

Article

Neuromuscular Activation and Symmetry in Isometric Squats: Comparing Stable and Unstable Surfaces

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Abstract

This study aimed to compare muscle activation and neuromuscular symmetry during isometric squat exercises performed on stable and unstable surfaces. Nineteen recreationally active males (aged 18–27) participated in the experiment. A hard floor represented the stable surface, while the unstable conditions included a BOSU ball with the dome side up, a BOSU ball with the flat side up, and a gymnastics mat. Participants performed two 10 s sets of isometric squats on each surface using body weight. Electromyographic (EMG) activity was recorded from the vastus medialis (VM), vastus lateralis (VL), medial gastrocnemius (MG), and lateral gastrocnemius (LG). The central focus of this study was neuromuscular symmetry, which is defined in biomechanics as the balanced muscle activity between homologous and synergistic muscle groups. Since surface instability may influence muscle coordination and postural control, this study investigated whether muscle activation symmetry differs across varying surface conditions. The results showed no statistically significant differences in muscle activation across all surfaces for VM, VL, MG, and LG ($p > 0.05$). These findings indicate that surface stability does not significantly impact the activation or symmetry of these lower limb muscles during isometric squats. Therefore, different surfaces may be used interchangeably in training or rehabilitation programmes without altering muscle engagement. This flexibility could be advantageous for athletes, clinicians, or individuals aiming to diversify exercise modalities or adapt routines based on surface availability.

Keywords: electromyography; BOSU ball; foam surface; surface instability



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1. Introduction

In recent years, training performed on different surfaces has gained increasing popularity in sports sciences, leading to numerous scientific studies in this field. The type of surface used in training plays a significant role in exercise effectiveness and muscle activation. Equipment such as TRX bands, BOSU balls, Swiss balls, wobble boards, and balance discs, along with surfaces like water and sand, are widely utilized in such training protocols.

These surfaces and tools create an unstable contact area, requiring athletes to maintain their balance, which is thought to challenge the neuromuscular system more than stable conditions, potentially leading to greater strength gains through neural adaptations [1–4].

One central concept underlying the evaluation of such exercises is symmetry, particularly in the context of muscle activation patterns, postural alignment, and neuromuscular control. In biomechanics, symmetry refers to the balanced and mirrored function or structure between corresponding body segments—most often between the left and right sides or agonist–antagonist muscle groups [2,5]. Symmetric activation is often a sign of optimal motor control, while asymmetries may indicate neuromuscular inefficiency or injury risk [6]. In isometric squat exercises, assessing whether muscle activity remains symmetric across unstable vs. stable surfaces can provide insight into how these surfaces affect coordinated muscle recruitment and functional balance [7,8].

However, when examining existing studies, different outcomes regarding this effect have been observed. Some studies have concluded that unstable surfaces increase muscle activation compared to stable surfaces [9–16], while other studies have reported either higher activation on stable surfaces or no significant difference between the surfaces [17–25].

The squat exercise is classified as a closed kinetic chain movement and is a widely used exercise for enhancing lower extremity strength. Squat exercises could be performed with both body weight and external load. Similarly to many exercises, squats can be performed using unstable surfaces. Studies focusing on lower extremity muscles similarly yield varying results. Some research suggests that training on different surfaces leads to a greater activation of the lower extremity muscles [26–28], while others indicate that this effect is more limited or that stable surfaces result in higher activation [23–25,27]. Buscà et al. [26] found that half squat exercises performed on the dome and flat sides of a BOSU ball resulted in a greater activation of the vastus lateralis (VL) and vastus medialis (VM) muscles compared to stable and foam surfaces. The unstable structure of BOSU balls was reported to increase muscle activity, providing greater activation than other surfaces. Similarly, Hyong and Kang [27] observed that squats performed on rubber air discs, which result in greater instability compared to stable and foam surfaces, significantly increased VM muscle activation. They suggested that highly unstable surfaces are preferential for enhancing VM muscle activation. Furthermore, Maior et al. [28] determined that squats performed on unstable surfaces elicited significantly higher VM and VL activation compared to stable surfaces, supporting the idea that unstable surfaces are more advantageous for muscle activation. Nonetheless, some studies have reported differing findings. For example, Kim and Choi [5] observed that during squat exercises performed on various surfaces, an increased surface instability led to a higher activation of the soleus muscle but decreased the activation of the quadriceps femoris muscle. In their study comparing the effects of isometric squats performed on surfaces with different stability, McBride et al. [29] reported lower VM and VL muscle activations on unstable surfaces, while no significant difference was observed in gastrocnemius medialis muscle activation. Similarly, McBride et al. [30] determined that dynamic squats performed under unstable conditions result in a significantly lower VL activation compared to stable conditions, suggesting that stable surfaces may be more advantageous for muscle activation. Additionally, Gündoğan et al. [31] reported that during the performance of dynamic squats on various unstable surfaces, VM and VL muscle activations did not show significant differences compared to the stable surface. In line with these findings, Saeterbakken and Fimland [32] also reported no significant differences in VM and VL muscle activation during squat exercises on stable and unstable surfaces.

