DR LACHLAN JAMES (Orcid ID : 0000-0002-0598-5502)

Article type : Original Article

The impact of strength level on adaptations to combined weightlifting, plyometric and ballistic training

Lachlan P. James[1,2], G. Gregory Haff [3], Vincent G. Kelly [1,4], Mark Connick[1], Ben Hoffman[5], Emma M. Beckman[1]

[1]*School of Human Movement and Nutrition Sciences, The University of Queensland, Brisbane, QLD, Australia*

[2]*Discipline of Human Movement and Sports Science, Federation University, Ballarat, VIC, Australia*

[3]*Centre for Sport and Exercise Science Research, Edith Cowan University, Perth, WA, Australia*

[4]*Brisbane Broncos Rugby League Football Club, Brisbane, QLD, Australia*

[5]*School of Health and Wellbeing, University of Southern Queensland, Toowomba, QLD, Australia*

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Corresponding author:

Lachlan Peter James

Human Movement and Sports Sciences

Federation University

Australia, 3353

+61 424 411 682

lp.james@federation.edu.au

ORCID identifier is 0000-0002-0598-5502

ABSTRACT

The purpose of this investigation was to determine if the magnitude of adaptation to integrated ballistic training is influenced by initial strength level. Such information is needed to inform resistance training guidelines for both higher- and lower-level athlete populations. To this end, two groups of distinctly different strength levels (stronger: one-repetition-maximum (1RM) squat = 2.01 ± 0.15 $kg \cdot BM^{-1}$; weaker: 1.20 ± 0.20 $kg \cdot BM^{-1}$) completed 10 weeks of resistance training incorporating weightlifting derivatives, plyometric actions and ballistic exercises. Testing occurred at pre-, mid- and post-training. Measures included variables derived from the incremental-load jump squat and the 1RM squat, alongside muscle activity (electromyography), and jump mechanics (force-time comparisons throughout the entire movement). The primary outcome variable was peak velocity derived from the unloaded jump squat. It was revealed that the stronger group displayed a greater (P = 0.05) change in peak velocity at midtest (baseline: 2.65±0.10 $m \cdot s^{-1}$, midtest: 2.80±0.17 $m \cdot s^{-1}$) but not posttest (2.85±0.18 $m \cdot s^{-1}$) when compared to the weaker participants (baseline 2.48 ±0.09, midtest. 2.47 ±0.11, posttest: 2.61 ±0.10 $m \cdot s^{-1}$). Different changes occurred between groups in the force-velocity relationship (P=0.001–0.04) and jump mechanics ($P \leq 0.05$), while only the stronger group displayed increases in muscle activation (P=0.05). In conclusion, the magnitude of improvement in peak velocity was significantly influenced by pre-existing strength level in the early stage of training. Changes in the mechanisms underpinning performance were less distinct.

Keywords: electromyography, jump squat, resistance training, athletic performance, neuromuscular, power

INTRODUCTION

It is understood that maximal impulse-related expressions (quantified by measures such as velocity, force, power and impulse itself), supported by maximal strength, are the most important muscular functions driving athletic performance (1), and are characteristic of higher-level competitors across a number of sports (2-5). Ballistic exercises are commonly used to develop these qualities (6) and are therefore of great interest to sports scientists and physical preparation coaches. These tasks are characterised by an acceleration that continues throughout the entire range of motion (i.e. weightlifting actions), often resulting in the athlete or object they are accelerating entering free space (i.e. plyometric activities and jump squats). It is theorised that a training plan incorporating all of these ballistic modalities under a variety of loads is the ideal strategy, as it allows for enhancement throughout the force-velocity spectrum and a superior transfer of training (7). Furthermore, greater variation in these factors (i.e. loading conditions, modalities and movement patterns) is considered advantageous as training experience and strength level increases (8, 9). Yet, despite its common use by coaches at the elite level (10-12), little is known about the adaptations to such a program design in stronger and weaker individuals.

It is hypothesised that stronger individuals possess neuromuscular adaptations that form the foundation for an enhanced response to ballistic resistance training (1). Of note, stronger individuals would generally possess greater neural drive (13), myofibrillar cross sectional area (14) and superior intermuscular coordination (9). As a result, such individuals are in the later stages of the sequence of events that lead to enhanced maximal ballistic expressions (15, 16). Indeed, cross-sectional investigations have consistently found higher maximal impulse capabilities in those who are stronger (5, 17-21). However, the notion of superior adaptive ability amongst these individuals is in contradiction to the principle of diminished returns (22) caused by a history of resistance training, commonplace in those who are strong. The influence of strength level on the ability to enhance high velocity capabilities is of particular relevance to a number of sports as maximal strength varies between athletes of differing competition levels (5, 23, 24). If an interaction between these factors is present then differing training strategies would be required for developmental and lower-level athletes compared to those at a higher level. However, there is limited research into this notion, with the few experimental investigations comparing the adaptations of stronger and weaker individuals to a ballistic power training intervention failing to produce definitive results (22, 25, 26). It is possible that the limited variation of the training stimulus (i.e. ballistic exercise selection and loading conditions) in these studies reduced the potential to optimise adaptations in the stronger participants.

Taken together, despite sound theoretical underpinnings, the experimental evidence available has failed to show significantly greater adaptations to ballistic training in stronger versus weaker individuals. Furthermore, because of the limited variation in these programs it is not known whether the adaptations to an integrated approach, such as those commonly found in high-performance settings, would be influenced by initial strength level. As the basis for these theorised preferential adaptations to high velocity training amongst stronger individuals is a more favourable neuromuscular profile (1), it is of particular interest to also investigate the changes in neural activation and movement mechanics responsible for the performance adaptations. It is therefore the purpose this study to compare performance changes alongside force-velocity, neural and force-time responses to an integrated ballistic training plan between stronger and weaker individuals. Peak velocity was chosen as the primary outcome variable due to its highly influential contribution to athletic performance (27). It is hypothesised stronger individuals will display more rapid adaptations to such training, underpinned by alterations in muscle activation, movement mechanics and the force-velocity relationship. Identifying the changes in the most important muscle functions across a multitude of sports that result from this stimulus will have a major impact on training practices in sport. Furthermore, if differing responses are revealed between the two groups then training interventions can be better tailored according to the physiological composition or development status of the individual.

MATERIALS AND METHODS

Experimental design

Two groups of distinctly different lower-body strength levels (relative 1RM squat) undertook the same 10-week integrated ballistic training plan for the lower-body. This prescription was divided into two 5-week training blocks with loading conditions and exercise selection based on the principles of periodization. Participants attended a single day testing battery at three separate occasions during the study (baseline, mid and post). Familiarisation for all testing and training techniques occurred across three 1 hour sessions before baseline testing. Measures derived from the incremental-load jump squat, in addition to strength level and muscle activation were obtained.

