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# Balance and plantar load in different squatting techniques

Equilibrio y carga plantar en diferentes técnicas de sentadilla

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**Abstract.** This research aims to analyze dynamic balance and plantar load in different squatting techniques, providing insights into the influence of these exercises in practitioners who incorporate weightlifting into their training routines. A sample of 21 subjects engaged in activities involving three squatting techniques: Back Squat (BS), Front Squat (FS), and Overhead Squat (OHS) was analyzed. Participants assumed a baseline posture and performed exercises with approximately 50% RM for each squatting technique. A plantar pressure measurement system was used to assess center of pressure (COP) displacement, peak pressure (PP), and plantar load in different regions of the foot. One-way Welch's ANOVA considering COP displacement, PP, and percentage of force for each foot region was measured. The results showed no significant effect of the squatting technique on COP trajectory during the exercises. However, a significant interaction was observed between the squatting technique and PP compared to the static balance situation. All three squats resulted in higher PP than static balance, with OHS exhibiting the highest values, followed by FS and BS. No significant differences were found between the squat techniques. These findings suggest that different squat techniques can influence plantar load, but do not affect the trajectory of the COP during the execution of the exercise. The heel region generated the greatest plantar load among the three squat techniques and should receive greater attention during the squat and its variations. This information can assist in prescribing exercises and developing more efficient training programs for weightlifters.
**Keywords:** Postural Balance; Strength Training; Force Sensor.

**Resumen.** Esta investigación tiene como objetivo analizar el equilibrio dinámico y la carga plantar en diferentes técnicas de sentadillas, proporcionando información sobre la influencia de estos ejercicios en practicantes que incorporan levantamiento de pesas en sus rutinas de entrenamiento. Se analizó una muestra de 21 sujetos que realizaron tres técnicas de sentadilla: Sentadilla Trasera (ST), Sentadilla Frontal (SF) y Sentadilla de Arranque (SA). Los participantes adoptaron una postura de referencia y realizaron los ejercicios con aproximadamente el 50% de su RM para cada técnica de sentadilla. Se utilizó un sistema de medición de presión plantar para evaluar el desplazamiento del centro de presión (COP), la presión máxima (PM) y la carga plantar en diferentes regiones del pie. Se midió un ANOVA de Welch unidireccional considerando el desplazamiento del COP, la PM y el porcentaje de fuerza en cada región del pie. Los resultados no mostraron un efecto significativo de la técnica de sentadilla en la trayectoria del COP durante los ejercicios. Sin embargo, se observó una interacción significativa entre la técnica de sentadilla y la PM en comparación con la situación de equilibrio estático. Las tres sentadillas resultaron en una PM más alta que en el equilibrio estático, siendo la SA la que mostró los valores más altos, seguida por la SF y la ST. No se encontraron diferencias significativas entre las técnicas de sentadilla. Estos hallazgos sugieren que las diferentes técnicas de sentadilla pueden influir en la carga plantar, pero no afectan la trayectoria del COP durante la ejecución del ejercicio. La región del talón generó la mayor carga plantar entre las tres técnicas de sentadilla y debería recibir mayor atención durante la sentadilla y sus variaciones. Esta información puede ayudar en la prescripción de ejercicios y en el desarrollo de programas de entrenamiento más eficientes para levantadores de pesas.
**Palabras clave:** Equilibrio Postural; Entrenamiento de Fuerza; Sensor de Fuerza.

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## Introduction

Generating high levels of muscular strength is crucial for success in many sports (López-Trujillo et al., 2022; Suchomel et al., 2016). Many sports incorporate weightlifting training to enhance muscular strength (Young, 2006). Weightlifting training with a bar involves moving the load freely in space through specific exercises where the distal part of the lower limb remains fixed, with squatting and its variations being prime examples (Jewiss, Ostman, & Smart, 2017). Squatting is a closed kinetic chain exercise used in physical and sports training (López-Trujillo et al., 2022). During this exercise, the hip, knee, and ankle joints flex during the eccentric muscle action and extend during the concentric phase (Escamilla et al., 1998). Athletes often include barbell squats in their training or rehabilitation programs (Pareja-Blanco et al., 2021; Wisløff et al., 2004).