Although previous studies have compared muscle activation on stable and unstable surfaces, no isometric squat study has included the use of a soft gymnastics mat. Fur-

thermore, studies evaluating the activation levels of gastrocnemius muscles are relatively limited. The existing studies have primarily focused on quadriceps muscles, not the activation patterns of the gastrocnemius muscle, which plays a critical role in impact absorption and postural balance. The gastrocnemius, together with the soleus tendon, contributes to the stabilization of both the ankle and knee during standing [33]. While prior findings reported no consistent differences in quadriceps activation between stable and unstable surfaces, we aimed to investigate whether such differences might emerge in the gastrocnemius due to its crucial function in joint stabilization. Considering the varying results in the existing literature, this study aims to address these discrepancies. The objective of this study was to compare the electromyographic activity levels of the VM, VL, MG, and LG muscles during isometric squat exercises performed on stable and unstable surfaces. To vary the level of instability, four different surfaces were used—a stable surface, a BOSU ball with the dome side up, a BOSU ball with the flat side up, and a soft gymnastics mat. A multi-joint movement like the isometric squat exercise was selected to evaluate the effects of exercise on different surfaces. The use of an isometric movement aims to enhance the accuracy and validity of muscle activity measurements [29]. Additionally, it is considered important to include the medial and lateral gastrocnemius muscles when evaluating the effects of surface training on lower extremity muscles. These muscles play a crucial role in absorbing impact and maintaining balance. Their position close to the surface emphasizes their function in maintaining dynamic balance and may contribute to a better understanding of their effects on muscle activation across different surfaces. Therefore, examining the activation of the medial and lateral gastrocnemius muscles is believed to contribute to a more comprehensive assessment of the effects of surfaces on the neuromuscular system. This study also aims to explore whether different surface conditions may disrupt or preserve neuromuscular symmetry in muscle recruitment. We hypothesized that the muscle activities of MG and LG would be higher on unstable surfaces than on stable surfaces. However, we also hypothesized similar muscle activities for VM and VL across the surfaces.

2. Material and Methods

2.1. Subjects

Nineteen recreationally active males (age: 22.53 ± 2.17 years; height: 175.43 ± 8.31 cm; body weight: 70.72 ± 11.64 kg; body fat percentage: $11.82 \pm 4.43\%$) were recruited in this study. This study was approved by Hitit University Non-Interventional Ethics Committee (Decision No: 2024-08) and all participants signed an informed consent form.

2.2. Procedures

A crossover experimental design was used in this study. In the familiarization session, all participants performed isometric squat exercises on all surfaces. After the familiarization session, participants were given a one-week rest period. In this study, all participants performed isometric squats on the stable surface (S), gymnastics mat (GM), and both sides of the BOSU ball (BB). The BB, both with the dome side up (BB_DU) and the flat side up (BB_FU), and the GM were used as the unstable surfaces. In this study, measurements were conducted over two sessions. In the first session, body weight, body fat, and height measurements were conducted. In the second session, electromyography (EMG) measurements were performed during isometric squat exercises on all surfaces. Before the measurements, participants were instructed to refrain from consuming caffeine or similar stimulants and to avoid engaging in intense physical activity.

