. Dietary data were analyzed using the Norwegian Directorate of Health’s diet tool (available at www.kostholdsplanleggeren.no). Throughout the study, participants recorded all habitual endurance training performed outside the mandatory military training. During the entirety of the 22-week intervention, HL and LL performed a mere 9.3 ± 7.7 and 7.5 ± 7.3 hours (P=0.546), respectively, of additional endurance-oriented training. All participants conducted 1-2 weekly mandatory training sessions organized by the academy. These sessions had alternating training focus with a duration of 60 min. Typically sessions included aerobic training such as long-distance running (low intensity), marching with military gear (moderate intensity), combat conditioning (moderate intensity) and interval training (high intensity) or circuit-based calisthenics, core strength, coordination, and mobility sessions. All additional sessions were, if possible, conducted on weekdays with no resistance training. If additional exercise was conducted on the same day, at least >4 hours separated the sessions to minimize muscle adaptations interference (1).

Testing days

Hormonal, body composition and physical performance (Day 1)

Blood sample

Fasting blood samples for hormonal analyses were obtained from an antecubital vein using serum-separating tubes while participants rested in a supine position. At all three time points (baseline, 10 week and 22 week), samples were obtained at the same time of the day (between 08.00-10.00 AM). Blood samples were incubated for 30 min at room temperature before they were centrifuged at $1500g$ for 10 min. Serum was aliquoted and immediately transferred to -80° C for storage until analyses. Serum concentrations of total Testosterone (TESTO), Cortisol (COR), Insulin-like growth factor 1 (IGF-1) and growth hormone (GH) were measured using an Immulite 1000 analyzer (Siemens Medical Solutions Diagnostics, NY, USA), using kits from the Immulite Immunoassay System menu (Siemens Medical Solutions Diagnostics, NY, USA), performed according to manufacturer's protocols. Reference intervals were as follows; TESTO (8.0-35.0 nmol.L^{-1}), IGF-1 (17-63 nmol.L^{-1}), COR (138-690 nmol.L^{-1}), GH (< 0,5 µg/l). Coefficient of variation (analytic) for the analyses were TESTO 14%, IGF-1 9%, COR 14%, GH 6%.

Muscle mass and fat mass (DXA)

DXA-derived estimates for lean body mass and fat mass were obtained using the standard scanning mode 13-25 cm (Prodigy Advance PA+302047, Lunar, San Francisco, CA, USA). Participants were positioned supine within the marked lines on the scanning bed and a strap secured around the ankles to ensure standardized body position in each of the two followup scans, in accordance with the manufacturer. At all test time points the soldiers were scanned in a fasted state between 07.00-09.00 AM, wearing limited clothing (boxer-short and sports top) and no jewelry. Before onset of each scanning session, a phantom scanning was conducted to prevent baseline drifting from affecting analyses. The same technician conducted all tests. Analyzes were performed using GE enCORE version 17.0 software (GE Healthcare, Madison, WI, USA).

Physical testing

Physical performance was measured using four functional tests, performed in the following order: CMJ, MIHS, 1RM bilateral biceps curl, leg press and bench press, and muscle endurance performance. The test session started with 10 minutes of general warm-up on a cycle ergometer, with intensities equivalent to 10-12 on the 6-20 Borg Rating of Perceived Exertion Scale. CMJ was performed on a force plate (SG-9, Advanced Mechanical Technologies, Newton, MA, USA, sampling frequency of 1 kHz). Participants were instructed to place their hands on their hips and feet in shoulder width on the platform. Participants descended to a squat position of self-selected depth and immediately jumped upward as high as possible. If the third attempt resulted in the highest jump, an additional jump was performed. Thirty sec rest was given between each attempt. Participants were blinded to the results and the three best jumps were averaged, wherein the lowest jump were removed when >3 attempts were performed, and subsequently used in the data analyses (20). The coefficient of variation between test attempts averaged for all time points were 3.6% (SD 2.2, Range: 0.9, 11.7) for HL and 4.3% (SD 2.4, Range: 0.8, 9.9) for LL.

MIHS was conducted on the same force plate as CMJ using a custom-built rack bolted to the floor with an attached fixed bar located over the force plate. MIHS was measured in a half squat position with a knee angle equivalent to ~60-65°. Knee angle and foot position was marked on the rack and force plate, respectively, to ensure similar body position at the two consecutive test time points. Participants were given 3-4 attempts with 2 min rest between attempts. Verbal encouragement was given throughout test and the participants were instructed to push as hard and as fast as possible for 5 sec. The three highest force values were averaged and used in data analyses. For MIHS the coefficient of variation between test attempts averaged for all time points were 4% (SD 3.9, Range: 0.1, 14.5) for HL and 4.8% (SD 3.7, Range: 0.1, 14.5) for LL.

1RM tests started with a specific warm-up, consisting of two sets with gradually increasing load (40% and 75% of expected 1RM) and decreasing number of repetitions (10 and 6).

The first attempt was performed with a load approximately 5% below the expected 1RM. If a lift was successful, the load was increased by approximately 2-5%. Upper limb 1RM tests were performed using biceps curl and bench press. In the biceps curl participants were sitting on a curl bench, using an olympic-curl barbell starting with the elbows extended. An attempt was considered successful when the curl barbell was lifted to full elbow flexion with their seat kept in contact with the bench and feet touching the floor throughout the lift. Bench press was determined with the participants laying supine with their shoulders and hips kept in contact with the bench throughout the test and with their feet touching the floor. Attempts were considered successful when the barbell in a controlled fashion touched the chest during the eccentric phase and the elbows were fully extended at the end of the concentric phase. For the lower limb, 1RM was determined in the leg press. Participants were seated with knee and hip flexed at approximately 90°-96° and 45°, respectively. Individual knee angle depth was marked on the side rack to ensure similar knee position across test time points. A successful 1RM was defined as the maximal resistance that could be moved through the full range of motion with proper form one time. Participants made 3-4 attempts and were given 2 min rest between each attempt in the biceps curl, bench- and leg press. The best attempt was used in data analyses. For each participant, the same supervisor controlled the lifts, seating adjustments and body positions, and gave vocal encouragement in all strength tests, at all time points.

