Surface electromyography analysis of three squat exercises

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Abstract

The aim of this study was to perform an electromyography comparison of three commonly used lower limb injury prevention exercises: a single-leg squat on a bench (SLSB), a double-leg squat (DLS) and a double-leg squat on a BOSU® balance trainer (DLSB). After determining the maximum isometric voluntary contraction of the hamstring and quadriceps, eight female athletes performed 3 repetitions of each exercise, while electromyography activity of the biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL) and vastus medialis (VM) was monitored. Comparisons between exercises revealed higher activation in BF (descending phase: $p = 0.016$, d = 1.36; ascending phase: $p = 0.046$, d = 1.11), ST (descending phase: $p = 0.04$, d = 1.87; ascending phase: $p = 0.04$, d = 1.87), VL (ascending phase: $p = 0.04$, d = 1.17) and VM (descending phase: $p = 0.05$, d = 1.11; ascending phase: $p = 0.021$, d = 1.133) muscles for the SLSB compared to the DLSQ. Furthermore, higher muscular activation of the ST (ascending phase: $p = 0.01$, d = 1.51; descending phase: $p = 0.09$, d = 0.96) and VM (ascending phase: $p = 0.065$, d = 1.03; descending phase: $p = 0.062$, d = 1.05) during the SLSB with respect to the DLSB was observed. In conclusion, the SLSB elicits higher neuromuscular activation in both hamstring and quadriceps muscles compared to the other two analysed exercises. Additionally, the higher muscle activation of both medial muscles (ST and VM) during the SLSB suggests that single leg squatting exercises may enhance lower limb medial to lateral balance, and improve knee stability in the frontal plane.

Key words: Injury prevention, ACL, EMG, hamstring to quadriceps ratio, knee stability, female, football players.

Introduction

The anterior cruciate ligament (ACL) plays an important role in stabilizing the knee (Guelich et al., 2016). The ACL injury is the most commonly and frequently injured knee ligament in team sports (Monajati et al., 2016; Stevenson et al., 2015). Although ACL injuries can be produced as a consequence of contact situations (e.g., an external load from other players), two thirds of ACL injuries are non-contact in nature (Alentorn-Geli et al., 2009) and, thus, are potentially preventable (Chappell et al., 2002; Silvers and Mandelbaum, 2007). Unilateral landing involving exaggerated knee abduction (valgus) has been identified as one of the most frequent actions associated with the incidence of ACL injuries (Boden et al., 2000; Ireland, 1999). Indeed, a similar body position with the knee close to full extension combined with slight rotation of the tibia (external or internal) and foot planted have been identified as a common knee valgus mechanism (Boden et al., 2000; Krosshaug et al., 2007; Olsen et al., 2004). It has been suggested that neuromuscular deficits, muscle activation strategy and poor muscle coordination during high-risk manoeuvres (unilateral landing, cutting, deceleration, etc.) can cause exaggerated valgus and consequently increase the risk of ACL injury (Ford et al., 2003; Hewett et al., 2005; Myer et al., 2005). Dedinsky et al. (2017) stated that a disproportionate quadriceps to hamstring activation might increase the load on the ACL and augment the risk of injury. Subsequently, a hamstring to quadriceps (H:Q) activation ratio of > 0.6 has been recommended as appropriate to decrease the risk of ACL injuries, whilst a ratio closer to 1 indicates a higher activation of the hamstring in supporting the ACL to resist anterior tibia translations and stabilising the knee. Furthermore, unbalanced medial to lateral muscle activations have been associated with increased knee valgus in the frontal plane (Myer et al., 2005).

Due to the synergistic muscle actions involving a coordinated contraction of hamstring and quadriceps, several squat exercises using different levels of stability (a double or single leg squat on stable or unstable surfaces) have been proposed to enhance knee stabilization and potentially avoid excessive valgus and varus in athletes (Escamilla, 2001). For instance, unilateral and bilateral squatting exercises such as single (Daneshjoo et al., 2012; Ortiz et al., 2010) or double leg squats (DiStefano et al., 2009) and lunges (Lim et al., 2009) performed on stable and unstable (Donnelly et al., 2012; Naclerio et al., 2013) surfaces, or using a combination of different squatting movements (Myer et al., 2006) have been suggested as effective strategies to improve neuromuscular control and prevent ACL injuries in team athletes.

