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Title:

Trunk muscle activation in the back and hack squat at the same relative loads

Running head:

Trunk muscle activation in back and hack squat

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Abstract

The hack squat (HS) is likely to produce a greater 1 repetition maximum (1RM) compared to the back squat (BS). This can be attributed to the support of the trunk during the HS compared to no support during BS. This support however, may compromise trunk muscle activation (TMA), therefore producing different training adaptations. Accordingly, the purpose of this study was to compare 1RM in BS and HS and TMA at 4 relative loads, 65, 75, 85 and 95% of maximal system mass. Ten males completed 3 test sessions:1) BS and HS 1RM, 2) HS & BS neuromuscular test familiarization, and, 3) Neuromuscular test for 3 reps at 4 loads for BS and HS. BS TMA was significantly greater ($p<0.05$) than HS for all muscles and phases except rectus abdominus in concentric phase. TMA increased ($p<0.05$) with load in all muscles for both exercises and phases apart from lumbar sacral erector spinae in HS eccentric phase. Mean HS 1RM and submaximal loads were significantly ($p<0.0001$) higher than the equivalent BS loads. Duration of the eccentric phase was higher ($p<0.01$) in HS than BS but not different in concentric phase. Duration increased significantly ($p<0.01$) with load in both exercises and both phases. Despite higher absolute tests loads in HS, TMA was higher in BS. TMA is sensitive to load in both exercises. BS is more effective than HS in activating the muscles of the trunk and therefore arguably more effective in developing trunk strength and stability for dynamic athletic performance.

Key words: back squat, hack squat, trunk muscles, neuromuscular, electromyography, core stability

INTRODUCTION

The squat exercise is a compound movement that engages all muscles below the shoulders including the lower limb. The primary purpose of both the back squat (BS) and hack squat (HS) are to develop strength and power in the lower limb[1–4]. Both are widely used for the development of performance capabilities for a variety of sports[2,5] and as a rehabilitative exercise for lower limb injuries and post-surgical programmes[1,6,7]. Recent research has focused on loaded compound exercises such the squat and deadlift as a method of developing trunk strength and stability. The hack squat (HS) has been used in a number of research training studies[8–10], however no trunk muscle activation data exists for HS.

Research investigating the BS[11–15], front squat[12,13,16], and overhead squat[15] have confirmed that the loaded, free barbell squat is an effective method of activating the stabilizing muscles of the trunk. There is also evidence that in BS magnitude of activation across the majority of muscle sites is sensitive to the external load[1,11,17,18]. As a result, a number of researchers concluded that BS is an effective method for developing dynamic trunk strength and stability for healthy function and athletic performance[11,17–19].

There are variations of the squat exercise performed in a machine supported set-up. These include leg press[6,20], HS[4] and Smith machine squats[14,21–23] and are generally performed at higher absolute loads than BS[14,21]. It is believed that these more stable versions of the squat compromise and reduce TMA due to biomechanical set-up and support[22,23]. Fletcher and Bagley (2014)[14] reported an 11% greater Smith machine one repetition maximum (1RM) compared to BS. Despite this, erector spinae electromyography (EMG) activity was significantly greater in BS compared to the Smith machine squat 1RM test.

The HS offers more support than the Smith machine squat; it is commonly viewed as a safe version of the loaded squat exercise, especially suitable in the absence of established barbell squat technique and for rehabilitation programmes[4,24]. The HS is performed in a machine angled posteriorly at 45^{o} where force is applied and resisted through padded shoulder yokes. The participant's back is positioned on a padded board offering greater support to the trunk during squat movement[4] contributing to higher loading capacity compared to Smith machine squat and BS. To our knowledge, there is no research comparing 1RM in HS to BS. However, untrained subjects developed a 1RM of over 250 kg after 8 weeks HS training[8,9]. This is equivalent to a relative 1RM of approximately 3.3 times body mass, greater that any previously reported BS relative 1RM. This suggests the supported characteristic of HS is accompanied by the ability to lift greater maximal loads than in free bar BS.

Centre of gravity of the person and external load, or the system load, in BS must remain over base of support[25] to prevent failure and or injury. As a result, force is resisted in the eccentric phase and expressed in the concentric phase through the line of gravity which determines how the loads are experienced by the affected muscles. When squatting in a linear motion machine, such as a Smith Machine or HS, the centre or line of gravity can safely sit outside the foot stance or the point where force is applied. This is the result of anterior foot placement which is made possible by the supported trunk and fixed external load. This introduces horizontal forces which potentially change load direction experienced by muscles of the body[25], including the prime movers and trunk stabilizers. To our knowledge there is no research describing or quantifying either trunk or lower limb muscle activation in HS.

Using a two dimensional model of a free body diagram, Abelbeck (2002)[25] assessed moments and work of the hip and knee joints for 6 foot positions anterior to the line of gravity. Position 1 was under the line of gravity and at position 6, knees were flexed to 90^o and thighs horizontal. Each foot position away from the line of gravity resulted in a greater moment about both joints. Net work done at the knee decreased while it increased at the hip with each anterior foot position. HS is a tilted and supported version of a linear motion machine squat. Escamilla[6] (1998) measured activation of 6 muscles of the lower limb in leg press and squat exercise at 12RM. Foot placement in the leg press was anterior to the line of gravity equivalent to position 6 in Ablebeck's[25] (2002) study. Apart from biceps femoris in extension where activation was greater in the squat than leg press, there were no significant differences in activation between the two exercises for all muscles in both flexion and extension.

It has been established that TMA, across majority of muscle sites, is sensitive to increases in external load in BS[1,11,17,18]. It is also accepted that load capacity of HS is greater than for BS[8,9]. In the BS, stabilization of the trunk is necessary to ensure that the centre of gravity of the system load remain over the base of support for the eccentric and concentric phases. Anterior foot placement in the HS, facilitated by fixed external load and trunk support, resulted in higher work at the hip joint[25] but no meaningful increase in activation of leg muscles[6]. Trunk muscle activation under these conditions is unknown. While there is an appreciation of these differences in applied strength and conditioning, these have not been measured and quantified.

Accordingly, we hypothesize that the requirement to stabilize the bar in BS places greater demands on muscles of the trunk than greater absolute loads in the more supported HS. In accordance with this, objectives of the study were to; 1) determine 1RM for HS and BS within a strength trained cohort, 2) compare TMA in HS and BS in a range of relatively equivalent external loads, and 3) determine whether TMA was load sensitive in HS and BS.