2.3. Exercises

Isometric parallel squats were conducted on all surfaces (Figure 1). Two sets of isometric squat exercises were performed on each surface, with each set lasting 10 s. The exercises were performed with body weight. Prior to the exercises, a general warm-up was performed, consisting of 5 min of running followed by 2 min of walking, as well as 5 repetitions of squats, respectively. A 3 min rest period was provided after the warm-up.

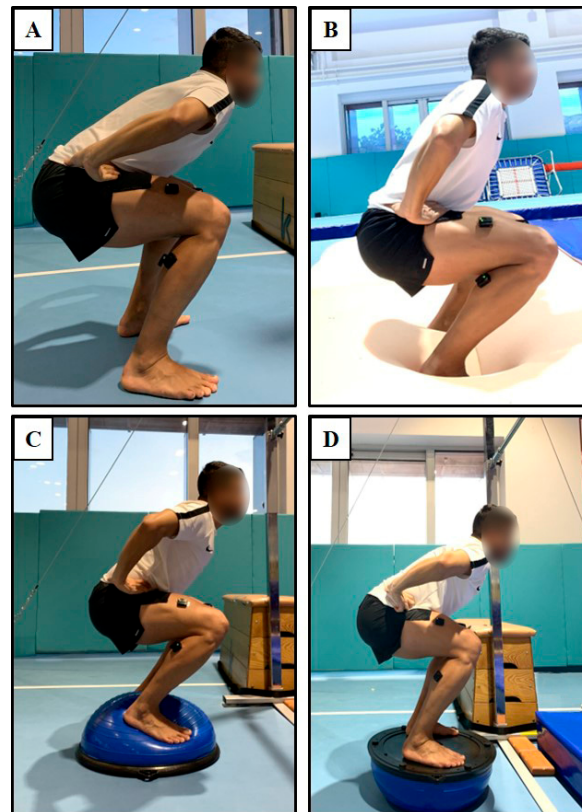


Figure 1. Isometric squat exercises on (A) a stable surface, (B) a gymnastics mat, (C) a BOSU ball with the dome side up, and (D) a BOSU ball with the flat side up.

2.4. Electromyography Measurements

The measurements were conducted using the Delsys Trigno 4-channel electromyography system (Delsys Inc., Boston, MA, USA). The surfaces of the VM, VL, MG, and LG were shaved and cleaned with alcohol before electrodes were placed on the dominant leg. The electrodes were positioned according to the recommendations of SENIAM [34]. The EMG signals were sampled at 2000 Hz and were bandpass filtered at 20–450 Hz. A resistance was provided by using a belt around the shank while participants flexed their knees at 90° in a seated position. In this position, participants tried to extend their knees with maximal force against the resistance in MVIC measurements for the VM and VL muscles [35]. Participants were asked to push a fixed bar upward as hard as possible on the dominant leg, with their knees fully extended and ankles in maximum plantar flexion for the MG and LG [36]. Each MVIC test was conducted over a duration of 5 s. Participants performed two sets of MVIC trials with 1 min rest. The first and last seconds of MVIC data were subtracted, and the middle three seconds of higher MVIC data were used for normalization. Root mean square (rms) analysis was used to analyze raw EMG data. The average peak data of two sets for each surface were normalized to MVIC. The Delsys EMGworks 4.0 Analysis software (Delsys, Boston, MA, USA) was used to analyze raw EMG data.

2.5. Statistical Analysis

All data were analyzed using SPSS software (IBM SPSS Statistic for Windows, Version 25.0, SPSS Inc., Chicago, IL, USA). Data are presented as mean and standard deviation (SD). All muscle activity data are shown as the percentage of MVIC (% MVIC). The Shapiro–Wilk test was used to check the normal distribution of the data. To compare the normalized muscle activities between the surfaces, a one-way repeated-measures analysis of variances (ANOVA) was used. Partial eta-squared (η_p^2) values were computed to evaluate the effect sizes (small: 0.01, medium: 0.06, and large: 0.14). Statistical significance was set at $p < 0.05$.