McBride et al. (2006) reported decreased muscle activation of both knee extensor and flexor muscles during an isometric unstable squat compared to an isometric normal squat. McCurdy et al. (2010) showed higher activation of hamstrings compared to quadriceps during a single leg squat with respect to a double leg squat. Furthermore, De et al. (2014) reported a similar muscle activation of the quadriceps along with a higher activation of the biceps femoris during a double leg squat compared to a single leg squat.

The aforementioned studies utilised either absolute or relative loads to monitor muscle activation. There is evidence that using external loads would elicit higher muscle activation, strength and neural enhancement (Fisher et al., 2017; Schoenfeld et al., 2016). However, in an attempt to provide a time efficient and easy to follow protocol, team sports coaches have extensively used body weight exercises with no external additional loads. In fact, most of the proposed preventive protocols such as FIFA11$^+$ and Harmoknee (Daneshjoo et al., 2012; Lim et al., 2009) utilised the resistance provided by the athletes' body weight. Consequently, in order to have a full understanding of the muscle activation profile during the most recommended injury prevention protocols an investigation focused on squatting exercises performed with no external loads is required.

To the best of authors' knowledge, no studies have investigated activation of both medial, lateral hamstring and quadriceps muscles during a single leg squat on a bench (SLSB), a double leg squat (DLS), and a double leg squat on a BOSU® balance trainer (DLSB). Such a study will provide useful information for proper integration of different squatting exercises in injury prevention programmes. The aim of the present study therefore was to analyse the electromyography activation of the biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL) and vastus medialis (VM) during ascending and descending movement-phases in three different squatting exercise modalities: a DLS, a DLSB and a SLSB.

Methods

Procedures

The present study utilised a single-group repeated measures design, with 3 within-participant conditions: a DLS, a DLSB and a SLSB. Once considered eligible for the study and consented to participate, participants were required to attend the laboratory on two different occasions. On the first visit, participants were assessed for body mass and height. In addition, they were familiarised with all the exercises. The second visit intended to determine participants' maximum voluntary isometric contraction (MVIC) before performing the DLS, SLSB and DLSB exercises. The muscle activities of BF, ST, VL and VM were monitored through surface electromyography (EMGs). To maintain suitable balance between all possible different order of treatments and minimise any confounding effects, the order of exercises was randomised in a controlled manner. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki and was approved by the University of Greenwich Research Ethics Committee.

Participants

Eight female soccer players from the English Women's Super League, second division (mean ± SD age 21 ± 4 yrs, body mass 55 ± 4.4 kg and body height 163 ± 4.1 cm) participated in this study. All participants were engaged in regular soccer training (3 sessions per week) for a minimum of 6 years, and used resistance exercises as an essential component of their conditioning preparation during the last 12 months before the beginning of the study. Participants were excluded if they had (i) hamstring injuries 6 months prior to the study; (ii) history of a knee injury; or (iii) participated in any hamstring injury prevention programme during the previous 12 months to the beginning of the study. Before participating in this study, all participants read and signed an informed consent form. Participants were asked to refrain from caffeine ingestion and any unaccustomed or intensive exercise during the 72-h before the assessment sessions.

Measures

Three trials of each exercise (DLS, SLSB and DLSB) were completed in randomised order. On the first visit participants were familiarised with and instructed on the correct technique for each exercise. During the next visit, participants performed as many repetitions as needed to achieve a correct technique. They were shown and instructed to maintain a good upper body posture by retaining the natural lower back curve and avoiding excessive trunk flexion throughout the movement. The pace was also practiced and controlled using verbal pacing cues. The remaining visit comprised the testing session that consisted of a 10-min warm up protocol involving dynamic stretching, jogging, running and jumping exercises. Participants had a 30 s rest between trials of the same exercise and 2 minutes between exercises to allow full recovery.

Exercises description

DLS: Participants stood on the floor with feet shoulder-width and arms crossed over the chest. They were asked to squat down to approximately 90° knee flexion. A counter guided the participants to perform the descending movement in three seconds. The first count indicated the start of the descending phase, and the third count indicated the lowest point of the squat (end of descending and start of the ascending phase). Subsequently, participants performed the concentric squatting phase with maximal possible velocity (Figure 1A).

DLSB: Participants were asked to stand on a BOSU® balance trainer with feet shoulder-width and arms crossed over the chest. The same procedure as in the DLS was followed. The trial was accepted if participants maintained their balance keeping both feet on the BOSU® balance trainer device (Figure 1B).