METHODS

Experimental Approach to the Problem

All subjects attended 3 test sessions (Figure. 1). In the first, a 1RM test was conducted for BS and HS. In session 2, subjects completed the neuromuscular test protocol familiarization with loads calculated from the 1RM. In the third session, the neuromuscular test protocol was repeated while EMG and kinematic measures were taken. All tests were conducted 5 to 7 days apart.

All BS repetitions were performed according to technique described by Earle and Baechle (2000)[26]. Starting with the barbell in high bar position, on the trapezius across the back of the shoulders with hip and knee joints fully extended. Feet were placed shoulder width apart with legs externally rotated by 3-5^{o} so that that the toes were turned slightly out. Hack squats[24] were performed with the back placed against the padded surface, shoulders wedged under the yokes and feet placed shoulder width apart to the front of the footplate. Both squat versions comprised of a descent through knee and hip flexion to where mid-point of the thigh joint was below mid-point of the knee joint with a minimum knee flexion of 90^{o}. The transition between the descent and the ascent was visually assessed as the point where the top of the thighs were horizontal in BS and parallel to the footplate in HS. The load was returned to the start position by extending the hip and knees in a controlled manner as fast as possible. All BS were performed using barbells and discs approved by International Weightlifting Federation (Eleiko, Sweden). BS tests were conducted in a safety power cage (FT700 Power Cage, Fitness Technology, Skye, Australia) and HS in a plate loaded Bodymax CF800 Leg Press/Hack Squat Machine.

Insert Figure 1 here

Subjects

Ten males actively participating in regular strength training with at least 1 years' experience in BS exercise were recruited for the study. Using G*Power software (3.1) we calculated a minimum of 10 participants was required for 90% power from the effect size of RMS increase in the eccentric phase of BS from 75-95% load[17]. Subject characteristics were; age: 27 ± 8 years, body mass: 86 ± 8 kg, squat training age: 6 ± 5 years, BS 1RM: 142 ± 29 kg, relative BS 1RM: 1.7 ± 0.3, HS 1RM: 171 ± 34 kg and relative HS 1RM: 2.0 ± 0.4. In accordance with Declaration of Helsinki (2013)[27], the local research ethics committee granted approval for the study. The risks and potential benefits of the study were explained to all subjects prior to signing an informed consent form. Signed parental consent was recorded for the subjects under the age of 18. Subjects abstained from strenuous exercise and followed usual dietary habits for 24 hours prior to test sessions which were conducted at the same time of day to account for circadian variation[28].

Procedures

1RM testing

Following a standardised warm-up of 5 minutes stationary cycling and 10 minutes body weight exercises, subjects completed BS 1RM test according to an established protocol[26]. Barbell warm-up comprised 3-5 sets of diminishing repetitions at progressive loads determined for each subject from previous 1RM test results and current training loads. BS 1RM test was performed first followed by HS 1RM to avoid possible potentiation effect of higher absolute loads reported for HS[8,9]. 1RM test scores were recorded as highest load lifted successfully through required range of movement within 4 attempts in BS and HS. Subjects were instructed to control cadence of descent and perform ascent as fast as possible under control. Three minute rest periods were allocated between each warm-up and test set[24,29–31]. Correct squat depth for both exercises was established during warm-up sets and reinforced during testing by an experienced strength coach, the principle investigator, who conducted all tests.

Neuromuscular test load calculation

Test loads for sessions 2 and 3 were calculated using the system mass (SM)[17,32] approach. This is calculated by adding 88.6% of body mass to 1RM, which is equivalent to body mass minus the mass of the shanks and feet. This represents total load lifted vertically when performing the squat[32]. The neuromuscular test protocol comprised 2 BS warm-up sets of 10 repetitions at 45 and 55% SM, followed by 4 sets of 3 repetitions at 65, 75, 85 and 95% SM for BS and then HS. Back squat and HS test loads were determined according to following equation:

SM max = 1RM + (0.886 x body mass) (kg)

External test load = (SM max x percentage of SM) - (0.886 x body mass) (kg)

Familiarization and neuromuscular test trials

In test session 2, subjects completed the standardised warm-up and neuromuscular test protocol at individually calculated loads for BS and HS. During this familiarization session exercise technique, squat depth and rest times were rehearsed. In test session 3, subjects were prepared for EMG and kinematic data collection which was confirmed during 2 warm-up sets before proceeding to neuromuscular test protocol. Subjects were instructed to control descent and perform ascent as fast as possible under control for both BS and HS. Squat depth was monitored using linear transducer data and observation.

Kinematic data

The duration and displacement of eccentric and concentric phases of both exercises were measured by linear transducer (Celesco, PT5A, California, USA). The linear transducer was placed directly beneath, and attached to the barbell in BS. In HS it was placed adjacent to the footplate and attached at shoulder height to the sled of the HS machine to measure full displacement of the load along the 45^{o} plane of travel[29,33].

A bespoke Matlab (Matlab R2010A, The Mathworks Inc., USA) programme was designed to identify initiation and completion of descent and ascent of the load in order to determine eccentric and concentric phases for EMG selection.

Electromyography

Muscle activity was measured from 5 sites on right-hand side of the body based on established bilateral symmetry of these muscles[34]; rectus abdominus (RA), external oblique (EO), lumbar sacral erector spinae (LSES), upper lumbar erector spinae (ULES) and vastus lateralis (VL)[11,23] using surface EMG (Biopac MP100, Biopac Systems Inc., Santa Barbara, CA). SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscles) recommendations were followed for skin preparation and application of electrodes[35]. Hair was removed, sites abraded with emery paper and cleaned with an alcohol swab in preparation for two Ag-AgCl EL258S bipolar 8 mm diameter electrodes (Biopac Systems Inc., USA). These were housed in custom made soft rubber mould with 20 mm inter electrode distance. They were filled with conductive gel and fixed in position with transparent adhesive dressing. Electrodes were fixed longitudinally along muscle fibre orientation according to SENIAM (ULES and VL)[23], (LSES, ULES and VL) and[11] (RA, EO, LSES and ULES). EMG was sampled at a rate of 2000 Hz, anti-aliased with a 500 Hz low pass filter and root mean square processed (RMS). We have previously demonstrated acceptable absolute (CV%) and relative (ICC) reliability of mean RMS data for these trunk muscles in the back squat exercise at similar loads[17].