Participants

Individuals who were male, uninjured and could competently perform a back squat were recruited from the university and surrounding community, resulting in 24 recreationally active males who undertook baseline testing. Subjects were then ranked in accordance with their relative 1RM squat performance. To establish two groups of distinctly different strength levels, the 8 middle ranked participants were eliminated. This resulted in a stronger (n = 8; BM = 76.82 ± 6.27; height = 1.72 ± 0.48m; 1RM squat = 2.01 ± 0.15 $kg \cdot BM^{-1}$, resistance training experience = 4.0 ± 1.31y) and weaker (n = 8; BM = 82.03±14.7; height = 1.83± 0.68m; 1.20 ± 0.2 $kg \cdot BM^{-1}$; resistance training experience = 1.38 0 ± 0.92y) strata, thereby enabling between group comparisons.

Such a methodology has been previously used to form stronger and weaker groups for similar purposes (25). Participant characteristics over the duration of the study are presented in Table 1. Written, informed consent was secured from all participants and the study was approved by the Bellberry Human Research Ethics Committee, Australia.

Training program

Before undertaking training, participants completed three 1 hour instructional sessions delivered by the primary investigator, who is certified with both the Australian Strength and Conditioning Association and the National Strength and Conditioning Association. These sessions included detailed coaching on all training and testing activities until proficiency was achieved. The training plan included three supervised 1 hour sessions each week over two 5 week blocks separated by 1 week to allow for mid-testing. Workouts were at least 24 hours apart and consisted of weightlifting derivatives, ballistic tasks and plyometric exercises using a variety of loads. Training emphasis shifted across blocks towards increased loads for weightlifting derivatives and a decrease in loading for jump squat actions, in addition to the incorporation of complex plyometric exercises. Specifically, during the first block training involved five sets of five repetitions of the power clean and jump squat on day 1 and 3. The power clean was performed with 70% 1RM, while the jump squat was performed with 40 and 50% squat 1RM on day 1 and 3 respectively. On day 2 the hang power clean (55% of the power clean 1RM) and snatch grip pull (70% of the power clean 1RM) were undertaken across four sets of five repetitions. During day 1 and 3 of the second block the loading of the jump squat was reduced to 0% (day 1) and 30% (day 2), while the power clean was increased to 85% 1RM for four reps across five sets. Additionally, subjects performed the depth jump from a 0.30 m box using the following sets and repetition scheme: Week 6 – 3 x 3, Week 7 – 3 x 4, Week 8 - 4 x 4, Week 9 and 10 - 5 x 4. Day 2 of the second block saw an increase in load for both the hang power clean and snatch grip pull to 70% and 85% 1RM (of the power clean) respectively across five sets of four repetitions. In addition to this, day 2 included a plyometric rebound split squat for four sets of three repetitions on each side. Weightlifting derivatives were encouraged to be performed with maximal intent, while ballistic and plyometric actions were executed with the goal of maximizing height. Furthermore, during the unloaded jump squat, participants were provided with immediate visual and audible peak velocity feedback for each jump (GymAware, Kinetic Performance Technology, Canberra, Australia). Three minutes of recovery was prescribed between each set. Subjects performed a general dynamic warmup at the beginning of each session (consisting of a series of squat, lunge and submaximal ballistic actions) and a series of warmup sets at progressively increasing loads before each exercise. No additional lower-body training was permitted for the duration of the study.

Testing overview

Testing sessions were undertaken at week 0 (pre), after week 5 (mid-training) and after week 10 (post-training). Post-training testing occurred no earlier than 7-days after the last training session in week 10, and no later than 10 days after, on the basis of the fitness-fatigue model (25). A week without training was allocated following the first block of training allowing for mid-testing to be conducted 3-5 days after the final session of week 5. Each assessment session commenced with the 1RM squat. The jump squat with an additional load representing 0% of 1RM (no added weight), +20%, +40%, +60% and +80% of 1RM was undertaken in a non-randomised order to determine maximal neuromuscular related variables. Finally, the isometric squat at a knee angle of 140 degrees was then administered. Simultaneous kinetic (force plate) and electromyography (EMG) readings were gathered during the session for selected tests.

Data acquisition procedures

1RM squat

A general, followed by a specific dynamic warm-up was undertaken before the administration of the 1RM squat. Trials were then performed until a 1RM was established, with each attempt separated by 5-minutes of passive recovery (25). A squat depth to an internal knee angle of <85 degrees of flexion as assessed by 2-dimensional motion analysis was considered a successful attempt (stronger: baseline = 82.13±2.42°, mid-test = 81.31± 2.90°, post-test = 80.5±2.33°; weaker: baseline = 79.63± 5.15°, mid-test = 81.00±3.63°, 80.75±2.49°). Data was captured by a Logitech HD Webcam (model C270, recording at 30fps) positioned 1.5 m to the right of the performer and 0.40 m above the ground. Processing occurred via Kinovea, (V0.8.15, www.kinovea.com).

Jump squat

Trials were conducted at a series of ascending relative loading conditions (+0% of 1RM, i.e. no additional weight, +20%, +40%, +60%, and +80% of the individuals' 1RM). Participants were instructed to perform a minimum of two non-continuous countermovement jump squats for maximal height utilising a countermovement to a depth resulting in an internal knee angle of 85° (Kinovea, V0.8.15). The jump containing the highest peak velocity in each loading condition was used for analysis. Three minutes of passive recovery was allowed between each set.

All jump squats were performed on a force plate (Bertec Corporation, Columbus, OH, USA) with the data sampled at 2000 Hz via a data acquisition device (NI USB-6259 BNC, National Instruments) and processed using a custom LabVIEW program (V.12.0f3, National Instruments) and saved offline for secondary processing. Vertical ground reaction force (Fz) provided direct measures of force applied to the system. A forward dynamics approach was used via the impulse-momentum relationship to assess velocity of the centre of gravity, while the product of force and velocity at each time point represented power. Peak velocity, force, power and acceleration was defined as the greatest instantaneous sample of the respective variable during the action before take-off. The velocity and force that occurred at peak power in each condition was also established to enable construction of force-velocity curves. The integral of force with respect to time for the values exceeding system weight during the jump represented impulse. Average power and velocity were calculated from the bottom of the countermovement (zero velocity) to take-off, while rate dependent measures of force and power were calculated between the respective minimum and maximum values throughout the movement. Force, impulse, power, rate of force development and rate of power development were divided by system mass to be expressed in relative terms. Variables were calculated during secondary processing via a custom designed Matlab program (The Mathworks, Inc., Natick, MA).

Isometric squat

After a 10-minute passive recovery, participants undertook an isometric squat in a modified power rack secured over the force plate. Subjects were positioned with a knee angle of 140 degrees and were instructed to apply maximal force ‘as hard and as fast as possible’ into the immovable bar for 3-seconds. The maximal force value attained during the effort was considered force at zero velocity. Strong verbal encouragement was delivered throughout.