SLSB: Participants standing on a 30 cm high platform on their dominant limb were asked to squat down to approximately 60° knee flexion. An adjustable plinth was used during the DLS to determine the 60° knee flexion for the SLSB. The same procedure as in the DLS test was followed to control the pace of movement. Trials were accepted if the participants succeeded to maintain their balance while keeping their non-stance foot off the floor and retain the proper technique (Figure 1C). For the three exercises, a qualified strength and conditioning professional controlled the correct execution technique, as instructed during the familiarisation period.

Figure 1

sEMG and kinematic data collection

The dominant (preferred kicking) limb was selected for data collection. Prior to electrode placement, the skin was shaved, abraded and cleaned with isopropyl alcohol. Parallel-bar EMG Sensors (DE-2.1, DELSYS, USA) were then placed over the BF, ST, VL and VM in accordance with SENIAM guidelines (Hermens et al., 2000). EMG signals were amplified (1 k gain) via a Delsys Bagnoli system (Delsys Inc. Boston, MA, USA) with a band-width of 20–450 Hz. A common mode rejection rate and input impedance were -92 dB and $>10^{15}\Omega$, respectively. Data was collected at 1000 Hz synchronously with the kinematic data.

Lower extremity planar kinematics was monitored using a 10-camera retroreflective system at 200 Hz (Oqus 3, Qualisys Gothenburg, Sweden). Four retroreflective soft markers (19 mm) were placed over the lateral malleolus, lateral knee joint, greater trochanter and acromion process of the dominant limb. Following tracking, kinematic and sEMG data were exported for analysis in Visual 3D (C-Motion Inc. USA).

Data processing

For the purpose of this study, the performed 3 exercises were analysed during both descending and ascending phases. The start and finish of the phases were determined using the vertical displacement of a marker placed on the greater trochanter. For each phase the Root Mean Square (RMS) of the EMG amplitude data was calculated.

sEMG normalization procedure

In order to compare values of different muscle activation patterns, sEMG data were normalised as a percentage of the EMG signal recorded during a dominant leg maximum isometric voluntary contraction of the knee flexors and extensors (MVIC). The MVIC test for knee flexors was performed with participants in the prone position with knees flexed to 30° (anatomical angle). The knee extensors' MVIC was performed with participants sat upright on a high bench with the knees flexed to 90° and hands grasping the edges of the bench for stabilization. MVIC was held for 5 s and the peak 3 s of the EMG signal were used for the normalization purpose. The muscle activity of the BF, ST, VL and VM was recorded and considered the reference value for normalizing EMG signals measured during the DLS, SLSB and DLSB tests.

Statistical analysis

A descriptive analysis was performed and subsequently the Kolmogorov-Smirnov and Shapiro-Wilk tests were applied to assess normality. Four independent 3 (exercises) x 2 (phases) mixed ANOVA models, one per muscle, were performed to determine differences in muscle activation between exercises and over the two phases.

Generalised eta squared (η_G^2) and Cohen´s *d* values were reported to provide an estimate of standardised effect size (small d = 0.2, η_G^2 = 0.01; moderate d = 0.5, η_G^2 = 0.06; and large d = 0.8, η_G^2 = 0.14). The level of significance was set at $p < 0.05$ for all tests. The statistical analyses were performed using IBM SPSS v.22, and the generalised eta squared was calculated by hand as proposed elsewhere (Bakeman, 2005).

Results

Biceps Femoris Activation:

Significant main effects for exercises [F(2,14) = 8.13, p = 0.005, η_G^2 = 0.29] and phases [F(1,7) = 17.33, p = 0.004, η_G^2 = 0.14], and a significant interaction between exercises and phases [F(2,14) = 3.97, p = 0.043, η_G^2 = 0.04] were observed. Subsequent pairwise comparisons revealed significantly higher activation and large effect size in the SLSB compared to the DLS during both descending (p = 0.016, d=1.36) and ascending (p = 0.046, d = 1.11) phases. In addition, close to statistical significance difference (p = 0.078) and a high effect size (d = 0.98), to produce a higher BF activation during the descendent phase in the SLSB compared to the DLSB were determined. Furthermore, close to statistical significance *p*-value and a large effect size to produce higher activation in the DLSB compared to the DLS during the ascending phase (p = 0.096, d = 0.94) were observed (Figure 2A). No other differences were determined.