Mean RMS for eccentric and concentric phases were calculated from 3 reps for each load and exercise. Mean RMS data for 75, 85 and 95% SM for each phase of both exercises were normalized to mean RMS of concentric phase of 65% SM in BS and presented as mean ± SD percentage normalized RMS. It has been demonstrated that submaximal dynamic contraction, not maximal isometric contraction, offer more reliable amplitude for EMG normalization of trunk muscles in healthy controls and patients with lower back pain[33]. We have previously shown that submaximal dynamic normalization was far more reliable and sensitive than MVC methods in BS exercise for VL[17,33].

Statistical Analysis

Statistics were performed using GraphPad Prism version 6.07 for Windows, GraphPad Software, La Jolla California USA. Data were analysed with a 2-way repeated measures analysis of variance (ANOVA) for condition (x2) and load (encoder displacement and duration x2, RMS x3). 1RM data were analysed using paired *t*-tests. F ratios were considered significant at $p<0.05$. Significant condition effect was followed by *post-hoc* Sidak's procedure for multiple comparisons. All data are presented as mean ± SD for each phase of both exercises and all test loads. Where appropriate, 95% lower and upper confidence intervals (CI) and Cohen's *d* effect sizes (ES)[36] calculated by:

Cohen's $d = Mean_1 - Mean_2 / SD_{pooled}$, where $SD_{pooled} = \sqrt{[(SD_1^2 + SD_2^2) / 2]}$.

ES were then interpreted as <0.2 = trivial, ≥0.2 - 0.5 = small, ≥0.5 - ≤0.8 = moderate, ≥0.8 = large [36]

RESULTS

Electromyography

In the eccentric phase RMS was significantly ($p<0.05$ to $p<0.0001$) greater in BS vs. HS in 7 of the 9 test loads for EO, ULES and LSES (Table 1). However, there was no difference in RA RMS in the eccentric phase between BS and HS; whereas concentric RMS was significantly ($p<0.05$ to $p<0.0001$) greater in BS than HS in all muscle sites and in 8 out of 12 instances (Table 2).

Insert Table 1 here

Insert Table 2 here

RMS increased with load in the following trunk muscle sites in the eccentric phase for both exercises (Figure 2): RA ($F_{(2, 18)} = 13.52$, $p<0.001$) EO ($F_{(2, 18)} = 5.258$ $p<0.05$), ULES $F_{(2, 18)} = 6.374$ $p<0.01$). There was no eccentric load effect for LSES for both BS and HS. RMS increased with load in all muscle sites and both exercises in the concentric phase (Figure 3): RA ($F_{(2, 18)} = 7.795$ $p<0.01$), EO $F_{(2, 18)} = 14.70$ $p<0.001$), LSES ($F_{(2, 18)} = 18.76$ $p<0.001$) and ULES $F_{(2, 18)} = 6.035$ $p<0.01$).

Insert Figure 2 here

Insert Figure 3 here

Mean VL RMS was significantly ($F_{(1, 9)} = 5.846$ $p<0.05$) higher for BS vs HS in the concentric phase and a tendency in the eccentric phase where *post-hoc* analysis demonstrated significance for 3 test loads (75% SM $p<0.0001$, 85% SM $p<0.01$, 95% SM $p<0.0001$). Muscle activation in VL produced a significant load effect in both exercises for both phases: eccentric ($F_{(2, 18)} = 18.85$ $p<0.001$) concentric ($F_{(2, 18)} = 3.711$ $p<0.05$).

1RM tests and test loads

The mean HS 1RM was significantly ($p<0.0001$) higher at 171 ± 34 kg when compared to 142 ± 29 kg in BS. As a result relative test loads at 65, 75, 85 and 95% SM were significantly greater in HS than BS by 16.5, 17.5, 20.5 and 23.0 kg respectively ($F_{(1, 9)} = 19.94$ $p<0.01$).

Kinematic measures

Eccentric displacement in BS was significantly ($F_{(1, 9)} = 33.62$ $p<0.001$) greater than in HS for 4 test loads by 21.4, 20.8, 21.5 and 22.2 cm (Figure. 2A). Eccentric displacement decreased significantly ($F_{(3, 27)} = 5.931$ $p<0.01$) with load in both BS and HS. Duration of eccentric phase was significantly ($F_{(1, 9)} = 18.54$ $p<0.01$) greater in HS compared to BS for all test loads (Figure.3A). Duration significantly ($F_{(3, 27)} = 5.371$ $p<0.01$) increased with load for both BS and HS for eccentric phase with a significant ($F_{(3, 27)} = 2.968$ $p<0.05$) interaction effect which occurred from progressively reduced differences from 20.4% (65% SM) to 10.6 (95% SM).

Insert Figure 4 here

Insert Figure 5 here

Concentric displacement was significantly ($F_{(1, 9)} = 26.30$ $p<0.001$) greater in BS than HS (Figure. 2B) for all loads. There was no displacement load effect for either exercise in the concentric phase. Concentric phase duration increased significantly ($F_{(3, 27)} = 115.5$ $p<0.0001$) for BS and HS alongside increases in load. There were no differences between BS and HS for duration of concentric phase during tests at 65, 75 and 85% SM. However, there was a significant ($F_{(3, 27)} = 14.82$ $p<0.0001$) interaction effect where BS duration at 95% SM was significantly ($p<0.0001$) greater than HS (Figure. 3B).

DISCUSSION

This is the first study to compare maximal strength and TMA in HS and BS. Anecdotal evidence that HS maximal strength capacity is greater than BS is confirmed under scientific research conditions. As hypothesized, TMA in BS was greater than HS in the majority of muscle sites, at the same relative loads. Furthermore, TMA in both exercises increased with each load increment which were similar to those commonly used in applied strength and conditioning practice.