Different types of squats can be used to progress the training load (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). The most common squat variations include the Back Squat (BS), where the individual performs the exercise with the barbell on their shoulders and behind the neck (Yavuz et al., 2015; Straub & Powers, 2024), the Front Squat (FS), where the barbell is positioned in front of the clavicle and over the anterior deltoid muscle (Spitz et al., 2019; Kasovic et al., 2019) and the Overhead Squat (OHS), where the barbell is held above the head with the elbows fully extended during the movement (Bautista et al., 2020; Roth et al., 2020). Studies have shown that, despite the similarities in squatting techniques for the lower limbs, they impose different demands on trunk muscles when comparing BS and OHS (Aspe & Swinton, 2014), with BS requiring greater trunk lean compared to FS (Diggin et al., 2011; Spitz et al., 2019). OHS is more challenging as it necessitates greater thoracic extension, a more upright posture, and stabilization of the humerus and scapula (Bautista et al., 2020). Therefore, it activates more muscles than other variations (Neto et al., 2023), requiring greater stability control.

Since stability and balance influence postural control and center of mass, they are key parameters for success in barbell lifts (Zemková, 2014). Barbell placement has the potential to alter trunk positioning, leading to increased instability and, consequently, greater requirements for balance. Few studies have examined balance and plantar load during squat variations. The pioneering study by Adelsberger & Tröster (2014) compared the effects of a general warm-up and stretching protocol on displacement of center of pressure (COP) displacement during squat techniques. The authors observed changes in stability following warm-up routines in only some squat techniques, with some contradictory results. This may have been due to the evaluations not using loads beyond the barbell during squats. Furthermore, not reflecting the realities of training allows the performer to execute movements at higher speeds, which could affect COP displacements. Since speed and external load have an inverse relationship, using less weight during lifting might cause practitioners to perform movements at a faster and non-habitual pace (Petridis, Pálinkás, Tróznai, Béres, & Utczás, 2021).

In this context, no evidence has been found so far for balance assessments with practitioners using external loads similar to their training. Therefore, the real influence of different squat types on dynamic balance and plantar load remains unknown. Thus, the aim of this study was to evaluate balance and plantar load in different types of squats. Based on the literature on this topic and the varying complexities of squat types, we hypothesize that there will be differences in balance and plantar load among the exercises.

## Methods

### *Sample*

Sample size was determined based on the results of Adelsberger & Tröster's study (2014) for an effect size of 0.89 (considered a large effect) with a statistical power of 99% and a p-value of 0.05, resulting in a minimum of 12 participants. The software used for calculation was GPower v 3.1.9.6 (GPower, Kiel, Germany). Considering the possibility of sample loss, this study evaluated 21 men with an average age of 31.1 ± 6.8 years, who were practitioners of activities involving all three squatting techniques. The participants had recreational strength training experience for a minimum of 36 months, with at least 150 minutes of training per week, performed more than once a week. Additionally, they had not suffered any injuries in the past three months or experienced any disabling muscle pain and had not trained in the 48 hours before the tests. The participants signed an Informed Consent Form (ICF) before participating in the study, which was approved by the local Ethics Committee under protocol number 3.290.772.

### *Experimental Design*

The tests were conducted at the same time of day, with an average duration of 40 minutes. All participants performed the tests barefoot. In the baseline test, the participants stood on two sensors, one for each foot, positioned 15 centimeters apart while fixating their gaze on a target located approximately at eye level, 4 meters away, for thirty seconds (Adelsberger & Tröster, 2014) subsequently, before performing the squats, participants underwent warm-up supervised by a coach. The warm-up routines consisted of a combination of 3 sets of 15 repetitions for BS and OHS with only a barbell. During warm-up sets, subjects were permitted a minimum of 2 minutes and a maximum of 4-minute rest (Aspe & Swinton, 2014). Participants performed the exercises with approximately 50% of their self-declared one-repetition maximum (1-RM) for each squatting technique. The order of squats was randomized. In each squat, the sensors were positioned according to each participant's base for each squat technique. Before performing each squat, the participants stood on the sensor while holding the barbell with the pre-defined load for sensor calibration and zeroing (Figure 1 A). This procedure was necessary because the load was specific to each squatting technique. The squat cadence was set at 60 beats per minute (BPM) with equal duration in the descending and ascending phases, controlled by a metronome. Regarding the depth of the squat, participants were asked to finish the eccentric phase when the thigh was approximately horizontal. A maximum of 15 repetitions were executed, with data collected from two cycles for each squat, totaling 8 seconds of data collection.