Semitendinosus Activation,

Significant main effect for exercises [F(2,14) = 13.39, p = 0.001, η_G^2 = 0.31], but not between phases [F(1,7) = 0.13, p = 0.733, $\eta_G^2 \approx 0$] or interaction of exercise and phases [F(2,14) = 0.08, p = 0.792, $\eta_G^2 \approx 0$] was determined. Pairwise comparisons showed higher significant activation and large effect size during the SLSB compared to the DLS for both, the descending (p = 0.042, d = 1.16) and ascending (p = 0.04, d = 1.87) phases. In addition, significant or close to significance differences along with large effect sizes to produce higher ST activation in the SLSB compared to the DLSB during the ascending (p = 0.01, d = 1.51) and descending phase (p = 0.09, d = 0.96) were also determined (Figure 2B).

Figure 2

Vastus Lateralis Activation

Significant main effects of exercises [F(2,7) = 5.78, *p* = 0.015, η_G^2 = 0.12] and phases [F(1,7) = 10.62, *p* = 0.014, η_G^2 = 0.05] were observed. However, no significant interaction effects [F(2,14) = 0.77, *p* = 0.480, η_G^2 ≈ 0] were determined. Pairwise comparison demonstrated significantly higher activation and large effect size in the SLSB with respect to the DLS for the ascending phase (*p* = 0.04, d = 1.17) (Figure 3A). No other differences were determined.

Vastus Medialis Activation

Significant main effect for exercises [F(2,14) = 9.05, = 0.003, η_G^2 = 18] and phases [F(1,7) = 23.97, *p* = 0.002, η_G^2 = 0.07], but no interaction effects [F(2,14) = 0.823, *p* = 0.459, η_G^2 ≈ 0] were determined. Pairwise comparison revealed higher activation and large effect size in the SLSB compared to the DLS during both descending (*p* = 0.05, d = 1.11) and ascending (*p* = 0.021, d = 1.13) phases. Furthermore, close to significance *p*-values and large effects sizes favouring a higher VM activation during the SLSB with respect to the DLSB during both, the descending (*p* = 0.062, d = 1.05) and ascending (*p* = 0.065, d = 1.03) phases were determined (Figure 3B).

Figure 3

Discussion

The main finding of the present investigation was that the SLSB elicited higher hamstring (BF and ST) and quadriceps (VM and VL) muscle activation compared to both the DLS and DLSB. Additionally, the DLS and DLSB produced similar levels of hamstring and quadriceps activation during both the descending and ascending phases.

The observed results can be explained by the higher relative overload applied by the single-leg stance position during the SLSB. The increased overload would potentially augment the demand for activation of the lower limb muscles. In addition, associated postural changes may also influence the higher muscle activity observed during the SLSB. The large relative mass of the trunk can potentially displace the centre of the body mass forward increasing the hip and knee loading and producing higher muscle activation during the unilateral squat (Hewett and Myer, 2011; Horan et al., 2014). Considering that the body acts as an inverted pendulum, in which the centre of gravity is constantly displaced with the trunk muscles acting to maintain the balance (Gage et al., 2004), when reducing the weight-bearing support during the SLSB, the trunk displacement would potentially increase. The degree of trunk displacement is associated with core stability and will be accentuated when the hip muscles are not strong enough to support the increased overload (Hewett and Myer, 2011). Therefore, the reduced support and concomitant increase of the trunk motion might be one of the reasons for the increased muscle activation during the SLSB.

Contrasting with the present study, De et al. (2014) demonstrated no differences in activation of hamstring and quadriceps between unilateral and bilateral squats. Furthermore, McCurdy et al. (2010) reported higher quadriceps and lower hamstring activation during unilateral with respect to bilateral squats. In contrast to our study where participants squatted with no external overload (only the resistance provided by the body mass), both aforementioned studies used different levels of external resistance that was substantially higher for the bilateral compared to the unilateral squat. Thus, the greater absolute overload imposed during the bilateral squat could have caused the similar muscle activation elicited by the single-leg and double-leg squatting techniques used by two mentioned investigations. Other possible causes of discrepancies would be the variety of techniques used to perform the unilateral squat. There is evidence that the position of the non-stance leg could significantly change the biomechanics of the trunk, pelvic and lower extremity (Khuu et al., 2016). In the present study, participants stood on a 30 cm high platform and the non-stance leg was extended throughout the movement. Conversely, the participants assessed by De et al. (2014) and McCurdy et al. (2010) stood on their squatting limb, keeping the other limb elevated behind them (knee flexed) with their toes placed on a stable platform. The contribution of the non-stance foot, specifically during lower positions, may result in an upright trunk position with less flexion of the hip that in turn reduces hamstring activation (Escamilla, 2001).