TMA was greater in BS vs. HS for all measured muscles during both phases, with the exception of rectus abdominus in the eccentric phase which demonstrated no such differences. This largely agrees with our hypothesis, although the rectus abdominus finding was also unsurprising given the previous equivocal reports of this muscle's RMS activity in

Smith Machine vs. BS[14; 22]. The likely cause of this variance is the flexed trunk position during most of BS, which causes skin to fold in the rectus abdominus region, thus moving electrodes away from activated motor units and inevitably increasing measurement variability. While the role of rectus abdominus as a stabilizer in squats remains unclear it appears from our data that rectus abdominus contribution to stabilization increases with load in both phases of both exercises, and this is greater in the concentric phase of BS.

In the lateral stabilizers, activation of external oblique muscle was significantly greater in BS than HS in all instances and both phases apart from 85% SM in eccentric phase. The shared function of rectus abdominus and external oblique muscles are to create intra-abdominal pressure during exertion through the trunk[37]. Individually rectus abdominus controls lumbar extension and external oblique controls lateral flexion and rotation of the trunk[37]. Logically, these functions will be challenged more in BS than HS which suggest greater trunk muscle adaptation potential in the free bar BS.

Activation of posterior stabilizers, lumbar sacral erector spinae and upper lumbar erector spinae muscles was greater in BS than HS in 9 out of 12 instances. Importantly, in these 2 muscle sites at the heaviest load, 95% SM, activation was higher in BS than HS. Hamlyn and coworkers[11] (2007) using the mean RMS calculated from a 1 second sample from each phase, eccentric and concentric, showed that LSES and ULES activation was more than twofold higher in back squat at 80% 1RM compared the bodyweight squats. The purpose of erector spinae muscle complex is to extend the trunk, or in the case of BS prevent trunk flexion[14,15,17]. In the free bar exercise this challenge is greater where back and trunk are unsupported. During the descent activation was significantly higher in BS than HS for all three loads in ULES and for 85 and 95% SM in LSES. This was similar for the ascent however the magnitude of activation was greater for both exercises and all three loads in both ULES and LSES (Tables 1 and 2) (Concentric RMS: 97-230% vs Eccentric RMS: 92-155%). The higher activation of trunk stabilizers in the concentric compared to eccentric phase has been reported in a number of studies.[12,13,15,38]

Activation of external oblique and erector spinae muscles have been shown to increase alongside load in BS with submaximal loads of 50 and 75% 1RM[39]. In 2 studies where higher loads were used, the primary purpose was to compare TMA in deadlift exercise and a range of dynamic[18] and isometric[11] trunk exercises. Both studies reported a load effect in the posterior trunk muscles for BS but this was not significant. In our recent study we demonstrated a significant load effect in BS for all trunk muscles in the eccentric phase and for lumbar sacral erector spinae, upper lumbar erector spinae and external oblique in the concentric phase[17]. In the current study we found a load effect for both exercises, both phases and all muscle sites except for lumbar sacral erector spinae in the eccentric phase in both BS and HS. LSES activation in the BS increased by load in the eccentric phase (Table 1) but this did not reach significance, possibly due to the size of the sample. Importantly, loads in both our studies reflected loads commonly used during training for development of athletic performance. Therefore, TMA responses are representative of what may be expected for this type of activity in moderate to well strength trained populations.

In this study where load was significantly higher in HS, vastus lateralis RMS was greater in the BS for all loads and both phases. Vastus lateralis RMS increased with load in both BS and HS which is well established for this muscle during both eccentric[17] and concentric phases [29]. This is similar to earlier work from our laboratory where there was higher activation of vastus lateralis in concentric phase at 100% 3RM compared to 75% 3RM despite higher power produced in the lower load test effort[29]. Fundamentally, this demonstrates the large effect comparatively lower forces, external load in BS vs HS, have on increasing activation of prime lower limb muscle where no external support is provided for lifting weights vertically against gravity.

Mean 1RM for HS was 29 kg (18%) greater than BS, significantly more than the 11% difference between Smith Machine and BS 1RM previously reported[14]. As such, we demonstrated that absolute test loads at 65, 75, 85 and 95% SM were higher in HS than BS. Eccentric displacement was on average 22 cm less in HS than BS across 4 test loads. This can be explained by the positioning in HS machine in which the moment about both knee and hip joint increase as the feet move anterior to the line of gravity[25]. At the same time, work done at the knee probably decreased due to reduced range of movement, while compensatory work at the hip may have increased. Therefore, the reduced overall displacement (external marker) and the higher absolute load (internal marker) in the HS possibly resulted in a greater moment and therefore work at the hip compared to the BS[25].

Eccentric displacement decreased across the 4 test loads for both squat versions. This is possibly due to compressive force of the incremental external loads causing spine shrinkage[40]. Wisleder[40] showed that an external load equivalent to body mass resulted in a mean shrinkage of 3.9 mm. This shrinkage would result in a progressively lower start point for the descent with each higher test load. This would reduce eccentric displacement despite completing a full depth squat. Interestingly, concentric displacement was not affected by load, probably due to subjects following the instruction to complete this phase as fast as possible, which may have ended in full extension overriding the shrinkage.

The eccentric phase of the BS was significantly faster for each load despite a significantly greater displacement. There was no difference between the duration of HS and the BS in the concentric phase apart from the heaviest load (95% SM) where HS was performed quicker than BS. This suggests that the instruction to ascend as fast as possible compensated the greater BS displacement and HS load respectively, in the concentric phase for 3 loads. While the instruction to descend in a controlled manner was applied to both exercises, BS descent was faster than HS. This occurred despite the greater support offered by the HS machine and the greater range of movement in the BS. A possible explanation could be familiarity with BS training reflected by mean squat training age of 6 years (Range: 1-17 years) compared to the relative novelty of the HS exercise within this group.

In our earlier study we established reliability of surface EMG in measuring trunk muscle activation in the BS[17]. The current study has confirmed and expanded those findings. The kinematic characteristics of the unsupported free bar BS are a greater range of movement, faster descent and lower absolute external loads than the HS. Importantly, this study has shown that under those conditions the BS places greater demands on the trunk stabilizers than the HS and that this increases with load. Three factors therefore explain greater trunk muscle activation in the BS, greater range of movement, faster descent and importantly, the requirement to control the unsupported external load through the full kinetic chain. This included lower limbs, hips and pelvis and, as shown by this study, the trunk. We have shown that both the BS and HS challenge the trunk stabilizers and that this activation increases in both exercises with load. However, BS is a significantly more effective method of activating the trunk stabilizers than HS. The conclusion therefore is that free barbell loaded squats are an effective exercise for the development of dynamic trunk strength and stability and for both BS and HS, trunk stability training effect is enhanced by increasing external load.