3. Results

The normalized muscle activities of the VM, VL, MG, and LG are shown in Table 1.

Table 1. Normalized (% of MVIC) muscle activation on four different surfaces.

Muscles	S	GM	BB_DU	BB_FU	<i>p</i>	η_p^2
VM	50.09 ± 17.68	51.77 ± 16.44	52.63 ± 16.20	54.31 ± 17.66	0.409	0.052
VL	40.96 ± 14.29	42.55 ± 13.33	42.55 ± 15.74	43.93 ± 17.06	0.332	0.060
MG	7.21 ± 3.73	7.37 ± 3.87	7.96 ± 3.75	6.82 ± 2.93	0.423	0.050
LG	7.76 ± 4.60	9.22 ± 6.28	8.64 ± 6.89	9.03 ± 5.87	0.357	0.056

S: stable surface; GM: gymnastics mat; VM: vastus medialis; VL: vastus lateralis; MG: medial gastrocnemius; LG: lateral gastrocnemius; BB_DU: BOSU ball with the dome side up; BB_FU: BOSU ball with the flat side up.

There were no significant differences in the VM ($F = 0.980$; $p = 0.409$), VL ($F = 1.141$; $p = 0.332$), MG ($F = 0.949$; $p = 0.423$), and LG ($F = 1.069$; $p = 0.357$) muscle activations across the surfaces ($p > 0.05$). Although there was no significant difference in muscle activation between surfaces, the VM muscle activation was greater in the GM, BB_DU, and BB_FU scenarios by 3.53%, 5.07%, and 8.42%, respectively, compared to the S scenario. Similarly, VL muscle activation was greater in the GM, BB_DU, and BB_FU scenarios by 3.88%, 3.88%, and 7.25%, respectively, compared to the S scenario. MG muscle activation was greater in the GM and BB_DU scenarios by 2.22% and 10.4%, respectively, compared to the S scenario. However, MG muscle activation was lower in the BB_FU scenario than in the S scenario by 5.41%. LG muscle activation was greater in the GM, BB_DU, and BB_FU scenarios by 18.81%, 11.34%, and 16.37%, respectively, compared to the S scenario.

4. Discussion

This study aimed to compare the effects of unstable surfaces on the muscle activations of the VM, VL, MG, and LG muscles during isometric squat exercises. No significant differences were found in the muscle activations of the VM, VL, MG, and LG muscles across the different surfaces tested during isometric squat exercises. This result indicates that the type of surface does not have a notable effect on the activation of these muscles.

Gündoğan et al. [31] investigated the activations of the VM and VL muscles in relation to squat exercises performed on a stable surface, a gymnastics mat, and a BOSU ball. The results showed that the stability of the surfaces did not affect the VL and VM muscle activations. Saeterbakken and Fimland [32] analyzed squats performed on four different surfaces—a stable surface, a power board, a BOSU ball, and a balance cone. Although no significant differences were found in muscle activation between the stable surface and the BOSU ball, a tendency for higher EMG activity in the soleus muscle was noted during squats on the BOSU ball. Moreover, they suggested that trunk muscles might play a primary role in maintaining balance rather than lower limb muscles. Andersen et al. [37] examined the effects of an unstable surface on the VM, VL, biceps femoris, and soleus during squats and Bulgarian squats. They found that using a foam cushion as an unstable surface did

not affect the muscle activity of the VM, VL, rectus femoris, and soleus. However, they stated that the unstable surface reduced the muscle activity of the biceps femoris during Bulgarian squats. Monajati et al. [38] reported no difference in the activation of the VM and VL muscles when comparing squats performed on a stable surface and on a BOSU ball. Similarly to the studies mentioned above, no significant differences were observed in the VM and VL muscle activations in our study, and the second hypothesis was confirmed.