Muscle activation

Simultaneous surface EMG of the vastus lateralis (VL), VM (vastus medialis) and biceps femoris (BF) on the right leg was acquired during the jump squat, in addition to the isometric squat. Before placing the EMG electrodes on the site, a razor was used to shave any hair from the skin. Following this the site was then lightly abraded and cleaned to ensure the best quality signal from the underlying muscles of interest. A bipolar electrode configuration was used whereby two stick-on electrodes were placed on the skin slightly distal to the middle of belly for each of the three muscles. To ensure consistent placement across testing sessions, the location of the electrodes and other landmarks on the leg were traced on to a closefitting elastic garment. To further aid in this process, multiple images of the locations were taken. A 16-channel wireless EMG system (MYON 320, Myon AG, Schwarzenberg, Switzerland) was used and this data was sampled and saved with the same equipment and parameters as for the force data above. Data were processed using a 6th order Butterworth bandpass filter of 50 – 300 Hz. The EMG signal over a 1-s period of continued maximal force production following the initial peak during the isometric squat was isolated to perform a root mean square (RMS) with a 50ms window. This generated the maximal voluntary contraction (MVC) for all measured muscles. To establish EMG activity during the jump squat, the RMS of the EMG signal from the initiation of the eccentric phase until take off was calculated then divided by the time to take off. This was then expressed relative to the MVC. Rate of EMG rise (RoR) was calculated as the rate of increase from the minimum to maximum RMS EMG. These EMG procedures are analogous to those used in earlier investigations of muscle activity during jumping (25, 28).

To directly compare force-time curves throughout the jump, individual trials were resampled to an equal number of frames. This was achieved by adjusting the time delta between each sample to achieve 300 samples from the initiation of the countermovement until the participant left the force plate (The Mathworks, Inc., Natick, MA). Consequently, these 300 samples represented 0 – 100% of normalized time allowing for point-by-point comparison of force characteristics throughout the action (25, 28).

Statistical analysis

Following confirmation of normality, a repeated measures general linear model was used in conjunction with a post-hoc Bonferroni adjustment to locate any differences between groups. An Alpha level of $P \leq 0.05$ denoted statistical significance. A power analyses revealed that for a statistical power of 80% to be attained, a minimum of 8 participants per group was needed. To establish practically relevant differences between means, ES calculations were employed with thresholds set at <0.2, 0.21-0.5, 0.51-0.8 and >0.8 for trivial, small, moderate and large magnitudes of effect, respectively. Data is presented as mean ± standard deviation. Statistical Package for Social Sciences (Version 23.0, IBM Corporation, Somers, New York, USA) was utilized to analyse non-magnitude based data, while ES were calculated using a custom designed spreadsheet (Microsoft Excel 2013, Microsoft Corporation, Washington, USA).

RESULTS

Transfer to athletic performance (0% jump squat, 1RM squat)

All participants across both groups completed 100% of the required training and testing sessions. The stronger group possessed a significantly greater 1RM squat than the weak group across baseline (stronger: 2.01 ± 0.15 $kg \cdot BM^{-1}$, weaker: 1.20 ± 0.2 $kg \cdot BM^{-1}$, $P < 0.001$), mid (stronger: 2.06±0.20, weaker: 1.36±0.16 $kg \cdot BM^{-1}$, $P < 0.001$) and postest (stronger: 2.04±0.23, weaker: 1.43± 0.15 $kg \cdot BM^{-1}$, $P < 0.001$).An improvement in this measure was attained by weaker participants at mid- and post-test ($P < 0.001$; ES at mid-test = 0.84; ES at post-test = 1.10), while the stronger group's performance remained unchanged. This resulted in a significantly different change between groups at mid- ($P = 0.03$) and post-test ($P = 0.01$). Both groups improved across a number of jump variables (Figure 1, Figure 2, Table 2). Of note, the stronger participants displayed a significantly greater change in peak velocity at mid-test than the weaker group. Any significant changes at post-test across velocity and power variables were already present at mid-test amongst the stronger group. In contrast, the weak subjects produced changes in these variables at post-test only. A significant decrease in force at peak power was displayed at post-test in the stronger participants, while both groups revealed a significant increase in impulse at mid- and post-test (Table 2).

Impact on the force–velocity relationship

Training resulted in changes to the force-velocity and force-power (Figure 3) relationship from baseline in both groups. Following a clear rightward and upward shift (to increased values) of the force-velocity relationship at mid-test in the stronger group, there was a notable regression to lower values under higher-force conditions at post-test. Conversely, the weaker participants displayed a gradual increase in the contributions of both force and velocity across all time points throughout the loading spectrum. These factors resulted in a greater magnitude of increase in velocity at peak power in the stronger participants at mid-test. In contrast to this, at multiple points throughout the curve the weak group produced a significantly greater magnitude of change in force, particularly at the final testing point. Accordingly, a similar pattern was found in the force-power interaction (Figure 3). In particular, a more pronounced elevation of this curve (to increased peak power values) can be seen in the stronger group at mid-test when compared to the weak participants. This resulted in a significantly greater magnitude of change in peak power in the high-force portion of this curve (80% 1RM jump squat condition) at the mid-test point when compared to the weak group. However, at post-testing the weaker subjects displayed a continued shift of this relationship to increased peak power values, while a general depression occurred amongst the stronger participants between the mid- and final testing point.

Electromyography

No significant differences were present in the change between groups for normalised Average RMS EMG or RoR across any of the measured muscles. However, the stronger group displayed a significant increase from pre to post training in VL rate of EMG rise. No other significant changes occurred in either group after training, however a number of practical changes existed in both groups (Table 3). Effect size changes in average RMS EMG and RoR were greater across VL and BF in the stronger group at mid- and post-test.

Jump mechanics

At mid-test, stronger participants displayed significant changes from 17.5% to 25% and 48.0% to 72.5% of normalized jump duration. Significant alterations amongst the weaker group at this timepoint were revealed from 19.5% to 25% and 72.5 to 78% of normalized jump duration. After training the stronger group had significant changes from 3.5% to 27.5% and 41.5 to 68% of normalized jump duration. At this timepoint the weaker group achieved significant changes from 14.5% to 29.5%, 42% to 61% and 83% to 90.5% of normalized jump duration. Figure 4 presents these results in graphical form.

DISCUSSION

This study revealed that a ballistic training plan incorporating a variety of modalities, movement patterns and loading conditions elicited a significantly different performance and mechanistic response between stronger and weaker participants over a 10-week training period. This is of great relevance as such training plans are commonplace in sporting settings (10, 11), and both strength level and high velocity capabilities are often characteristic of superior athletes in a given sport (5, 6, 23).