PRACTICAL APPLICATIONS

This study presents a number of interesting and novel findings particularly applicable to evidence based, applied strength and conditioning coaches. The key finding is that the free barbell back squat elicits greater trunk muscle activation than HS at the same relative load. This strengthens the case made in previous studies[11,17–19] and confirms applied anecdotal evidence that back squat is an effective method of developing dynamic trunk strength and stability. Similarly, we have presented novel research evidence to demonstrate and quantify greater absolute maximal strength capacity in HS compared to BS for a cohort of well-trained subjects. A further novel finding was the greater activation of vastus lateralis in the concentric phase of BS compared to HS despite significantly higher absolute HS loads. We also confirmed previous research[1,11,17,18] showing that increases in external load in both the BS and HS produce greater trunk muscle activation.

The implication of these findings for applied setting, is that free barbell squat is an effective exercise for the development of dynamic strength and stability in the trunk. The more stable hack squat is less effective for this purpose, however in both exercises trunk stabilization training effect can be enhanced by increasing external load.

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Figures

Figure 1. Experimental design illustrating the timing and content of the three test sessions and the standardised warm-up. 1RM – 1 repetition maximum.

Figure 2. Mean RMS for the eccentric phase for 3 test loads, 75, 85 and 95% SM for the 4 trunk muscle sites; A – rectus abdominus, B – external oblique, C – lumbar sacral erector spinae and D – upper lumbar erector spinae. Significant load effect: * (p<0.05), ** (p<0.01), *** (p<0.001) and significant difference between BS and HS: # p<0.05 and p<0.0001.

Figure 3. Mean RMS for the concentric phase for 3 test loads, 75, 85 and 95% SM for the 4 trunk muscle sites; A – rectus abdominus, B – external oblique, C – lumbar sacral erector spinae and D – upper lumbar erector spinae. Significant load effect: ** (p<0.01), *** (p<0.001) and significant difference between BS and HS: # (p<0.05 to p<0.0001).

Figure 4. Kinematic data for the BS and HS where panel A is eccentric displacement and B concentric displacement. Significant load effect in both conditions: # (p<0.01), and significant difference between HS and BS: * (p<0.001).

Figure 5. Kinematic data for the BS and HS where panel A is eccentric duration and B concentric duration. Significant load effect in both conditions: # (p<0.01) and significant difference between HS and BS: * (p<0.001) ** (p<0.0001).

Table 1. Normalized mean percentage RMS in the eccentric phase, Mean diff., 95% confidence intervals, *p*-values, Cohen's *d* and effect size (ES) and for hack squats and back squats performed at the 3 test loads, 75, 85 and 95% SM.

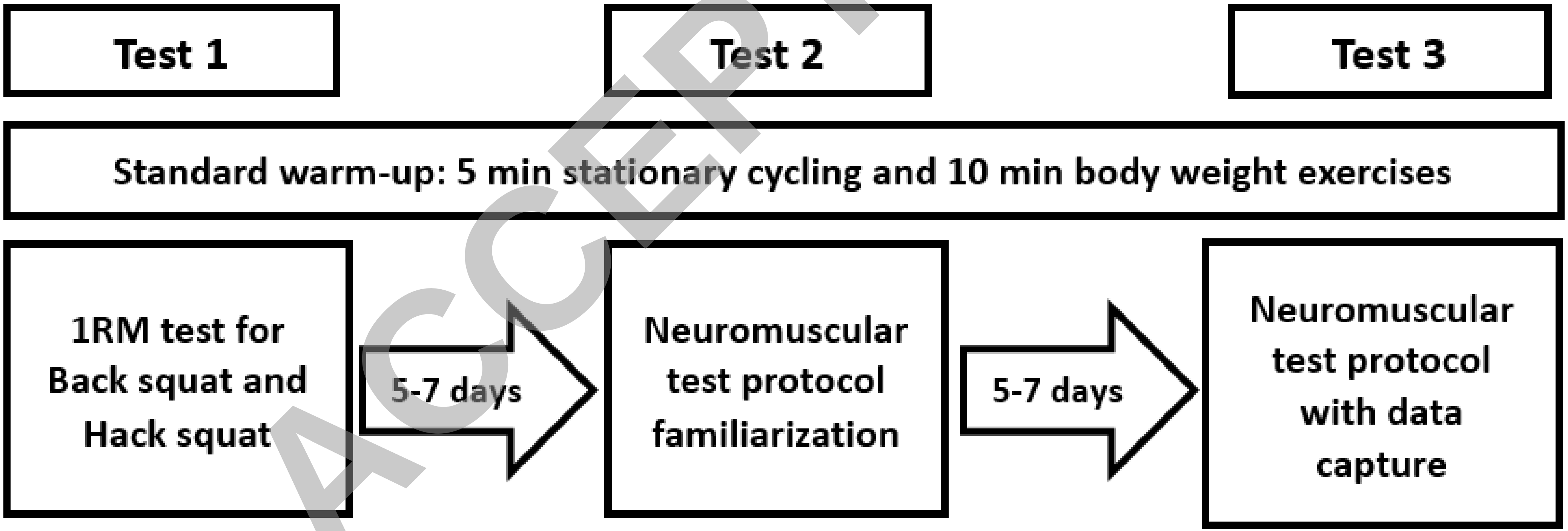
					95% CI of diff.			Cohen's	
	Test load	Hack squat (mean ±SD)	Back squat (mean ±SD)	Mean Diff.	Lower	Upper	*P*	*d*	ES
	75%	64 ±30	65 ±22	-0.9	-18.7	16.9	>0.999	-0.03	Trivial
RA	85%	73 ±34	68 ±22	4.7	-13.1	22.5	>0.999	0.16	Small
	95%	86 ±35	82 ±22	3.7	-14.1	21.6	>0.999	0.13	Small
	75%	57 ±31	87 ±33	-29.4	-48.8	-9.9	0.003*	-0.91	Moderate
EO	85%	62 ±27	80 ±26	-19.2	-38.6	0.3	0.054	-0.72	Moderate
	95%	70 ±31	94 ±27	-24.0	-43.4	-4.5	0.013*	-0.84	Moderate
	75%	92 ±38	118 ±56	-26.1	-40.8	-11.5	0.001*	-0.55	Small
ULES	85%	84 ±39	130 ±47	-45.9	-60.5	-31.3	<0.0001*	-1.07	Moderate
	95%	85 ±41	155 ±64	-69.2	-83.8	-54.6	<0.0001*	-1.29	Large
	75%	72 ±21	88 ±12	-16.0	-34.1	2.1	0.096	-0.92	Moderate
LSES	85%	75 ±19	95 ±15	-19.8	-38.0	-1.7	0.030*	-1.14	Moderate
	95%	75 ±24	107 ±22	-32.5	-50.7	-14.4	0.001*	-1.44	Large