Muscle endurance performance was determined in the leg-extension exercise using a load corresponding to 60% of pre-test body mass. Participants were instructed to perform as many repetitions as possible to muscular failure with proper form. Cadence of repetitions was set to 2 seconds in both concentric and eccentric phase, which was controlled with a metronome. Participants were positioned with the lever arm two fingers proximal of the medial malleol, and the knee joint was aligned with the lever-arm axis. The test was terminated when the cadence was missed two consecutive times. The same absolute load was used at all test time points (Week 10 and 22). Maximal repetition was used for analyses.

Speed (Day 2)

Agility run time was measured using timing gates from a 3-point stance start position. The electronic timer (Brower Timing System, Utah, USA, 2013) started with participant's first movement. From the starting position, participants were given instruction to run to either the right or left (determined by coin flip) for 4.56 m and touch a line with the hand, reverse direction and run 9.1 m, touch an opposite line with the hand, and run back through the timing gate that recorded the elapsed time. Participants had two attempts in each direction (right and left sides). Two minutes of rest was given between trials and attempts were averaged for each direction and used in analyses.

Biological tissue sampling (Day 3)

Muscle micro biopsy.

A muscle specimen was obtained from *m. vastus lateralis* under local anesthesia (Xylocain, 10 mg ml-1, AstraZeneca AS, Oslo, Norway) using a fine needle (12g Universal-plus, Medax, San Possidonio, Italy) operated with a spring loaded biopsy instrument (Bard Magnum, Bard Nordic, Helsingør, Denmark). The first biopsy was sampled at one third of the distance from basis patella to anterior superior iliac spine, and subsequent biopsies were sampled two cm proximal/distal to the first incision. The tissue sample was quickly dissected free of connective tissue and blood in ice-cold sterile saline solution (0.9% NaCl), and fixated in formalin (~10 mg) for immunohistochemistry preparations.

Immunohistochemistry. Formalin-fixed muscle biopsies were processed for 2.5 h using a Shandon Excelsior ES (Thermo Scientific, USA), paraffin-embedded and sectioned into 4 µm. Transverse sections were double stained for determination of muscle fiber types BF-35 (5 µg x ml-1, Developmental Studies Hybridoma Bank, deposited by Schiaffino, S.) and MyHCSlow (1:4000, catalog M8421L, Sigma-Aldrich Norway AS, Oslo, Norway). The primary staining was identified by BMU UltraView DAB and UltraView RED (Ventana Medical System, Inc. Tucson, USA). Fiber types were counted as either type 1 (red; mean fiber count = 76.2, range =17-164), type 2A (brown; mean fiber count = 75.7, range = 15-223), type 2X (unstained; mean fiber count = 5.9, range = 1-22) or hybrid fibers type 2A/2X (light-brown; mean fiber count = 8.8, range = 1-30).

Statistical Analyses. Descriptive data are presented as mean and standard deviation (SD). Linear mixed-effects models (2) were used to estimate differences between treatment conditions. Relative changes from baseline for 1RM strength, muscle mass and performance variables were used as dependent variables and groups (HL vs. LL), and time as main fixed effects. Baseline values were used as a co-variate together with sex. Interaction term between conditions and time points were included as fixed effects, and models were specified with random intercept by participant. Estimated means and pairwise comparisons were computed with the contrasts function from the emmeans package for R (19), allowing interpretation of the direction and width of the 95% confidence interval (CI), indicating the magnitude of treatment effects and the certainty of the true population value (mean) (9). Additionally, Hedge's g effect size was calculated and interpreted as small 0.35-0.80, moderate 0.80-1.50, and large >1.5. Assumptions were checked by visual inspection of residual plots to assess uniformity of variance over the fitted range. Whenever deviations from the assumption were observed, data were log-transformed, and models were refitted. Weights functions was applied to fiber cross sectional area data to account for variances in standardized residuals across the fitted range (homoscedasticity). Weighted combined factors were calculated for muscle mass and muscle strength. For muscle mass, lean mass and cross sectional area were normalized to the highest value of the variables baseline test. Likewise, for muscle strength, upper limb combined factor included maximal strength in biceps curl and bench press and lower limb combined factor included leg press and maximal isometric in half squat. Subsequently, computed factors for each subject were calculated as the mean of the normalized values for each outcome variable. To measure specific strength, we used the DXA derived estimates calculated as the ratio between the weighted combined factor for upper and lower limb muscle strength and mass. All analyses were run in R (41). Significance level was set to $\alpha = 0.05$.

RESULT

Adherence to the protocol, training characteristics and dietary intake

Both HL and LL groups showed high degrees of adherence to the protocol, completing an average of 92% (SD 8) and 96% (SD 7) of the prescribed 37 resistance exercise sessions (range 29-37), respectively, with no difference between groups (P=0.172). HL was associated with a higher relative training load (75.5 %1RM, 95% confidence interval (CI): [71.7, 79.2] vs 50.8 %1RM, [47.2, 54.5], P<0.001) and a lower average training volume (load x repetitions per week) compared to LL (13687 kg, [12324, 15049] vs 25119 kg, [23720, 26518], respectively P<0.001) corroborating with previously observed differences between high-load and low-load training modalities performed to concentric failure (34).

Both training protocols led to marked increases in muscle strength and lean-body mass in upper and lower limbs over the course of the study, evident as 0.46 (SD 0.34) % and 0.76 (SD 0.56) % increases in muscle strength $\times$ training session^{-1}, respectively, and 0.17 (SD 0.17) and 0.10 (SD 0.13) % increases in lean mass $\times$ training session^{-1}, with muscle strength measures representing a pooled average for training modalities and muscle strength exercises. The efficacy was thus in the expected range of responses to resistance training in moderately trained individuals (34).

For both HL and LL, the average training-load per-session increased less for upper than for lower body exercises from baseline to week 10 (35 vs. 66%, respectively, P<0.001, group interaction; p=0.423, 0.262, respectively, Figure 1B), whereupon the elevated load was maintained to Week 22 (P=0.154 and P=0.976, respectively, group interaction; P=0.208, 0.186, Figure 1B). Furthermore, dietary intake of macronutrients (Range p-values: 0.203-0.616) and total energy (kcal, P=0.420) were similar in HL and LL at Week 9 (Table 1). HL and LL had similar blood levels of endocrine variables throughout the intervention (testosterone, IGF-1, GH, cortisol, no effects of time, Table 2).