Adaptations in athletic performance

When the extent of improvements were compared between the two groups, those who were stronger displayed preferential adaptations to the training stimulus. Alongside a significantly superior increase in peak velocity after only 5 weeks, the stronger participants displayed significant improvements at this time-point across all velocity based variables (peak velocity, average velocity and jump height). Following this, the magnitude of improvement across many performance measures was not markedly different from mid-test values after 10 weeks. In contrast, the weaker group did not achieve significant improvements in these measures until 10 weeks. To the authors' knowledge, this present investigation is the first to report a statistically greater improvement in a primary outcome measure in stronger versus weaker individuals following ballistic training. In large part this can be attributed to the design of the training intervention, whereby a spectrum of loading conditions, weightlifting derivatives and plyometric actions were included, resulting in a potent stimulus for adaptation.

The reduced positive adaptations between 5 and 10 weeks in the stronger group was likely a consequence of an inhibition in the development of force producing capabilities. This is indicated by a significant loss of force at peak power after training, resulting in a significantly different change from the weaker group. Furthermore, stronger participants displayed only trivial changes in peak dynamic force upon completion of the study (ES: -0.17), while the stimulus produced a large effect (ES: 1.04) in this variable amongst the weaker group. As stronger individuals generally undertake regular heavy strength training, the cessation of additional lower-body resistance training for the duration of the study was likely responsible for this response. This highlights the importance of maintaining heavy strength training throughout a training plan, even in those who are already strong and seek to improve high velocity expressions. Similar findings have been reported when stronger individuals were exposed to jump squat training with 0% and 30%1RM loads (25). However, the findings of this present investigation also suggest that despite the inclusion of high force actions throughout the intervention (i.e. power cleans and snatch grip pulls at 70-85% of the power clean 1RM), force losses during ballistic-only training still occur in stronger individuals. While training had little impact on the magnitude of dynamic force production in the strong group, these data suggest that it was the temporal aspects of performance that were most notably influenced. This can be seen by the significantly greater improvement in the velocity at peak power than the weaker participants. Because of the limited change in dynamic force and controlled depth (internal knee angle of 85 degrees), such improvements are likely a result of a reduced movement time. In addition, significant increases in the rate at which force was produced (RFD) was present in the stronger group at mid-test, while the weaker participants displayed no significant changes in this variable. Such temporal based factors driving performance enhancement in the stronger group is in alignment with previously reported mathematical modelling of power development (15, 16).

Another notable finding is the greater ES increases in average velocity and average power with respect to their peak (instantaneous) variants, and is in contrast to what is previously reported in the literature for single modality training interventions (25, 28). This is particularly pronounced for power whereby the magnitude of increase in average power (Stronger: ES = 1.01; Weaker: ES = 0.77) was approximately twice that of peak power (Stronger: ES = 0.55; Weaker ES = 0.31) at mid-test. As instantaneous variables in this study are representative of 1/2000th of a second epoch, it can be argued that the average values provide a better indication of the characteristics of the entire movement. Although an instantaneous velocity will determine the precise spatio-temporal outcome of a technique, in the case of power it may be more advantageous to produce higher average levels than peak. This is because the work done occurs over a period of time, rather than an instant. For example, decisive actions in sport occur across epochs of 100 to 250ms (29, 30) because they require force to be expressed over some distance for a brief period of time. What may be responsible for the differences in peak and average values is the variety of movement patterns the subjects were exposed to in this study. As peak velocities and powers often occur at different body positions dependent on the lift performed, this present training intervention provided an effective stimulus for improved performance throughout the action, rather than a single point.

Mechanistic adaptations

Force-velocity relationship

Training resulted in contrasting shifts of the force-velocity and force-power relationships between groups. This is most notable in the significantly greater improvements to force at peak power under multiple higher-force conditions by the weaker participants. As a result, there was a progressive rightward translation of the curve (to increased force) over the duration of the study. In contrast to this, the stronger group exhibited significantly increased velocity capabilities at both extremes of the force-velocity relationship at mid-test. However, there was a general regression to lower values throughout the curve between 5 and 10 weeks of training, indicating that a decay of strength occurred. Accordingly, a significantly greater increase in peak power produced under loaded conditions was attained by the stronger group at 5 weeks, while this newly attained value was reduced at post-test. These findings are similar to previous reports of somewhat different force-velocity responses between high and low strength individuals exposed to a ballistic training intervention (25). Taken together, this suggests that the ability of an individual to operate in different force-velocity environments following training is influenced by initial strength capabilities.

Muscle activation

The aforementioned improvements in expressional timing can at least be partly explained by the significant enhancement of intra-muscular activation rates (VL RoR) amongst the stronger group. This is in contrast to the weaker participants who displayed no significant changes. Furthermore, when effect sizes are examined, stronger individuals also displayed a practically greater magnitude of change at post-test across all measured muscles for both RoR and AvRMS. Although the procedures in this present investigation cannot determine the contribution of motor unit firing frequency or recruitment to this increased muscle activity, previous research has reported extremely large increases in motor unit firing frequency following ballistic training (31). However, further research is required to determine how strength level influences these contributions to muscle activation following such a training stimulus. Increases in muscle activation during a sports-specific movement have been reported alongside improvements in expressions of power and velocity (25, 28, 32-35). Low load (thus high velocity) jump training has resulted in increases in RoR in both strong and weak individuals previously (25). The lack of clear response in this measure amongst the weaker subjects in this present study may be a reflection of the combined high-force/high-velocity stimulus of the intervention causing more general adaptations in this group. As training induced neural responses differ between a high force and high velocity stimulus (28), it can be expected that when these stimuli are combined there would be a more broad change in these neural measures than would occur in an isolated loading condition. Although the stronger group were exposed to the same training, this represented a more velocity dominant stimulus to these participants (as indicated by the aforementioned changes to their force-velocity relationship). This is consistent with findings of increased jump squat RoR in response to low load ballistic training, while only changes in maximal muscle activation in an isometric squat were experienced in response to heavy strength training (28).

Jump mechanics

In order for strength to translate into improved jump performance, the control of force must be optimized (36). The normalized jump force-time curves provide valuable information on the characteristics of force application throughout the movement, and therefore explain how jump performance was achieved. At mid-test, stronger individuals displayed an increased unweighting (drop into the countermovement, before active lengthening). This led to greater eccentric forces and attainment of peak force earlier in the jump, with no change in its magnitude. These changes are similar to the distinguishing jump characteristics of higher- versus lower-level strength-power athletes (37). While there were little further changes to the second half of the jump (active lengthening and concentric phases) at post-test in this group, there was a continued improvement in unweighting (i.e. a greater reduction of force upon initiation of the countermovement, prior to active lengthening) at the beginning of the jump. Weaker participants achieved improvements in similar phases of the jump, however the epochs were considerably smaller. This indicates that while both groups improved their ability to utilize the stretch shortening cycle, this was achieved to a greater extent by the stronger group in the early stages of training. However, these improvements continued through post-test in the weaker participants resulting considerably greater forces that were achieved earlier in the jump compared to mid- and pre-test.