Buscà et al. [26] examined muscle activations during half-squat exercises performed on different surfaces in a sample of 14 elite male and female track and field athletes. Four surfaces were used—a stable surface, foam, the flat side of a BOSU ball, and the dome side of a BOSU ball. The study found that VM and VL activations were higher on the flat and dome sides of the BOSU ball compared to the stable and foam surfaces. The researchers attributed these findings to the unstable conditions provided by the BOSU ball, which enhanced the stabilization functions of the muscles, leading to higher activation levels. Hyong et al. [27] evaluated VM and VL activations during squats performed on rigid plates, foam, and rubber air discs in 14 healthy individuals. Squats performed on the rubber air discs, which offered the most unstable surface, resulted in significantly higher VL and VM activations compared to the other surfaces. Maior [28] conducted a study on 20 males experienced in resistance training to compare the muscle activations of the VM, VL, and rectus femoris on squats performed on stable and unstable surfaces. The findings revealed that squats performed on unstable surfaces led to significantly higher muscle activities compared to on stable surfaces. Aguilera-Castells et al. [39] have reported that no significant differences were found in VM and VL muscle activation between the conditions where the rear foot was on the suspension device and the front foot was on the domed surface of the BOSU ball, where the rear foot was on the suspension device and the front foot was on the stable surface, and where both feet were on the stable surface during the performance of Bulgarian squats.

McBride et al. [29] investigated VL and VM activations during isometric squats on stable and unstable surfaces. The results showed higher VL and VM activations on stable surfaces compared to unstable surfaces during isometric squats. However, no significant differences were found for the medial gastrocnemius between surfaces. Similarly, McBride et al. [30] reported that VL activations were higher on stable surfaces compared to unstable surfaces during dynamic squat exercises. Kim and Choi [5] examined the relationship between soleus and quadriceps femoris activations during squats performed on different surfaces, including a stable surface, an inclined wedge, and a dynamic TOGU balance device. The results indicated an inverse relationship between soleus and quadriceps activations. The quadriceps femoris showed the greatest muscle activity during squats performed on the wedge, whereas the soleus exhibited the highest activation on the TOGU device, which provided greater instability than the other surfaces. These findings suggest that as surface instability increases, soleus activation rises, while quadriceps femoris activation decreases. Wahl and Behm [7] compared the electromyographic activity of the lumbosacral erector spinae, lower rectus abdominis, biceps femoris, rectus femoris, and soleus on a stable surface, a Swiss ball, Dyna Discs, a BOSU ball with the dome side up, a BOSU ball with the flat side up, and a Wobble board during both standing and squatting postures. They reported that the muscle activity of the soleus and lower rectus abdominis in the squatting posture was greater in the Wobble board and Swiss ball conditions. No significant differences were found in relation to other muscle activity among the surfaces. No significant differences were observed in relation to the muscle activities of MG and LG across the surfaces in our study. Therefore, our first hypothesis was not confirmed. Since the gastrocnemius muscle is close to the unstable surface, we expected a greater MG and LG muscle activation in order to absorb the imbalance caused by surface instability. Anderson

and Behm [8] stated that trunk muscle activity was greater on unstable surfaces than on stable surfaces. Saein et al. [40] reported that lumbar erector spinae and multifidus muscle activity on a BOSU ball was higher than on a stable surface during weight-lifting exercises. In addition, Monajati et al. [37] stated that the trunk muscle may work more than the lower extremities to maintain balance as a primary stabilizer during squat exercises. Therefore, there might not have been a significant difference between stable and unstable surfaces in the selected lower extremity muscles in this study.

5. Conclusions

In this study, the activation of the VM, VL, MG, and LG muscles during isometric squat exercises on stable and unstable surfaces was examined. The results showed no significant differences in muscle activation across the surfaces. These findings indicate that different surfaces do not significantly affect the activation of these muscles during squat exercises, suggesting that these surfaces might be used interchangeably in terms of muscle activation. This outcome may encourage athletes and coaches to adopt a more flexible approach to surface selection, as the surfaces used did not produce any noticeable difference in muscle activation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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