(Include Table 2 here)

Comparing the effects of HL and LL on muscle strength, muscle mass and muscle fiber characteristics

For upper body limbs, 22 weeks of HL led to larger increases in muscle strength than LL (Figure 2), evident as larger increases in both 1RM in specific resistance exercises (Biceps curl, 9.1 % mean difference, 95% CI [0.1, 18.1], P=0.049; Bench press, 7.8 % mean difference, [1.6, 14.1], P=0.016) and as larger increases in muscle strength measured as a weighted combined muscle strength score (10% mean difference, [2.8, 17.1], P=0.010, ES [95% CI] 1.31 [0.28, 2.31]; Figure 2A). The more pronounced effects of HL were accompanied by greater increases in lean mass of the arms (5.2 % mean difference, [1, 9.4], P=0.018, ES: 0.99 [0.15, 1.81]; Figure 3A).

The benefits of HL in the upper body were manifested during the first phase of the training intervention for both muscle strength (baseline to Week 10: 10.3 % mean difference, [4.4, 16.1], P<0.001) and lean mass (5.3 % mean difference, [1.2, 9.3], P=0.013; Figure 2 and 3), with no differences being seen during the second phase (Week 10 to Week 22: -0.3 % mean difference, [-8, 7.4], P=0.938 and -0.1 % mean difference, [-3.4, 3.3], P=0.956, respectively; Figure 2 and 3). HL and LL led to similar improvements in specific strength (baseline to Week 22; 4 % mean difference, [-3.6, 11.6], P=0.275. Figure 3E), calculated as ratios between the weighted combined upper body muscle strength score and arm lean mass.

(Include Figure 2 and 3 here)

For lower body limbs, 22 weeks of HL led to larger increases in muscle strength measured as 1RM leg press than LL (14.7 % mean difference, 95% CI [3.9, 25.6], P=0.016; Figure 2), while the two training modalities led to similar improvements in MIHS (7.1 % mean difference, [-2.3, 16.5], P=0.130, Figure 2). After combining the two measures into a weighted muscle strength score, HL led to more pronounced increases in muscle strength (9.9 % mean difference, [1.1, 18.6], P=0.029, ES 0.87 [0.05, 1.68]; Figure 2B). The superior effect of HL seemed to accumulate gradually throughout the intervention, as no significant differences were observed between the groups during either of the two intervention phases (baseline to 10 weeks 6.7 % mean difference, [-1.6, 14.9], P=0.123, and 10 weeks to 22 weeks 3.2 % mean difference, [-1.2, 7.5], P=0.158, respectively; Figure

2B). For lower body limbs, HL and LL led to similar increases in markers of muscle mass, measured as both lean leg mass (1.3 % mean difference, 95% CI [-1.6, 4.1], P=0.374, ES 0.41 [-0.38, 1.19], Figure 3B), pooled muscle cross-sectional area (4.0 % mean difference, [-14.7, 22.7], P=0.656, no difference between groups in either fiber type; Figure 3C), and the weighted combined measure of lean leg mass and cross-sectional area (0.9 % mean difference, [-8.6, 10.4], P=0.845, Figure 3D), contrasting observations made for upper body limbs. Consequently, there seemed to be a decoupling of development of muscle strength and muscle mass between load conditions in the lower limb, with HL tending to induce more pronounced improvements in specific strength compared to LL, at least during the second phase of the intervention (9.6 % mean difference, [-0.8, 20.1], P=0.079, Figure 3E). HL and LL led to similar changes in muscle fiber proportions in *m. vastus lateralis*, with both leading to complete eradication of type IIX fibers (Table 3), presumably due to transition from IIX to IIA.

(Include Table 3 here)

Effects of HL and LL on muscle power, agility, and endurance

Twenty-two weeks of resistance training (HL and LL) led to improved performance in CMJ, agility and muscle endurance (time effect: P<0.001, P=0.0268, P=0.004, respectively; Figure 4). For CMJ, HL led to larger improvements than LL (5.5 % mean difference, 95% CI [1.4, 9.6], P=0.011, ES 0.60 [-0.20, 1.38]; Figure 4A), a phenomenon that was manifested during the first phase of the training period (baseline to Week 10, 5.2 % mean difference, [1.4, 9], P=0.012), with no additional advantage being observed during the second phase (Week 10 to Week 22, 0.3 % mean difference, [-3.2, 3.8], P=0.865). For agility and muscle endurance, no differences were observed between training modalities (Figure 4B-C).

(Include Figure 4 here)

DISCUSSION

To the authors' knowledge, this is the first study to compare the effects of prolonged whole-body resistance exercise training (>13 weeks) with high vs. low loads on muscle strength, performance, and biological characteristics in active military cadets. Briefly, for upper body limbs, HL led to greater increases in muscle strength and lean mass than LL. Similarly, for lower body limbs, HL led to more pronounced improvements in muscle strength and jump performance, though this was not the case for other outcome measures such as muscle endurance performance, agility, and measures of muscle mass (LBM and muscle fiber CSA), and muscle fiber composition, for which the two load conditions led to similar changes. Together, these data advocate high-load training as the preferred resistance training modality for young, moderately trained military cadets.

The observed differences between upper and lower body muscles underline the notion that different muscle groups can display differential responses to different training modes (22,26,30). This phenomenon is likely linked to differences in muscle properties, and potentially covaries with characteristics such as genetics, age, health, and training status (37,43). Indeed, these sources of variation may underlie the current lack of consensus for the effects of varying training variables such as load for development of muscle strength and mass (4,23,24,34), together with variation in study protocols (4,21,24,40). Notably, the present study protocol was conducted as part of a military training and education program, with the study population consisting of prospective soldiers. Hence, while the data provide insight into the effects of high- and low-load resistance training modalities that are generalizable to the overall population, they also provide insight into their specific efficacies in a military environment. For this purpose, our findings suggest that two weekly resistance training sessions are sufficient to increase strength and muscle mass in military cadets, in both upper and lower body, irrespective of training load. Resistance training thus seems to be a potent way of maintaining and developing muscle characteristics during military training programs, a perspective that is supported by a recent 15-week study (11). Importantly, the military setting is quite unique, and despite its potential drawbacks such as periods of exhaustive field exercises and military leave, it stands out as an intriguing model for exercise interventions. For example, as it offers remarkable standardization of variables such as nutrition (25), levels of physical activity, and circadian rhythm across study participants and groups (6), while also involving non-protocol stressors such as field exercises (17). In the present study, this likely reduced the potential negative impact of these confounding factors between the two groups, acting to improve the biological validity of training load-based interpretations, together with study design characteristics such as close supervision of every training session and blinding of test personnel to load conditions.