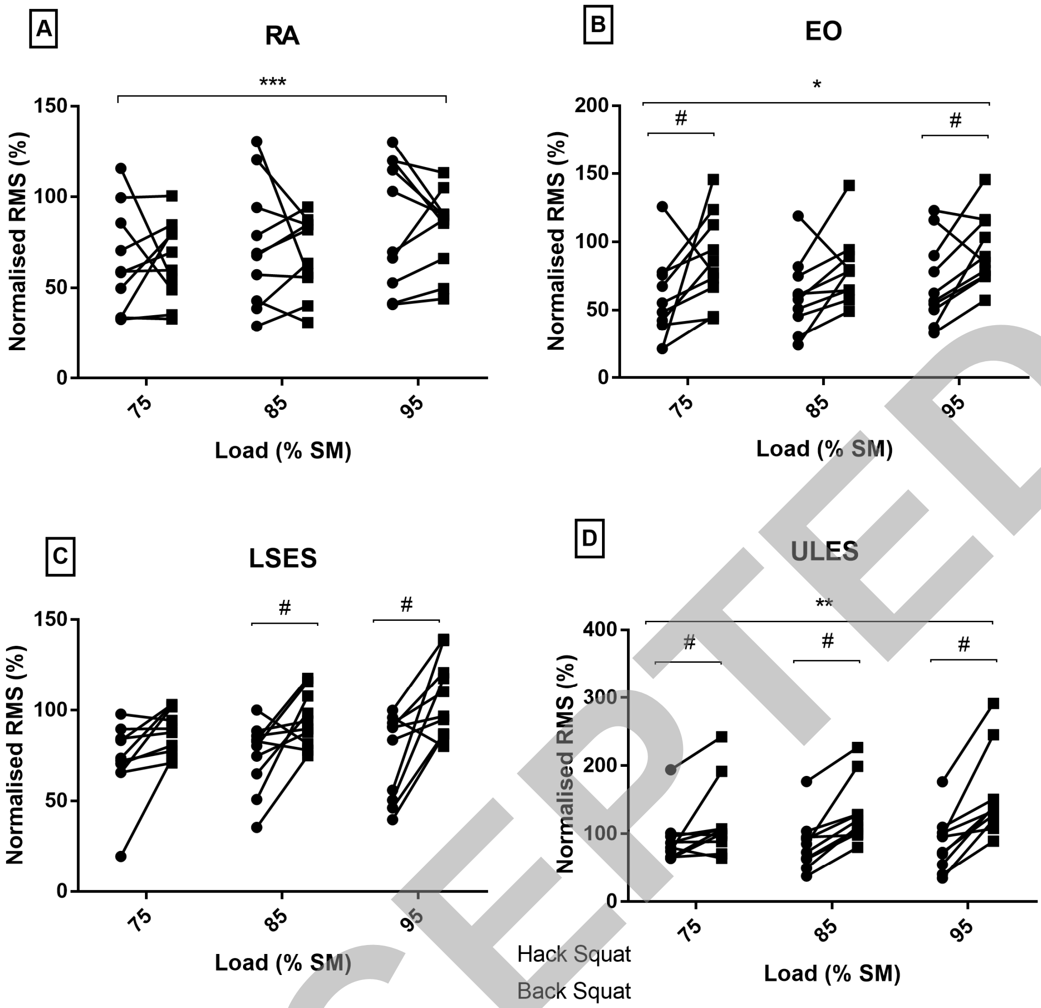
Note: *Significant greater mean RMS in back squat compared to hack squat ($p<0.05$).

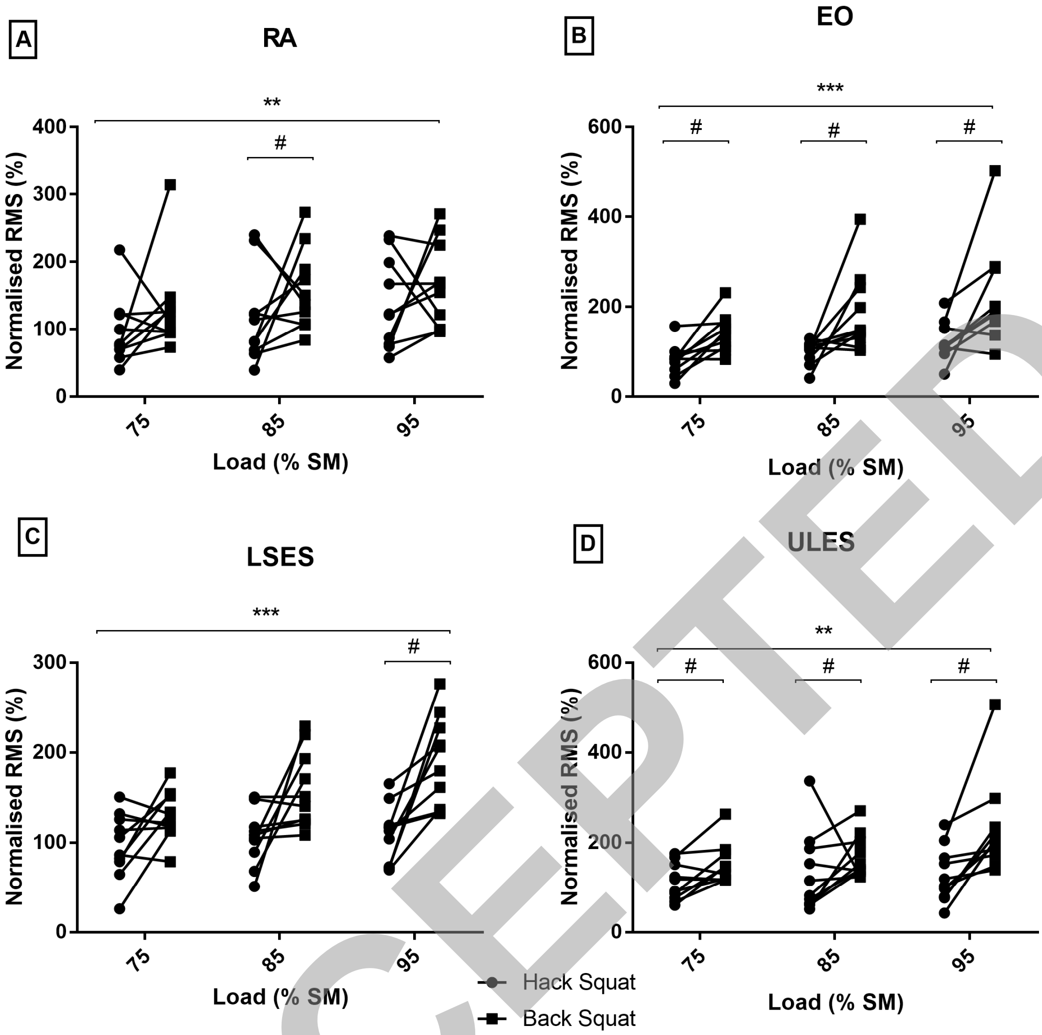
Table 2. Normalized mean percentage RMS in the concentric phase, Mean diff., 95% confidence intervals, *p*-values, Cohen's *d* and effect size (ES) and for hack squats and back squats performed at the 3 test loads, 75, 85 and 95% SM.