PERSPECTIVE

The present results reveal that the development of maximal velocity based expressions is influenced by pre-existing strength level, with greater early stages improvements experienced by those who are stronger. The mechanisms driving the changes in performance are also different between groups, with neural, force-velocity and mechanical adaptations characteristic of improvements in maximal velocity in those with already high levels of strength. This is in contrast to the weaker group who displayed more general adaptations to training (shifts of both force and velocity alongside moderate changes in the magnitude and rate of muscle activation). These findings are of great value to training practices as they reveal that it is advantageous for individuals to attain a high level of strength before emphasising plyometric, weightlifting derivatives and ballistic training. However, those who are stronger should not remove heavy strength training, as the decay of force producing capabilities likely limited improvements, particularly after 5 weeks. The results of this study might also have important implications for technical training. As many technical factors are dictated by velocity also (27, 38), the findings of this investigation provide evidence that those who are stronger may more quickly respond to technical training.

ACKNOWLEDGEMENTS

LPJ was supported through an Australian Postgraduate Award (APA) Scholarship. The authors would like to thank Associate Professor Glen Lichtwark for his input.

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Figure Legends

Figure 1. Change in peak velocity, average velocity and jump height in the 0% 1RM jump squat between groups at mid-test (A) and post-test (B).

$^{\Omega}$ Significantly different magnitude of change from the weak group (≤ 0.05). ** Significant change from baseline at ≤ 0.01.

Figure 2. Change in peak power, average power and peak force in the 0% 1RM jump squat between groups at mid-test (A) and post-test (B).

*Significant change from baseline at ≤ 0.05. ** Significant change from baseline at ≤ 0.01.

Figure 3. A. Change in the force-velocity relationship between groups and across time points. Measurement points represent the jump squat with 0, 20, 40, 60, 80 and 100% of the one-repetition-maximum back squat. $^{\Omega\Omega}$ Significantly different magnitude of change from the alternate group (≤ 0.01). $^{\Omega}$ Significantly different magnitude of change from the alternate group (≤ 0.05). *Significant change from baseline at ≤ 0.05. ** Significant change from baseline at ≤ 0.01. **B.** Change in the force-power relationship between groups and across time points. $^{\Omega}$ Significantly different magnitude of change from the alternate group (≤ 0.05). *Significant change from baseline at ≤ 0.05. Only significant changes with respect to peak power are indicated. Significant changes in force at peak power are indicated in Figure 3A.

Figure 4. Changes in the normalized force-time curve for the 0%1RM jump squat in the stronger (A) and weaker (B) groups. *Significant change from baseline to mid-test at ≤ 0.05. $^{\delta}$Significant change from baseline to post-test at (≤ 0.05).

Table 1: Participant characteristics

	BM (kg)	IsoSquat/BM (N/kg)	Peak Velocity (m/s)	Average Velocity (m/s)	Jump height (m)
Stronger group					
Baseline	76.82 ±6.27	38.37 ±6.77	2.65 ±0.10□	1.34 ±0.10□	0.33±0.04□
Midtest	77.49 ±6.06	41.94 ±6.20*	2.80 ±0.17**Ω	1.51 ±0.14**	0.38 ±0.05**
Posttest	77.55 ±5.94	41.14 ±5.06	2.85 ±0.18**	1.52 ±0.11**	0.37 ±0.04**
Weaker group					
Baseline	82.04 ±14.07	34.63 ±5.13	2.43 ±0.09	1.20 ±0.12	0.26± 0.01
Midtest	82.26 ±14.37	36.56 ±6.68	2.47 ±0.11**	1.26 ±0.08**	0.28 ±0.02**
Posttest	82.24 ±14.88	39.23 ±5.41*	2.61 ±0.10**	1.35 ±0.06**	0.30 ±0.02**

** Significant change from baseline ($P \leq 0.01$). * Significant change from baseline ($P \leq 0.05$). Ω Significantly greater change from baseline compared to the weaker group. □Indicates significant difference from the weaker group at baseline ($P \leq 0.01$) BM: Body mass. Velocity and jump height measures are derived from the unloaded jump squat.

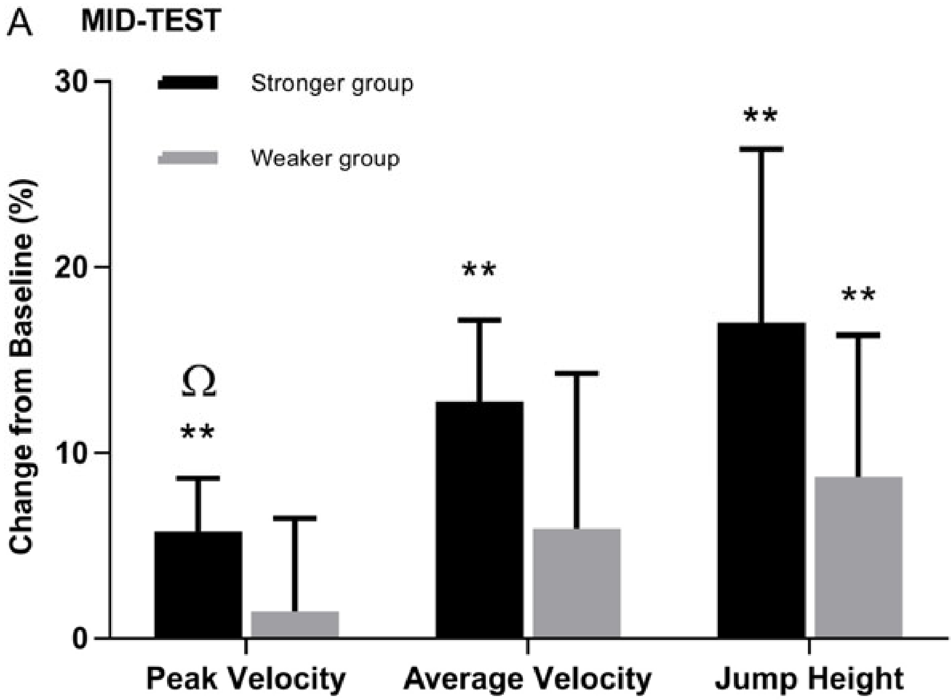
Table 2. Magnitude of change from baseline for performance variables derived from the 0% 1RM jump squat condition.