The superiority of HL for increasing muscle strength in both upper and lower-body limbs was evident by larger increases in specific 1RM muscle strength tests, as well as larger increases in weighted muscle strength, calculated from the weighted average of several measures of strength, as previously described (10). These benefits largely corroborate with conclusions from previous studies (4,18,23,34), including recent meta-analyses (29,32), though it contrasts conclusions from other studies (21,24,40). Of note, in one meta-analysis study, high-load training was found to lead to superior performance in RM-tests but not in maximal isometric tests (32), which was indeed also seen in the lower limbs in the present study. While this implies that some of the observed benefits of high-load training may be due to skill acquisition connected to performing training exercises that more greatly resemble test procedures (3,23), it also underlines the need for multiple strength measures to ensure proper estimation of the effects of any resistance training intervention on muscle strength performance (3). Of note, in the present study, both loading conditions led to increases in muscle strength irrespective of factors such as sex (no interaction; data not shown) and the concurrent performance of endurance-oriented training. Thus, albeit high-load training led to more pronounced strength responses, low-load training also led to marked improvements. Therefore, heavy-load training stands out as the preferred load modality for moderately trained cadets , supported by the moderate effect size of HL compared to LL, offering adaptational benefits while at the same time involving lower training volume and shorter duration of training, all of which are advantageous in a demanding military context with time restrictions (17). Still, low-load training is likely to offer valuable benefits to maintain operational readiness.

In contrast to the muscle strength results, HL did not offer universal benefits for increments in muscle mass compared to LL. Whereas HL led to more pronounced muscle mass accretion in upper limb, measured as arm lean mass, it offered no such benefits in lower limbs, measured as either lean leg mass, muscle fiber CSA of *m. vastus lateralis* or a combination thereof. In light of the universal benefits of HL for improving muscle strength, the muscle mass discrepancy may suggest a more pronounced decoupling between strength and muscle mass development in the lower limbs (i.e. that strength can be improved without increasing mass) (5), reflected by a less pronounced effect estimate between groups in lower-body muscle mass accretion. This is supported by a tendency for HL to lead to greater improvements in specific strength, potentially mediated by neuromuscular adaptations or factors such as changes in muscle morphology (i.e improved force transmission) (8).

The differential muscle accretion responses to the two load conditions between upper and lower limbs may have several explanations. First, it may be related to a pre-intervention difference in training status between the limbs. Indeed, upper body limbs are likely to be rather unstimulated in resistance training-naive individuals, as opposed to lower body limbs, which are necessary for everyday mobility. Adding to this, the military cadets had more than one year of academy-related training prior to the intervention, during which they conducted at least two training session per week, targeting primarily lower-limb muscles (i.e., circuit training, running, and marching). It is thus reasonable to speculate that tweaking other training variables, such as adding a higher training volume, may have been necessary to induce sufficient training stimuli for muscular adaptations to occur in the more trained lower body limbs (30). Based on this line of arguments and our observations, upper- and lower-body limbs represent two rather different experimental models that are likely to show differential responses to a given training stimuli. This is supported by findings in a previous study, where eight weeks of resistance training with heavy loading (90% 1RM) led to more pronounced muscle growth (and increases in strength) than lighter loading (70% 1RM) in the upper body but not in the lower body of resistance training-experienced men (22). Second, the observed differences between upper and lower limbs in the present study may have been a direct consequence of the concurrent aerobically-oriented training conducted alongside the study protocol. This may have compromised resistance training-related adaptations in the lower body limbs (44). Importantly, however, any such academy-related training was predominately conducted on separate days, ensuring at least 12 h between aerobic and resistance training sessions. This should have been enough to reduce its negative effects (1). Furthermore, it cannot be ruled out that lower limb muscles are more sensitive to periods of disturbed sleep and energy deficit, such as experiences during the field exercise, potentially activating molecular signaling pathways that are antagonistic to muscle protein synthesis and, therefore, leading to attenuated muscle mass and strength adaptations (12). Having noted this, all cadets were part of the same unit, and hence experienced similar stressors during the training intervention, making them less likely to have had an impact on group comparisons. Third, the difference in response to resistance training between upper and lower limbs may be related to inherent differences in muscle biology. For example, upper body muscle fibers (*m. trapezius*) have previously been shown to express higher densities of androgen receptors compared to lower body muscles fibers (*m. vastus lateralis*) (13). Albeit speculative, such biological differences may lead to differential responses to a given anabolic stimulus, mirroring a differential responsiveness to either mechanical stimulus (high-load training) or metabolic stimulus (low-load training) (27).

Initially, we anticipated any differences in the efficacy of high-load and low-load training protocols for developing muscle strength and mass to emerge towards the end of the intervention. While this is supported by the observed development of specific strength in lower body limbs, though without leading to differential responses over the course of the intervention, all other outcome measures deviated from our expectation. Indeed, for variables such as upper limb strength and upper limb lean mass, the time-course development showed the opposite relationship with time, with benefits of high-load training emerging during the initial phase of the intervention (Week 0 to Week 10). The causative explanation behind these observations is difficult to address thoroughly based on the present data. However, for the differential development of specific strength in the lower limbs, it seems plausible that the benefits of high-load training involved neuromuscular or structural adaptations (8), as previously discussed. As for the upper limbs, the benefits of high-load training involved simultaneous increases in muscle strength and mass, with no observable differences in the development of specific strength between load conditions. This suggests that the enhanced force-generating capacity was associated with greater muscle hypertrophy, with responses being more pronounced in the initial phase. Despite this, no associations were found between changes in muscle strength and muscle mass on an individual level, reiterating on the debated relationship between changes in muscle strength and muscle hypertrophy (5).