### *Pressure sensor measurement system*

The data was measured using an F-Scan™ sensor (Tekscan Inc., MA, USA), composed of a thin plastic insole containing 1260 force-sensitive resistors (Figure 1 A), capable of estimate balance and plantar load (Adelsberger, Valko, Straumann, & Troster, 2015). Force data were structured in a two-dimensional matrix, including the displacement of center of pressure (COP) in mm² in the anteroposterior and mediolateral directions. The X coordinates represented transverse (mediolateral) displacement, and the Y coordinates represented longitudinal (anteroposterior) displacement. The total displacement of the COP is determined by the root mean square of the anteroposterior and mediolateral displacements. The COP data acquired by the sensors are correlated with the individual's ability to manage balance. Plantar load data was used to determine the loads distribution (pressure in Kpa) on the feet during the squat. The feet were divided into three regions (heel, midfoot, and forefoot), and the relative load on each region was determined as a percentage of body weight (Mann et al., 2015; Sterzing et al., 2016).

***Statistical Analysis***

Data are presented as the mean and standard deviation. Normality of the data was assessed using the Kolmogorov-Smirnov test. To examine the interaction between squats, a one-way analysis of variance (ANOVA) was performed considering COP displacement, pressure, and the percentage of force for each foot region, followed by Games-Howell post hoc analysis. The assumption of sphericity was checked using Mauchly's test. The magnitude of differences was calculated using $\eta^2$ (eta-squared) (Bakeman, 2005). The adopted effect size classification was: 'small' (0.0 - 0.25), 'medium' (0.25 - 0.40), 'large' (above 0.40) (Richardson, 2011). Data collected were exported to the SPSS statistical software package (SPSS 18.0, SPSS, Inc., Chicago, IL, USA). The significance level was set at $p < 0.05$ for all tests.

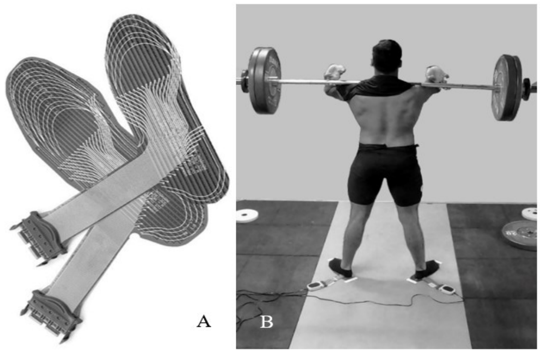


Figure 1. Pressure sensor (A) and execution of the Front Squat on the sensors (B).

## Results

The ANOVA results indicate that there is no significant effect of the squatting technique on the COP trajectory (Figure 2) when compared to the static balance situation (baseline) or among the squats [F (3, 43.210) = 2.303; p= 0.091].

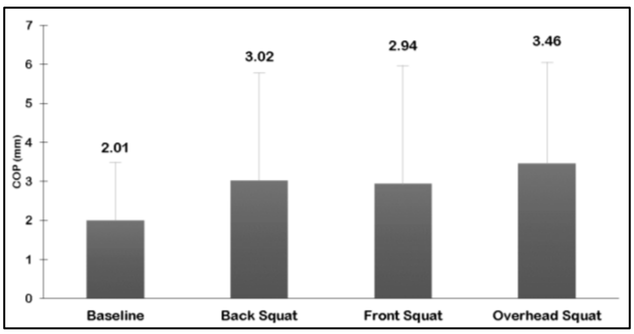


Figure 2. Total COP trajectory (mm) in the baseline position and in the three squatting techniques.

In relation to the peak pressure (PP), an interaction between the squatting technique and the static balance situation (baseline) was observed [F(3, 45.250) = 11.335; p= 0.001]. All three types of squats resulted in higher PP compared to the baseline, with the highest values observed during the Overhead Squat (OHS) execution, followed by Front Squat (FS) and Back Squat (BS), all showing a large effect size (d= 1.24) for each squat technique. No significant differences were found between BS and FS (p=0.933), BS and OHS (p=0.898), or FS and OHS (p=0.999). Figure 3 illustrates the results for peak pressure.

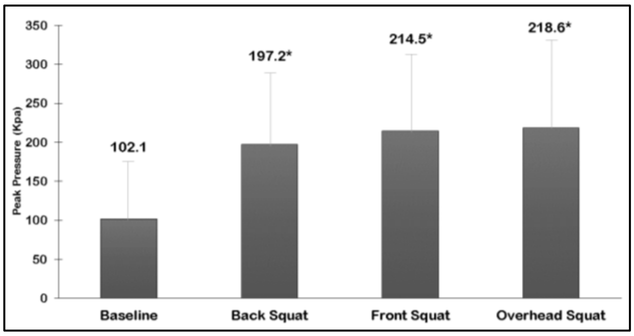


Figure 3. Peak pressure (Kpa) in the baseline position and in the three squatting techniques. *Difference from baseline (p<0.05).