The present findings suggested no differences in the level of muscle activation when performing a double-leg squat on a stable compared to an unstable surface. These results are in line with previous studies (Andersen et al., 2014; Anderson and Behm, 2005; McBride et al., 2006; Saeterbakken and Fimland, 2013; Wahl and Behm, 2008). Wahl and Behm (2008) reported no significant differences in the lower limb muscles activation when squatting on different unstable surfaces (ie, a BOSU, a Swiss ball, a wobble board etc.). Andersen et al. (2014) showed no differences in muscle activation during a double-leg squat on stable and unstable surfaces (cushion foam). On the other hand, Anderson and Behm (2005) found increased truck muscles activation (i.e. lumbosacral erector spinae and lower abdominal) when squatting on unstable compared to stable surfaces. Therefore, it is possible that the trunk, instead of lower limb muscles, works as the primary stabilizer to maintain balance while squatting on unstable surfaces such as a BOSU, a foam cushion, etc.

In the present study, both the medial hamstring (ST) and quadriceps (VM) produced higher activation (with a large effect size, $d > 1$) during the SLSB than the DLSB in both, the descending and ascending phase. Literature suggests that co-contraction of the hamstring and quadriceps would decrease the load on ACL and potentially prevent ACL from excessive overloading.

Disproportionate increases in activation of the VL also may result in a low quadriceps medial to lateral ratio, an increase in the anterior shear force and the load on the ACL. In addition, high activation of the BF may combine with an unbalanced quadriceps medial to lateral ratio and compress the lateral knee joint, resulting in dynamic valgus (Myer et al., 2005). Serpell et al. (2015) showed that medial hamstring and quadriceps co-activation reduced knee rotation, abduction and translation. Despite the wide utilization of unstable exercises to prevent ACL injury, results from the present investigation indicate that the SLSB elicits higher medial hamstring and quadriceps compared to both the DLS and DLSB. Therefore, using the SLSB would be recommended for improving stability in the frontal plane and potentially prevent ACL injury.

Even though the calculated medial to lateral activation ratio for both hamstring and quadriceps during the SLSB was adequate (> 1), the observed Hamstring to Quadriceps (H:Q) activation ratio was very low (0.20) compared with the recommended value (0.60) to reduce ACL injury risk. The H:Q ratio observed in the present study for the SLSB was in line with others. Dedinsky et al. (2017) reported the H:Q activation ratio during a unilateral squat between 0.17 and 0.39 in females. The low observed ratio would be due to the fact that females are often quadriceps dominant in functional movements and preferably activate their quadriceps over hamstring (Myer et al., 2005). There is evidence that co-activation of the quadriceps and hamstring can decrease the elongation stress on ACL and enhance knee stabilization. Therefore, the SLSB may be beneficial in improving medial to lateral knee balance in the frontal plane, but the level of hamstring relative to quadriceps activation is not sufficient to decrease the quadriceps load on ACL.

Our study is not without limitations. As we compared exercises using athlete's body weight with no external additional loads, the greater muscle activation determined by the unilateral squat movement (SLSB) could be mainly caused by the higher relative overload and not by the exercise technique. Future studies should consider equalising the relative imposed overload to evaluate the level of muscle activations elicited by single vs. double leg squat movements. However, when exercising on stable and unstable surfaces using only athletes' body weight, unilateral squat movements such as the SLSB may improve the knee medial to lateral balance in the frontal plane. Nonetheless, it is important to highlight that as the observed H:Q activation ratio was below the recommended values, combining single leg squatting exercises with other active lengthening hamstring movements, such as eccentric dead lift and Nordic Curl would be also recommended (Monajati et al., 2016).

Conclusions

The SLSB elicited a high level of hamstrings (BF and ST) and quadriceps (VL and VM) compared to other analysed exercises. The higher activation of both the medial hamstring and quadriceps during the SLSB suggested that performing this exercise may be a better option compared to the DLSB to decrease the risk of ACL injury by reducing knee rotation, abduction and translation during different sports movements such as landing and change of direction. However, results of the present study do not invalidate the benefit of unstable exercises, as they may increase activation of trunk stabilizers and improve balance.