Limitations

In the present study, resistance training protocols were not volume-matched between groups (reps x load x set). As there is a dose-response relationship between resistance-training volume and increases in muscle strength and hypertrophy (33), this may have affected the outcomes. However, the significant larger volume load lifted in LL did not translate into superior muscular adaptations compared to HL, making our observations inversely related to the expected effects of increased training volume. Furthermore, the study did not include a negative control group, i.e, a group of cadets that did not conduct resistance training. While this should not have affected the ecological validity of our between-group comparisons, this cannot be ruled out, as standard military training with light loads and high velocities are known to be beneficial for muscle strength (11,14), and may interact with HL and LL stimuli in different manners.

In conclusion, 22 weeks of high-load resistance training led to more pronounced improvements in upper limbs muscle strength and lean mass compared to low-load resistance training in moderately trained cadets. Similar benefits of high-load training were seen for lower limb muscle strength and jump performance, but not for other lower limb characteristics such as muscle endurance performance, agility, measures of muscle mass (lean mass and muscle fiber cross-sectional area in *m. vastus lateralis*) and muscle fiber composition (*m. vastus lateralis*). Overall, the benefits of high-load training were manifested during the initial ten weeks of training. Although further interventions are needed to establish the full benefits of resistance load in challenging military contexts, our data provide evidence for high-load training as being the preferred resistance training modality for in-training prospective soldiers. Still, low-load training is likely to offer a valuable asset for soldiers during extreme circumstances such deployed operations, when high-load resistance-training may not be feasible.

PRACTICAL APPLICATIONS

Based on the current data, it is apparent that incorporating resistance exercises into the weekly training routines of military personnel, as previously suggested (11,16,20), can yield significant benefits. In addition to augmenting muscle strength, endurance, and mass, these exercises contribute to enhancements in jump height and agility performance. These aspects are particularly pertinent as they align with well-established evaluation protocols that hold relevance for military-specific tasks (35). Comparing the impact of high-load and low-load training, it becomes evident that high-load training produces more noticeable effects on muscle strength and mass, particularly in the upper body. Nevertheless, it's important to note that both training modalities yield considerable improvements. Notably, the viability of low-load training emerges as an attractive option for soldiers, especially in scenarios where access to heavy exercise equipment or training facilities is restricted, such as during deployment or field exercises. This underscores the potential suitability of low-load calisthenics exercises as a viable substitute. However, given the paramount importance of maximal strength and power in enhancing soldiers' performance in operational settings, it is advisable to capitalize on the advantages of high-load training whenever feasible.

It's worth mentioning that the findings from this study are likely transferrable to other populations of moderately trained individuals, thus broadening the scope of applicability beyond just military personnel.

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Figure Legends

Figure 1. A) Time-line of the study, including overview of measurements performed at baseline and at week 10 and week 22, a three-week military leave, a two-week military field exercise, and a dietary survey (Week 9). Prior to baseline testing, familiarization to all physical test protocols were conducted. DXA, scan for body composition; Blood, blood sampling; CMJ, counter movement jump; MIHS, maximal isometric half squat; 1RM, 1 repetition maximum; END, muscle endurance performance; Agility, running time; Biopsy, muscle sample from *m. vastus lateralis*.

B) Relative increases in training load from week 1 to week 2, week 10 and week 22 for upper limb (exercises combined; seated pull down, standing rowing, bench press, biceps curl) and lower limb exercises (squat, leg press, leg curl) in HL and LL. Data are mean ± 95% CI.

Figure 2. Effects of high-load (HL) and low-load (LL) resistance training on muscle strength in upper-and lower body exercises. A) Muscle strength in Upper body exercises combined (weighted average of 1RM biceps curl and bench press; left panel) and in specific exercises (right panel). B) Muscle strength in lower-body exercises combined (weighted average of 1RM leg press an maximal isometric half squat) and in specific exercises. Values are estimated means ± 95% CI. In both A and B, differences between groups are presented as weighted percent point mean difference (Δ HL - Δ LL; means ± 95% CI; left panels).

Figure 3. Effects of high-load (HL) and low-load (LL) resistance training on markers of muscle mass in upper- and lower body limbs. A, B) Lean body mass in upper- (A) and lower-body limbs (B), shown as group specific estimated means (left panel) and as differences between groups (right panels). C) Cross-sectional area of muscle fiber types I and II in *m. vastus lateralis*, shown as group-specific estimated means (left panel) and as differences between groups (right panel). D) Weighted combined measure of markers of lower-body muscle mass (lean mass and muscle fiber CSA), shown as changes from baseline (left panel) and as differences between groups (right panel). E) Specific strength in upper (weighted muscle strength per lean mass) and lower limbs (weighted muscle strength

per weighted muscle mass), shown as percent changes from baseline to weeks 10 and 22, and as differences between groups (right panel). Group-specific estimated means are shown as mean ± 95% CI. Differences between load conditions (groups) are shown as mean percentage point difference ± 95% CI (ΔHL - ΔLL).

Figure 4. Effects of high-load (HL) and low-load (LL) resistance training in muscle performance measured as counter movement jump (A), agility (B), and muscle endurance performance (C). Data are presented as groups-specific estimated means (estimated means ± 95% CI; left panel) and as differences between groups (mean percent point difference ± 95% CI; Δ HL - Δ LL).