	Stronger Group	**Weak Group**
Velocity	Change from baseline (ES, ±95%CI)	Change from baseline (ES, ±95%CI)
Change at mid-test		
Peak ($m{\cdot}s^{-1}$)	0.15 (0.99, 0.64 to 1.35)**$^{\Omega}$	0.03 (0.35, 0.11 to 0.59)
Average ($m{\cdot}s^{-1}$)	0.17 (1.14, 0.85 to 1.43)**	0.06 (0.60, 0.18 to 1.02)
At Peak Power ($m{\cdot}s^{-1}$)	0.17 (1.13, 0.75 to 1.52)**$^{\Omega}$	0.02 (0.28, 0.27 to 1.47)
Change at post-test		
Peak ($m{\cdot}s^{-1}$)	0.21 (1.18, 0.72 to 1.63)**	0.17 (1.35, 0.64 to 2.05)**
Average ($m{\cdot}s^{-1}$)	0.18 (1.28, 0.78 to 1.79)**	0.15 (1.25, 0.60 to 1.89)**
At Peak Power ($m{\cdot}s^{-1}$)	0.23 (1.30, 0.81 to 1.79)**	0.15 (1.28, 0.52 to 2.04)**
Force		
Change at mid-test		
Peak ($N{\cdot}kg^{-1}$)	0.79 (0.35, -0.63 to 1.33)	0.81 (0.79, 0.24 to 1.33)
At Peak Power ($N{\cdot}kg^{-1}$)	-0.44 (-0.35, -0.98 to 0.28)	0.24 (0.31, 0.07 to 0.36)
Net Impulse ($m{\cdot}s^{-1}$)	0.49 (1.20, 0.85 to 1.56)**	0.34 (1.15, 0.35 to 1.70)**
RFD ($N{\cdot}kg{\cdot}s^{-1}$)	28.94 (1.07, 0.45 to 1.68)**	12.62 (1.00, 0.31 to 1.70)
Change at post-test		
Peak ($N{\cdot}kg^{-1}$)	-0.24 (-0.17, -0.83 to 0.48)	1.55 (1.04, 0.08 to 2.00)
At Peak Power ($N{\cdot}kg^{-1}$)	-0.88 (-0.68, -1.19 to -0.17)*$^{\Omega\Omega}$	0.52 (0.57, 0.05 to 1.08)
Net Impulse ($m{\cdot}s^{-1}$)	0.77 (1.58, 1.25 to 1.91)**	0.65 (1.51, 1.14 to 1.89)**
RFD ($N{\cdot}kg{\cdot}s^{-1}$)	25.76 (1.20, 0.68 to 1.72)**	29.99 (1.34, 0.65 to 2.04) **
Power		
Change at mid-test		
Peak ($W{\cdot}kg\text{-}^{1}$)	2.5 (0.55, 0.06 to 1.05)	1.05 (0.31, 0.10 to 0.53)
Average ($W{\cdot}kg\text{-}^{1}$)	4.06 (1.01, 0.62 to 1.40)**	1.67 (0.77, 0.24 to 1.31)
RPD ($W{\cdot}kg{\cdot}s^{-1}$)	62.62 (1.07, 0.45 to 1.68)**	25.88 (0.87, 0.27 to 1.48)
Change at post-test		
Peak ($W{\cdot}kg\text{-}^{1}$)	2.69 (0.54, 0.15 to 0.92)*	4.06 (1.13, 0.59 to 1.67)**
Average ($W{\cdot}kg\text{-}^{1}$)	2.98 (0.90, 0.48 to 1.32)**	3.37 (1.31, 0.74 to 1.88)**
RPD ($W{\cdot}kg{\cdot}s^{-1}$)	36.18 (0.69, 0.20 to 1.18)	50.97 (1.29, 0.51 to 2.07)**

$^{\Omega}$ Significantly different magnitude of change from the weak group (≤ 0.05). $^{\Omega\Omega}$ Significantly different magnitude of change from the weak group (≤ 0.01). *Significant change from baseline at ≤ 0.05. ** Significant change from baseline at ≤ 0.01. ES: Cohen's *d* effect size. CI: Confidence interval.

Table 3. Magnitude of change from baseline for electromyography (EMG) measures derived from the 0% 1RM jump squat condition. Magnitude is expressed as Cohen's *d* effect sizes (ES) and respective classification. CI: Confidence interval. RMS: Root mean square. VL: vastus lateralis. VM: vastus medialis. BF: biceps femoris.

	Stronger Group		**Weak Group**	
Average RMS EMG	ES (±95%CI)	Classification	ES (±95%CI)	Classification
Change at mid-test				
VM	0.31 (-0.28-0.89)	Small	0.17 (-0.42-0.76)	Trivial
VL	0.53 (-0.25-1.31)	Moderate	0.42 (-0.32-1.15)	Small
BF	0.38 (-0.08-0.84)	Small	0.36 (-0.25-0.96)	Small
Change at post-test				
VM	0.42 (-0.10-0.95)	Small	-0.12 (-0.79-0.54)	Trivial
VL	0.72 (-0.04-1.40)	Moderate	0.65 (-0.33-1.62)	Moderate
BF	0.68 (-0.01-1.36)	Moderate	0.54 (-0.05-1.13)	Moderate
Rate of EMG rise				
Change at mid-test				
VM	0.07 (-0.58-0.72)	Trivial	0.25 (-0.33-0.82)	Small
VL	0.59 (-0.23-1.41)	Moderate	0.41 (-0.40-1.22)	Small
BF	0.42 (-0.16-1.0)	Small	0.23 (-0.38-0.84)	Small
Change at post-test				
VM	0.16 (-0.40-0.73)	Trivial	0.08 (-0.49-0.65)	Trivial
VL	0.81 (0.15-1.46)*	Large	0.57 (-0.44-1.59)	Moderate
BF	0.64 (0.07-1.21)	Moderate	0.46 (-0.06-0.98)	Trivial


A MID-TEST
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Change from Baseline (%)
Stronger group
Weaker group
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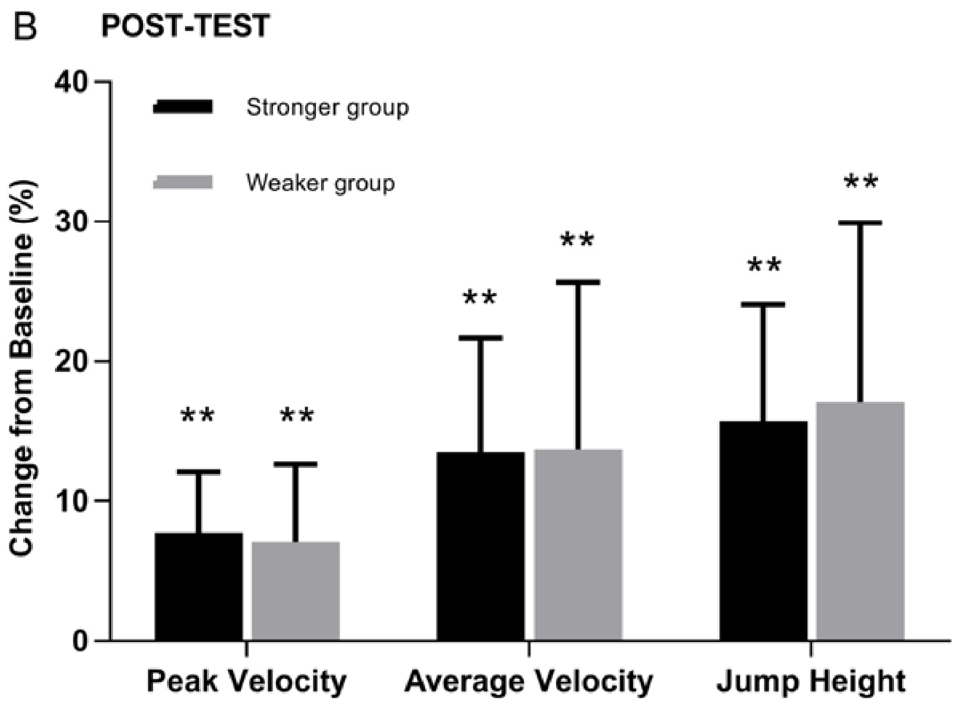
Peak Velocity
Average Velocity
Jump Height