Regarding plantar load in each foot region, the squatting technique had a significant effect on the relative force to body weight in the heel region [F(3, 42.574) = 12.628; p= 0.001], in the metatarsal region [F(3, 43.151) = 4.576; p= 0.008], but no effect in the midfoot region [F(3, 79) = 2.241; p= 0.072] (Figure 4). The heel region exhibited the highest percentage values of plantar load, followed by the metatarsal and midfoot regions, in both the baseline and squatting conditions. Games-Howell post hoc analysis revealed differences in the heel region compared to the baseline for BS (p= 0.004), d= 0.35 (considered medium), FS (p=0.001), d= 0.12 (considered small), and OHS (p= 0.001), d= 0.58 (considered large), with higher values in FS. In the heel region, there were no significant differences in relative force to body weight between BS and FS (p=0.949), BS and OHS (p= 0.989), or FS and OHS (p= 0.790).

Games-Howell post hoc analysis also showed differences in the metatarsal region compared to the baseline, with the highest values in BS (p= 0.001), presenting a large effect size of d= 0.89, followed by FS (p= 0.001), with a large effect size of d= 0.66, and OHS (p= 0.001), with a large effect size of d= 0.62. In the metatarsal region, there were no significant differences between BS and FS (p=0.993), BS and OHS (p=0.646), or FS and OHS (p= 0.902).

The midfoot region exhibited lower percentage values of plantar load. In comparison to the baseline, there were no differences between BS (p= 0.086), FS (p= 0.074), and OHS (p= 0.194), with higher values observed in the back squat execution. In this region, there were no significant differences between BS and FS (p= 0.999), BS and OHS (p= 0.619), or FS and OHS (p= 0.568).

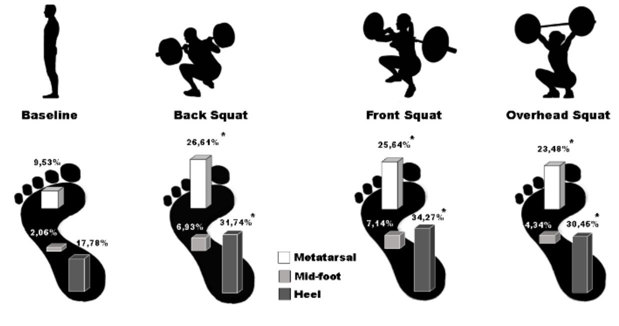


Figure 4. Plantar load in (N) relative to body mass in the baseline position and in the three squatting techniques. *Difference from baseline (p<0.05).

## Discussion

The aim of this study was to assess dynamic balance and plantar load in different squatting techniques. The main results showed that the three squatting techniques did not exhibit significant differences among them in any of the measured variables. Consequently, we reject our initial hypothesis regarding potential differences in different squatting techniques. Similar results were found in the comparison between BS and OHS in peak force assessment using a force platform (Aspe & Swinton, 2014).

When compared to the baseline position, COP displacement did not show significant differences for the different squats. Despite the bar being positioned differently in each squat and requiring body adjustments, the balance management among the three squat types was similar. This result may be attributed to the task performed by the practitioners and their technical efficiency in weightlifting (Zemková, 2014). Efficient technique would result from a 'compensatory mechanism' that improves balance by keeping the center of gravity aligned (Christ et al., 1989; Roth et al., 2020). This could happen because the bar's position affects trunk muscle activity more, and these balance corrections would result in a smaller center of pressure trajectory (Roth et al., 2020). According to Kitamura et al. (2019) the center of pressure displacement can change based on individuals' trunk positions. The more flexed the trunk is, the greater the anteroposterior displacements performed by the COP. Therefore, the OHS would be more challenging and susceptible to greater displacements (Gholami Borujeni & Yalfani, 2019). Athletes in this discipline are able to perform squats correctly with minimal postural oscillations, which is why their balance is similar, as they always perform the movements with the same support base, favoring balance in unstable situations (Zemková, 2014).