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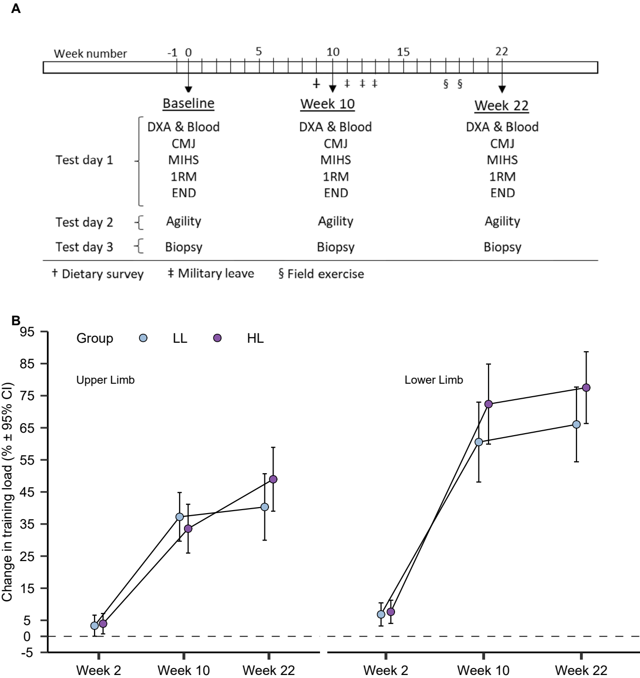
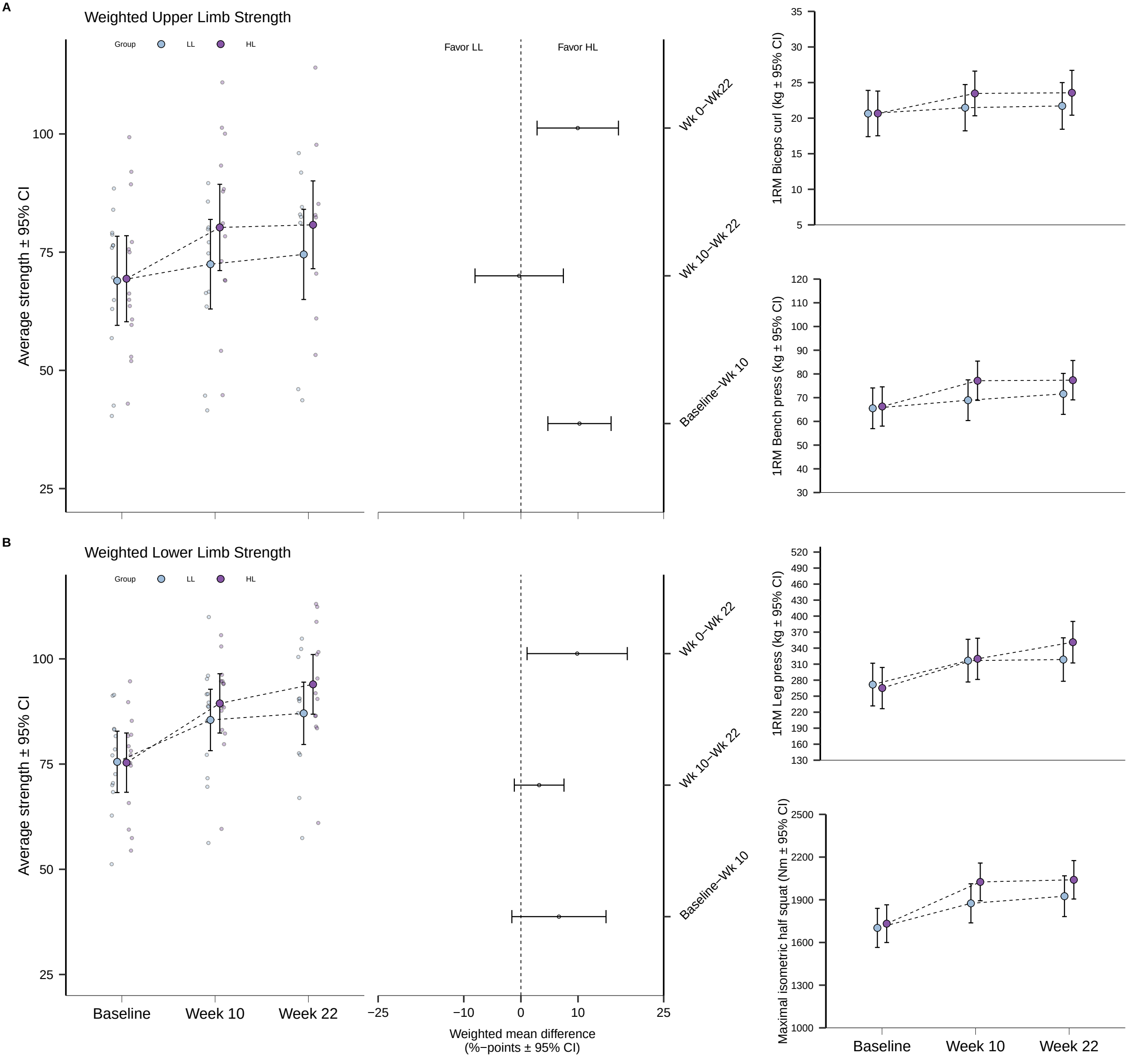
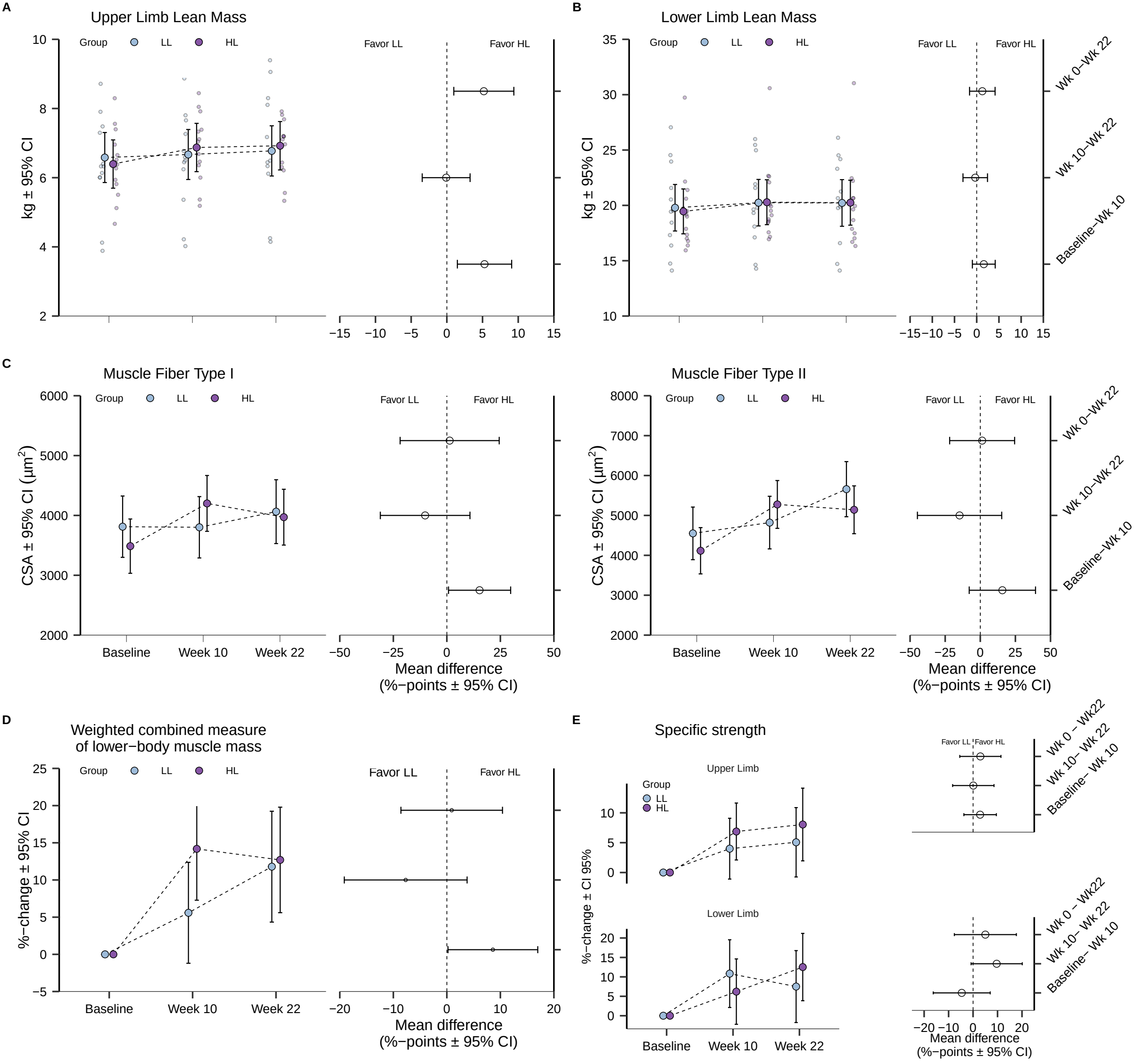