B POST-TEST
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Stronger group
Weaker group
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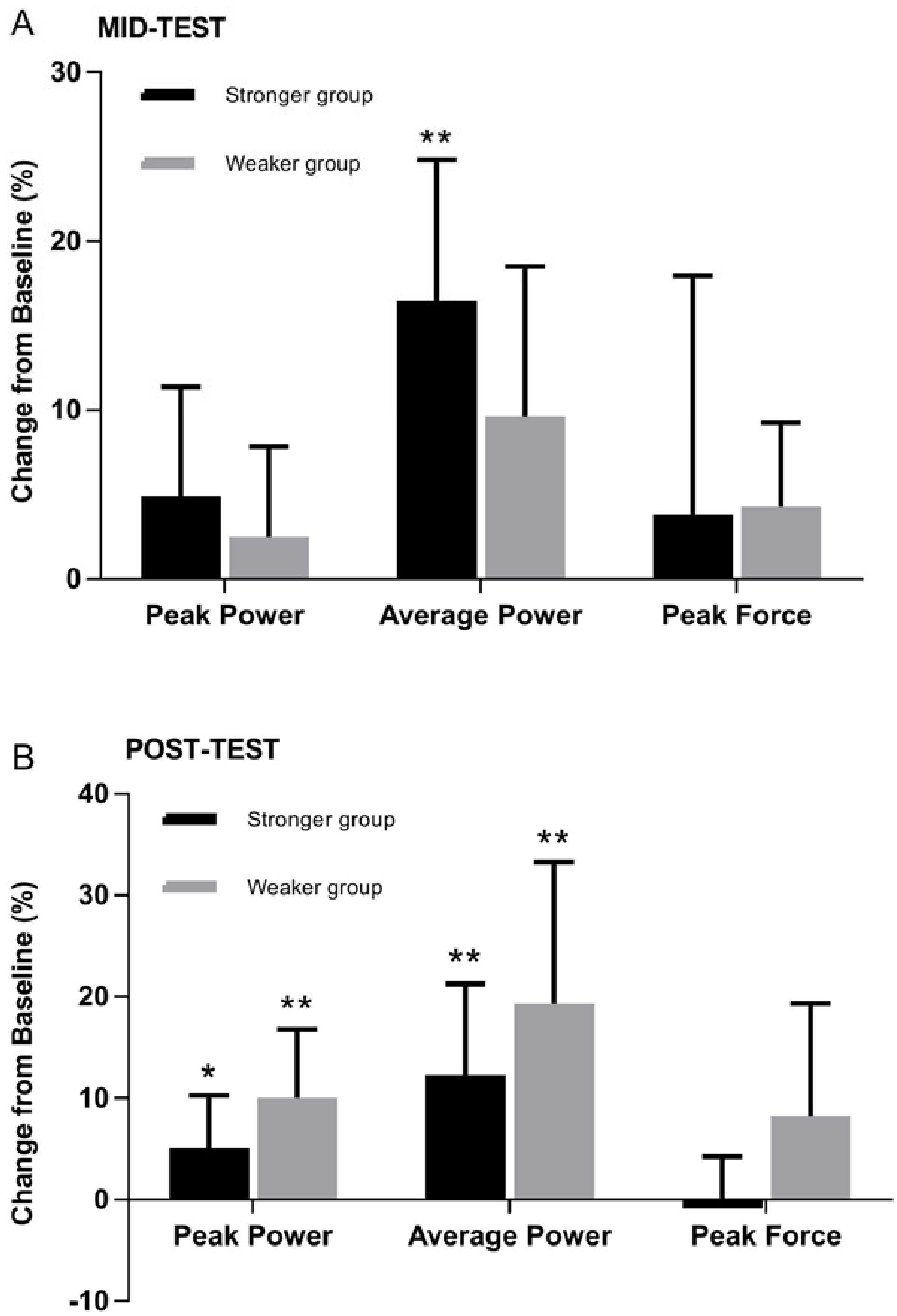
Peak Velocity
Average Velocity
Jump Height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Change from Baseline (%)
Stronger group
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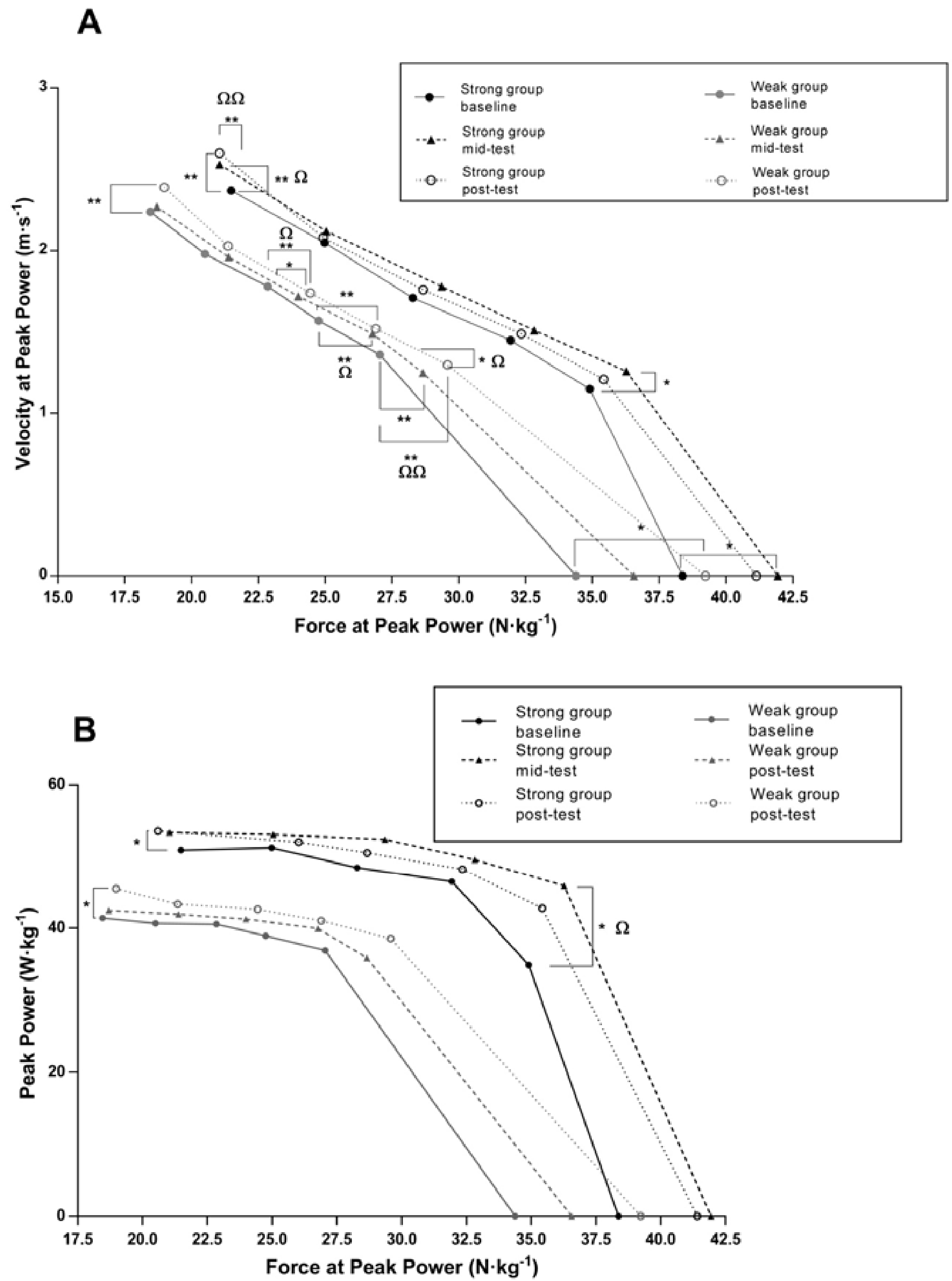
A
Strong group baseline
Strong group mid-test
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Weak group baseline
Weak group mid-test
Weak group post-test
Velocity at Peak Power (m·s-1)
Force at Peak Power (N·kg-1)