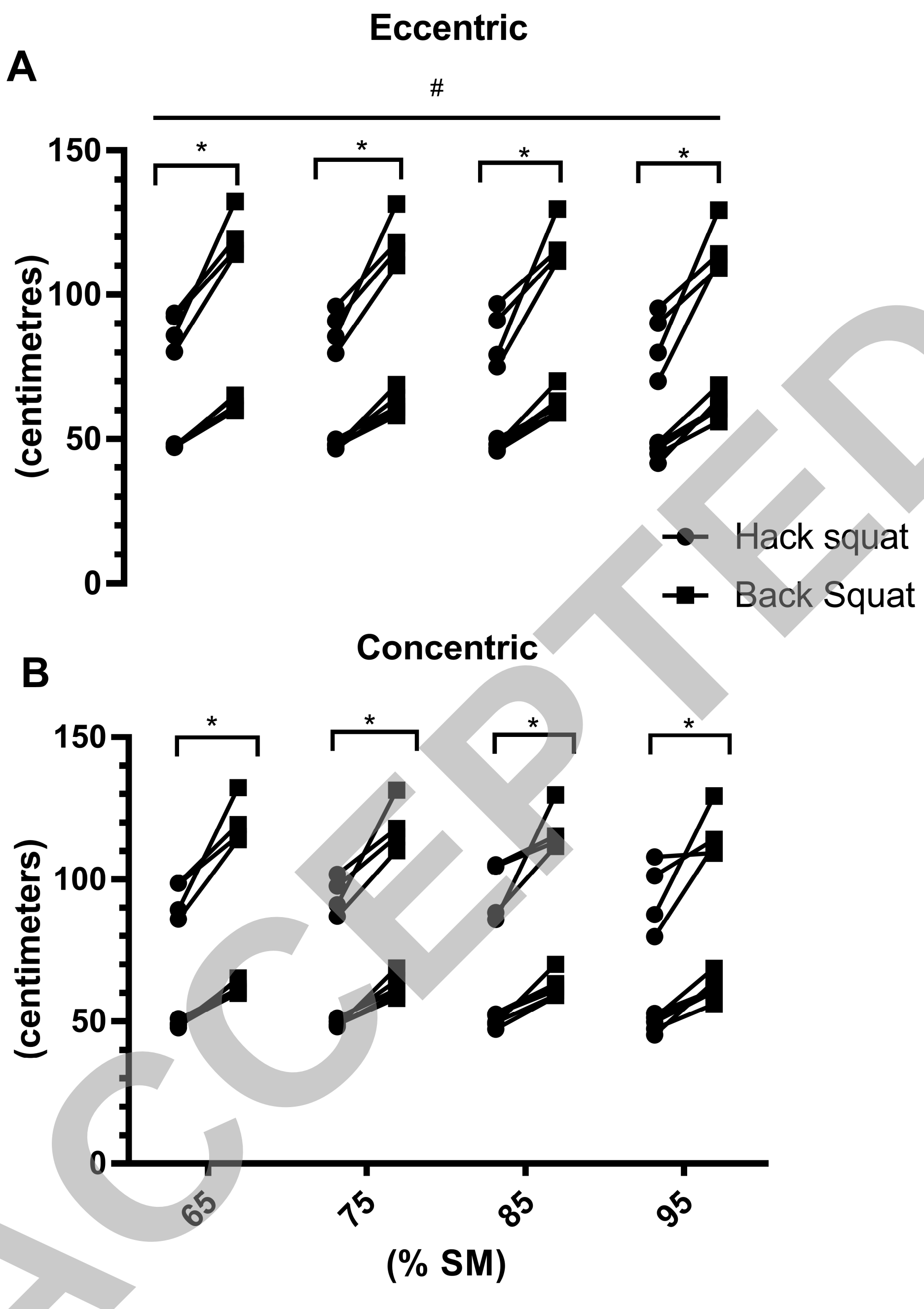
					95% CI of diff.			Cohen's	
	Test load	Hack squat (mean ± SD)	Back squat (mean ± SD)	Mean Diff.	Lower	Upper	*P*	*d*	ES
	75%	96 ±51	132 ±68	-36.4	-73.6	0.5	0.054	-0.61	Moderate
RA	85%	117 ±68	159 ±60	-41.6	-78.6	-4.7	0.024*	-0.65	Moderate
	95%	138 ±67	166 ±64	-27.4	-64.3	9.6	0.199	-0.42	Small
	75%	81 ±34	142 ±42	-61.1	-102.1	-20.1	0.003*	-1.60	Large
EO	85%	99 ±26	188 ±90	-89.0	-130.0	-47.9	<0.0001*	-1.34	Large
	95%	123 ±43	224 ±114	-100.7	-141.8	-59.7	<0.0001*	-1.16	Moderate
	75%	112 ±42	152 ±46	-39.8	-64.5	-1.4	0.039*	-0.90	Moderate
ULES	85%	133 ±90	169 ±49	-36.1	-84.7	-21.6	0.001*	-0.50	Small
	95%	128 ±62	230 ±107	-102.2	-112.3	-49.2	<0.0001*	-1.17	Moderate
	75%	97 ±37	130 ±27	-33.0	-91.3	11.8	0.170	-1.02	Moderate
LSES	85%	105 ±31	159 ±43	-53.1	-87.7	15.4	0.243	-1.42	Large
	95%	110 ±32	191 ±50	-80.7	-153.7	-50.6	0.000*	-1.92	Large