A
Week number
-1
0
5
10
15
22
†
‡ ‡ ‡
§ §
Baseline
Week 10
Week 22
Test day 1
DXA & Blood
CMJ
MIHS
1RM
END
Test day 2
Agility
Test day 3
Biopsy
† Dietary survey
‡ Military leave
§ Field exercise
B
Group
LL
HL
Upper Limb
Lower Limb
Change in training load (% ± 95% CI)
95
85
75
65
55
45
35
25
15
5
0
-5
Week 2
Week 10
Week 22
Week 2
Week 10
Week 22


A
Weighted Upper Limb Strength
Group
LL
HL
Average strength ± 95% CI
25
50
75
100
Favor LL
Favor HL
Wk 0–Wk22
Wk 10–Wk 22
Baseline–Wk 10
1RM Biceps curl (kg ± 95% CI)
5
10
15
20
25
30
35
1RM Bench press (kg ± 95% CI)
30
40
50
60
70
80
90
100
110
120
B
Weighted Lower Limb Strength
Group
LL
HL
Average strength ± 95% CI
25
50
75
100
Wk 0–Wk 22
Wk 10–Wk 22
Baseline–Wk 10
Baseline
Week 10
Week 22
−25
−10
0
10
25
Weighted mean difference
(%−points ± 95% CI)
1RM Leg press (kg ± 95% CI)
130
160
190
220
250
280
310
340
370
400
430
460
490
520
Maximal isometric half squat (Nm ± 95% CI)
1000
1300
1600
1900
2200
2500
Baseline
Week 10
Week 22


A
Upper Limb Lean Mass
Group
LL
HL
kg ± 95% CI
10
8
6
4
2
Favor LL
Favor HL
−15
−10
−5
0
5
10
15
B
Lower Limb Lean Mass
Group
LL
HL
kg ± 95% CI
35
30
25
20
15
10
Favor LL
Favor HL
−15
−10
−5
0
5
10
15
Wk 0−Wk 22
Wk 10−Wk 22
Baseline−Wk 10
C
Muscle Fiber Type I
Group
LL
HL
CSA ± 95% CI (μm²)
6000
5000
4000
3000
2000
Baseline
Week 10
Week 22
Favor LL
Favor HL
−50
−25
0
25
50
Mean difference
(%−points ± 95% CI)
Muscle Fiber Type II
Group
LL
HL
CSA ± 95% CI (μm²)
8000
7000
6000
5000
4000
3000
2000
Baseline
Week 10
Week 22
Favor LL
Favor HL
−50
−25
0
25
50
Mean difference
(%−points ± 95% CI)
Wk 0−Wk 22
Wk 10−Wk 22
Baseline−Wk 10
D
Weighted combined measure
of lower−body muscle mass
Group
LL
HL
%−change ± 95% CI
25
20
15
10
5
0
−5
Baseline
Week 10
Week 22
Favor LL
Favor HL
−20
−10
0
10
20
Mean difference
(%−points ± 95% CI)
E
Specific strength
Upper Limb
Group
LL
HL
10
5
0
Lower Limb
20
15
10
5
0
%−change ± CI 95%
Baseline
Week 10
Week 22
Favor LL
Favor HL
Wk 0 − Wk22
Wk 10− Wk 22
Baseline− Wk 10
Wk 0 − Wk22
Wk 10− Wk 22
Baseline− Wk 10
−20
−10
0
10
20
Mean difference
(%−points ± 95% CI)