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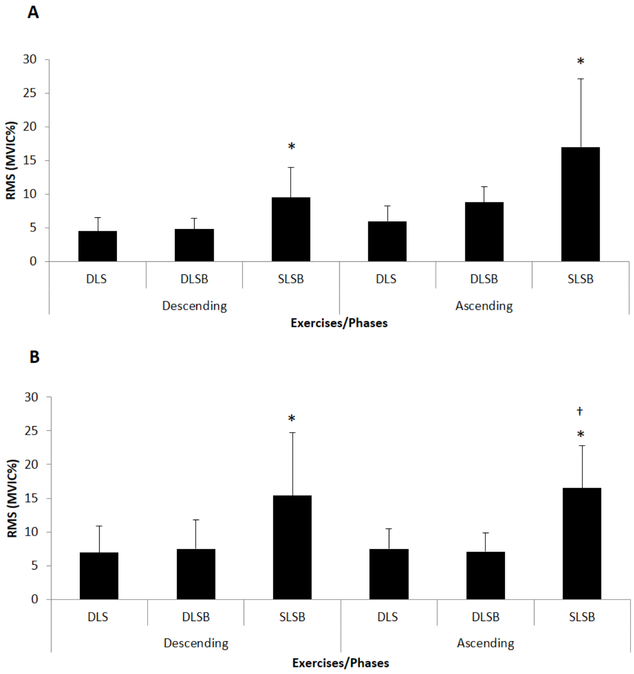
Figure 1. Exercises

Double-Leg Squat (A), Double-Leg Squat on a BOSU® (B) and Single-Leg Squat on a Bench (C).

Figure 1. Normalised EMG activity for the Biceps femoris (A) and Semitendinosus (B). (Mean ± 95% confidence intervals).

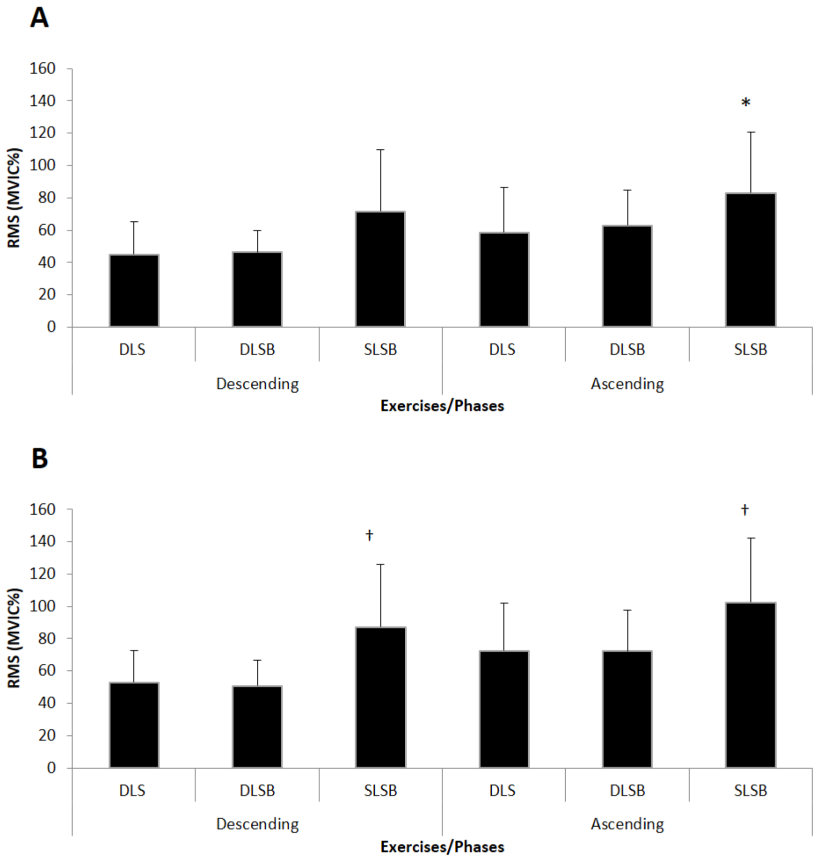


**p < 0.05 from the SLSB to the DLS during both phases for both biceps femoris and Semitendinosus*

† p = 0.01 from the SLSB to the DLSB during the ascending phase for the Semitendinosus

DLS: Double-Leg Squat, DLSB: Double-Leg Squat on a BOSU® and SLSB: Single-Leg Squat on a Bench

Figure 3. Normalised EMG activity for the Vastus Lateralis (A) and Vastus Medialis (B). (Mean ± 95% confidence intervals).



**$p = 0.04$ from the SLSB to the DLS during the ascending phase for Vastus Lateralis*

† $p < 0.05$ from the SLSB to the DLS during both phases for the Vastus Medialis

DLS: Double-Leg Squat, DLSB: Double-Leg Squat on a BOSU® and SLSB: Single-Leg Squat on a Bench.