When comparing the baseline position to each squat, significant differences were found in PP and force in the foot regions. In relation to baseline PP, OHS showed the highest values (114.6%), followed by FS (110.6%) and BS (93.5%). These higher values for the squat compared to baseline were expected since each participant used the bar and load in all three squat techniques. The highest loads were in BS, followed by FS, and OHS. However, OHS had the highest PP value despite having the lowest external load among the squats. Thus, we can deduce that the increased pressure was due to a reduction in the force application area. This could be a strategy to reduce oscillations in this more challenging squat technique (Gholami Borujeni & Yalfani, 2019).

Regarding plantar load, compared to the baseline position, the heel and metatarsal regions showed significant differences, but there were no differences in the midfoot region. In the baseline position, there was greater force in the heel, consistent with the study by Hawrylak & Gronowska (2020).

Heel load showed differences in relation to the baseline in different squat techniques. There was a 92.1% increase in plantar load in FS, followed by BS (78%) and OHS (71.6%). This is in line with the findings of Koh et al. (2015). The FS moves the bar and the center of gravity more anteriorly, leading to a compensatory movement in which the trunk becomes more vertical, transferring pressure to the heel region, as observed by Yu et al. (2018), indicating a potential strategy to improve balance and reduce COP oscillation. The BS and OHS allow the torso to lean more forward compared to the FS. As the trunk leans forward and the hip joint flexes, this results in a backward movement of the hip (Hoogenboom et al. 2023) and consequently there is greater inclination of the tibia (Straub & Powers, 2024). Therefore, depending on the flexibility of the ankle joint, as the tibia tilts, there would be a decrease in the load placed on the heel due to ankle dorsiflexion. This could explain why the BS and OHS loads were slightly lower. This change occurs mainly in the ankle plantar flexor structure, which is attributed to the favorable changes in postural balance (Vásquez-Orellana et al., 2022; Sáez-Michea et al., 2023). The concentration of force near the ankle joint might serve to minimize external torque generated by the horizontal distance between the bar and the ankle joint during the squat cycle.

In comparison with the baseline, the metatarsal region displayed distinct force patterns, with BS recording the highest force (179%), followed by FS (169.7%) and OHS (146.4%). This phenomenon can be linked to the inherent instability introduced by squatting, resulting in greater oscillation, especially in the anteroposterior direction (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). This oscillation causes a transfer of forces from the forefoot to the heel region and vice versa, with a reduced load in the midfoot. The dominance of anteroposterior oscillation during the squat cycle, as discussed by Escamilla, Fleisig, Lowry, Barrentine, & Andrews (2001), underscores the intricate interplay of biomechanical factors. Additionally, the uniaxial movement of the ankle joint, situated closer to the heel, plays a pivotal role in influencing forces in the anteroposterior direction (Trajković, Kozinc, Smajla, & Šarabon, 2021). This study has some limitations, one of the main ones being the comparison of dynamic squatting movements with an almost static position. Certainly, these differences would be found because the baseline position generates low demand in terms of oscillations and plantar load. However, our study provides a much more realistic assessment of sport's reality.

The positioning of the feet during the execution of the movements was customized, with adjustments made for each participant. The sensors were placed in the position in which each participant performed each squat, potentially leading to variations in plantar pressure and center of pressure parameters with different support bases. Nonetheless, these adjustments aimed to closely replicate each participant's training conditions. Another aspect to consider was the standardization of squat execution speed, which may have contributed to minimal differences in COP and PP parameters during squats. However, this standardization was deemed necessary as it aimed to maintain consistency in squat techniques evaluated, rather than examining the relationship with execution speed.

The use of self-declared one-repetition maximum may also be considered a limitation. The accuracy of this load may not reflect the exact value for the test. On the other hand, all participants have experience with weightlifting, and they all know approximately what their personal record, or 1RM, is. Fifty percent of this value allows participants to perform at least 12 repetitions without experiencing fatigue. Another point is that before each squat, participants stood on the sensor while holding the bar with the pre-defined load, and the sensor was zeroed. Therefore, the load did not interfere with the values analyzed in this study.

## Conclusion

The different bar positions in the three squat techniques created varying demands that were offset by the technical efficiency of the participants. The heel region generated the greatest plantar load among the three squat techniques and should receive greater attention during the squat and its variations. Regarding balance management, it was possible to observe that, in relation to the basal position, the OHS proved to be more challenging. The heel region generated the greatest plantar load among the three squat techniques and should receive greater attention during the squat and its variations. New studies relating plantar load and balance to possible injuries or in different percentages of 1-RM may provide more information about the squat.

## Conflicts of interest

The authors declare no conflict of interest.

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