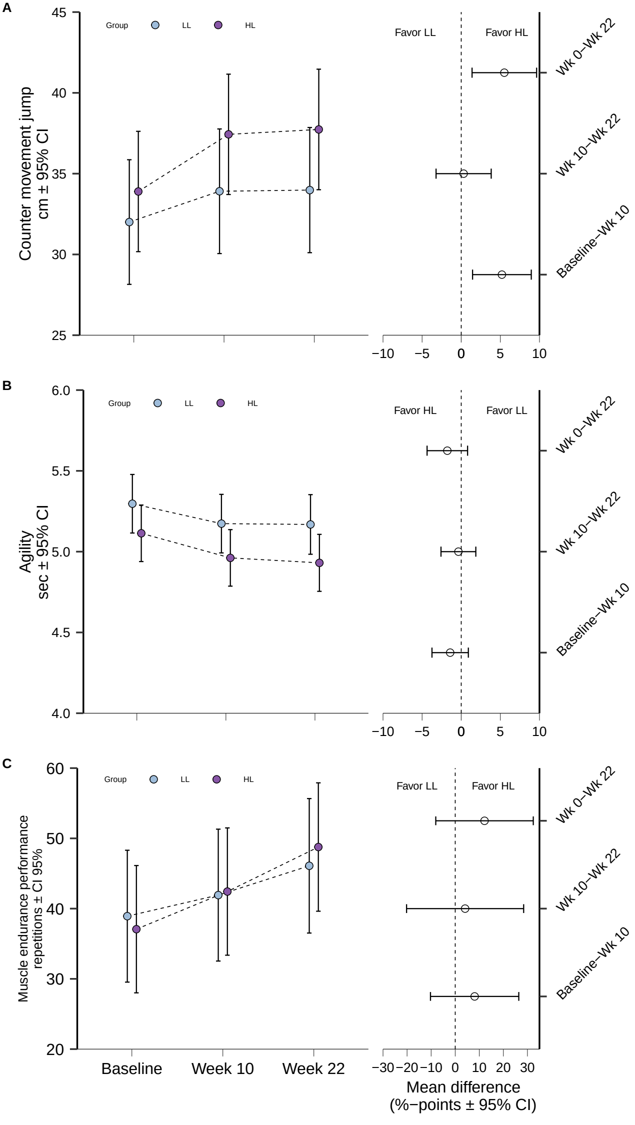

A
Group
LL
HL
Counter movement jump
cm ± 95% CI
45
40
35
30
25
Favor LL
Favor HL
Wk 0–Wk 22
Wk 10–Wk 22
Baseline–Wk 10
−10
−5
0
5
10
B
Group
LL
HL
Agility
sec ± 95% CI
6.0
5.5
5.0
4.5
4.0
Favor HL
Favor LL
Wk 0–Wk 22
Wk 10–Wk 22
Baseline–Wk 10
−10
−5
0
5
10
C
Group
LL
HL
Muscle endurance performance
repetitions ± CI 95%
60
50
40
30
20
Favor LL
Favor HL
Wk 0–Wk 22
Wk 10–Wk 22
Baseline–Wk 10
Baseline
Week 10
Week 22
−30
−20
−10
0
10
20
30
Mean difference
(%−points ± 95% CI)

Table 1 Participants characteristics and energy intake. Data are mean ± (SD)

		High-load		Low-load	
		Female (n=2)	Male (n=12)	Female (n=3)	Male (n=10)
Baseline	Age (year)	20.6 (1.1)	20.8 (0.7)	21.4 (0.4)	21.0 (1.0)
	Stature (cm)	171.0 (1.4)	183.1 (5.0)	173.5 (5.9)	186.2 (10.9)
	Body mass (kg)	67.6 (7.2)	75.4 (12.2)	71.5 (16.5)	79.2 (12.6)
	Fat mass (kg)	18.2 (6.8)	14.6 (6.3)	22.8 (8.0)	15.7 (6.5)
	Lean body mass (kg)	46.9 (0.2)	57.7 (6.3)	46.0 (8.6)	60.2 (8.6)
Week 10	Body mass (kg)	67.7 (4.5)	76.9 (12.1)	70.6 (15.5)	79.9 (12.3)
	Fat mass (kg)	16.9 (6.0)	14.0 (6.2)	21.9 (7.4)	15.0 (6.2)
	Lean body mass (kg)	48.2 (1.7)	59.8 (6.4)	46.0 (8.7)	61.6 (8.7)
Week 22[a]	Body mass (kg)	66.6 (3.5)	76.8 (11.7)	61.9 (5.3)	81.1 (11.2)
	Fat mass (kg)	15.6 (4.8)	14.0 (5.5)	17.7 (6.3)	15.0 (6.1)
	Lean body mass (kg)	48.4 (1.5)	59.7 (6.6)	41.8 (0.9)	62.8 (7.9)
		kcal day^{-1}	CHO kg^{-1} day^{-1}	Protein kg^{-1} day^{-1}	Fat kg^{-1} day^{-1}
HL	Energy[b]	2633.7 (867.6)	4.3 (2.1)	1.8 (0.7)	1.4 (0.5)
LL		2686.2 (1023.1)	4.1 (1.8)	1.6 (0.7)	1.4 (0.6)

[a] High-load: male n = 11, Low-load: female n = 2, male n = 9

[b] Data from dietary survey

Table 2 Hormone measurements

	Sex	High-load			Low-load		
		Baseline	Week 10	Week 22	Baseline	Week 10	Week 22
Testo (nmol l^{-1})	Female	0.8 (0.1)	0.7 (0.1)	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)
	Male	13.2 (2.7)	14.5 (2.3)	12.2 (2.5)	12.7 (3.1)	12.4 (2.3)	12.1 (3.6)
IGF-1 (nmol l^{-1})	Female	29.1 (5.5)	24.6 (8.1)	27.8 (8.6)	27.3 (6.3)	25.0 (7.3)	24.5 (2.6)
	Male	23.6 (6.0)	20.9 (4.5)	22.5 (4.3)	26.4 (6.7)	23.1 (4.0)	22.7 (4.5)
GRH (µg l^{-1})	Female	2.2 (2.8)	3.4 (4.7)	2.1 (2.6)	2.5 (2.1)	6.8 (7.5)	1.4 (0.6)
	Male	0.2 (0.1)	0.2 (0.4)	0.1 (0.1)	1.4 (2.9)	0.5 (1.0)	0.1 (0.0)
Cortisol (nmol l^{-1})	Female	629.0 (97.6)	539.5 (111.0)	484.5 (48.8)	483.7 (169.5)	516.7 (66.1)	465.5 (391.0)
	Male	395.3 (106.8)	382.1 (93.1)	310.8 (111.3)	378.2 (123.4)	369.1 (115.4)	287.6 (89.9)

Testo = Testosterone, IGF-1 = Insuling growth factor, GRH = Growth hormone, data are means ± (SD)