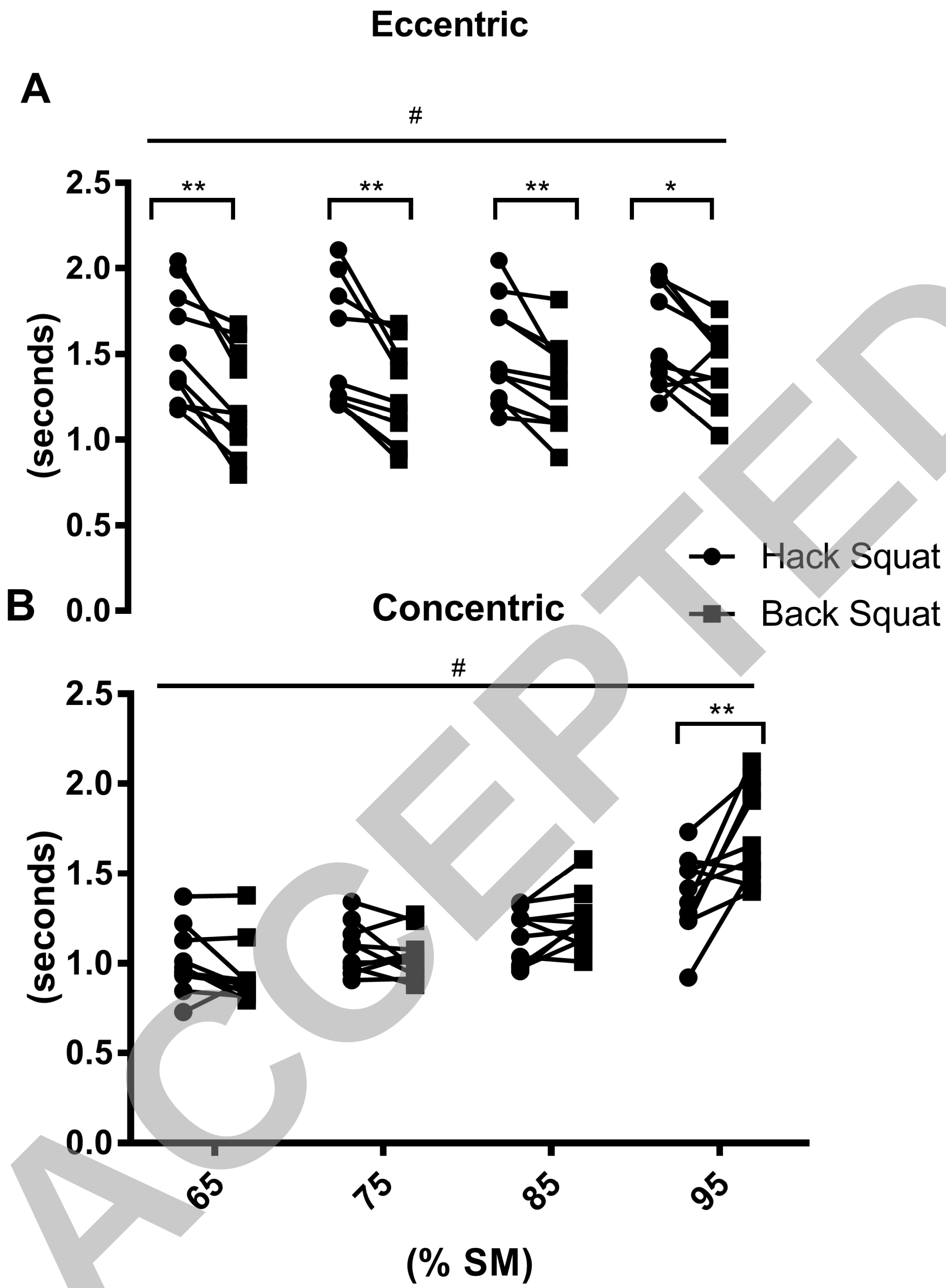
Note: *Significant greater mean RMS in back squat compared to hack squat (p<0.05).


Test 1
Test 2
Test 3
Standard warm-up: 5 min stationary cycling and 10 min body weight exercises
1RM test for Back squat and Hack squat
5-7 days
Neuromuscular test protocol familiarization
5-7 days
Neuromuscular test protocol with data capture


A
RA
***
Normalised RMS (%)
150
100
50
0
75
85
95
Load (% SM)
B
EO
*
#
#
200
150
100
50
0
Normalised RMS (%)
75
85
95
Load (% SM)
C
LSES
#
#
Normalised RMS (%)
150
100
50
0
75
85
95
Load (% SM)
D
ULES
**
#
#
#
400
300
200
100
0
Normalised RMS (%)
75
85
95
Load (% SM)
Hack Squat
Back Squat


A
RA
**
#
Normalised RMS (%)
400
300
200
100
0
75
85
95
Load (% SM)
B
EO
***
#
#
#
600
400
200
0
C
LSES
***
#
300
D
ULES
**
Hack Squat
Back Squat


Eccentric
A
#
150
100
50
0
(centimetres)
*
Hack squat
Back Squat
Concentric
B
150
100
50
0
(centimeters)
65
75
85
95
(% SM)



Eccentric
A
#
2.5
2.0
1.5
1.0
0.5
0.0
(seconds)
**
**
**
*
Hack Squat
Back Squat
B
Concentric
#
**
(seconds)
65
75
85
95
(% SM)