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1
2
3
15.0
17.5
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30.0
32.5
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B
Strong group baseline
Strong group mid-test
Strong group post-test
Weak group baseline
Weak group post-test
Weak group post-test
Peak Power (W·kg-1)
Force at Peak Power (N·kg-1)
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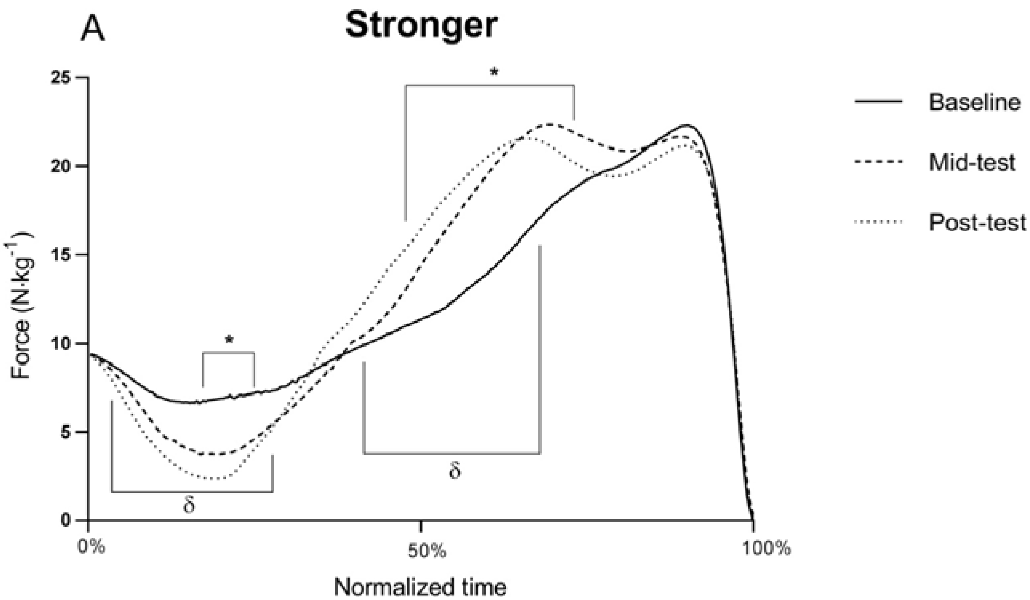
A
Stronger
Force (N·kg-1)
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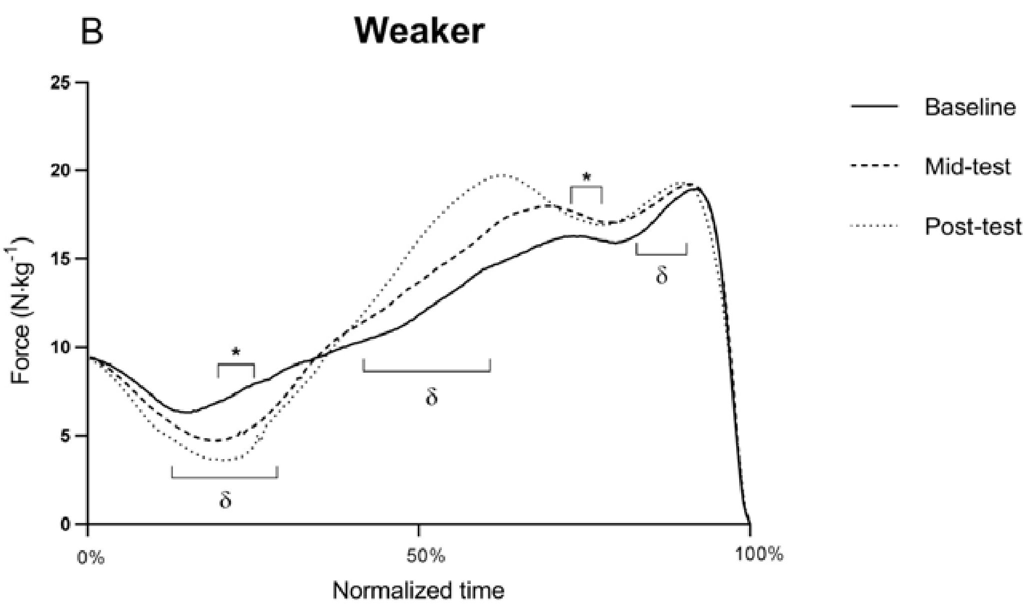
Baseline
Mid-test
Post-test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