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Influence of the base of support widths on postural control and feet loading symmetry during squat – preliminary study

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Purpose: The symmetry of feet loading and adequate postural control are crucial aspects of proper squat performance. The study aimed to evaluate the effect of various stance widths during squat on postural control and symmetry of feet loading. *Methods*: Thirty healthy individuals participated in this study. Each participant performed one type of squat with a narrow stance (NS), hip stance (HS) and wide stance (WS). *Results*: A significantly higher value of CoP path length, the velocity of sways and Area95 were obtained for the WS squat compared to NS and HS. In addition, the wide feet setting significantly affected not only the feet loading symmetry but also the strategy (high LyE), the amount of irregularities (high SampEn) and the CoP time-series roughness complexity (high FD). It has been shown that as the base of support grew, the asymmetry index grew. *Conclusions*: The wide squat is less stable, requiring more complex postural control behavior and more flexibility. Performing this squat significantly shifts the pressure to the dominant limb.

Key words: *biomechanics, fractal dimension, sample entropy, center of pressure, symmetry index*

1. Introduction

Daily activities such as sitting down, standing up, picking up things from the ground have components of a squat movement pattern [23]. Squat exercises are commonly used in the physiotherapy process (e.g., to restore quadriceps muscle strength [41]) and in training to enhance performance and build injury resilience [29]. Squatting requires a full range of motion in multiple joints and is considered an almost symmetrical task. Symmetry is one of the most important aspects of biomechanics and other scientific areas. It is commonly used to quickly assess the correctness of performing movements with symmetrical definitions [1], [3]. The symmetry of motion can be assessed based on kinematics (joint angles) and kinetics (ground reaction forces, joint torques) parameters [2]. These parameters can be obtained from motion capture systems and platforms. There are many indices used to assess the degree of asymmetries such as symmetry index, symmetry ratio and symmetry angle. In recent years, more sophisticated methods of assessing symmetry, such as: statistical parametrical mapping [38], dynamic time warping [3] and principal component analysis [27] have emerged. Researchers use various techniques and factors to assess different types of squats [37]. These are stance width, foot angle placement and additional load.

One of the most important elements of performing a correct squat is the symmetrical distribution of plantar pressure [20] and proper postural control. Plantar pressure is defined as the distribution of force over the foot sole. Therefore, the foot's placement during the squat may disturb its symmetry and correct performance. The only possible way to assess postural

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control is to measure the movement of the center of mass (CoM) or center of foot pressure (CoP). According to Swinton et al. [39], during the traditional squat, the knee traveled past the toes resulting in anterior displacement of the system center of mass. In contrast, during the powerlifting and box squat, a more vertical shin position was maintained, resulting in posterior displacements of the CoM. Thus, the wide feet placement caused the decreasing displacements of the center of pressure in the sagittal plane. The center of pressure is the linear parameter that assesses displacements in anterior-posterior and medio-lateral directions. Its most common use is to assess postural stability [15]. Woo Ram Yoon [42] reported that changes of CoP during squats provide quantitative information to trainers who would like to teach correct movements for developing muscles. Da [5] reported that the CoP was moving towards the heel as squat depth increased.

The different method to assess the CoP signal is associated with the dynamic approach [15]. There are nonlinear measures that make it possible to asses the regularity, adaptability to the environment, stability and complexity of the CoP signal [17]. It is worth adding that nonlinear measures provide indirect insight into the work of the nervous system and allow for a more comprehensive assessment of postural control. The first nonlinear measure is sample entropy (SampEn), which is used to determine the regularity of postural sway and quantifies the temporal structure of the signal [33]. Lower values of SampEn point out that the CoP signal is predictable, more regular, which is related to less complexity of the system. Higher values indicate increased complexity, larger irregularity of the signal and less predictability [13]. This is also a sign of improved self-organization and effective strategy in postural control [8]. The next nonlinear measure is fractal dimension (FD), which indicates the complexity of the signal [7] and may be indicative of a change of the control strategies used for upright control [9]. The Lyapunov exponent (LyE) is a measure that assesses the resistance of the human control system to perturbations. A higher LyE points out to the capability of the more rapid response of balance control in different body movements [22]. The low values of LyE mean the rigidity of the system and inability to adapt to the environment, high values indicate the ability to react faster to destabilizing factor and better control of balance [31]. In the current literature, no studies analyzing the complexity of postural control and symmetry of feet loading during the squat have been found. This study aims to quantify the effect of various stance widths on postural control during squat and symmetry feet loading.

2. Materials and methods

2.1. Participants and procedures

Thirty healthy people (15 men and 15 women) aged 22.96 ± 1.8 years with a mean body height of 1.67 ± 0.02 m, a body weight of 66.08 ± 6.78 kg participated in this study (Table 1). Most of the participants were students at the Rehabilitation Department and most of them have been fitness instructors or personal trainers with an average of 2 years of experience.

Table 1. Mean and standard deviation of participants' characteristics

Subjects	Age [years]	Body height [m]	Body weight [kg]
Female (*n* = 15)	22.87 ± 1.64	1.67 ± 0.02	66.08 ± 6.78
Male (*n* = 15)	23.73 ± 1.94	1.68 ± 0.02	69 ± 7.94
Total (*n* = 30)	22.96 ± 1.8	1.67 ± 0.02	66.08 ± 6.78

All participants reported practicing physical activity (gym or aerobics) at least twice a week. The instructors trained for at least 2 hours every day. Various squats were one of the most frequently performed parts of their training. Each of the study participants was previously observed during fitness classes. It allowed for the elimination of people who were not able to perform the correct squats (e.g., limited mobility in the joints). The squats were assessed based on the guidelines provided in the paper [30]. In addition, no participants declared any sensory impairment, physical injury, or increased physical or mental stress that hindered the performance of the squat tasks. Moreover, all of them declared to have a dominant right leg. According to Promsri, Longo, Haid, Doixand Federolf [34], leg dominance was defined as the preferred leg for kicking a ball. The dominant leg of all participants was coincidental with their dominant hand determined from the writing hand. Thus, in this case, the left leg was considered the supporting (non-dominant) limb. In the week in which the measurement was to take place, the subjects were not to have intense activities causing them muscle pain or the presence of soreness. The research was carried out in the morning (10 a.m. – noon). Before the measurement, the participants were informed about the procedures used and the possibility of withdrawing from the experiment at any moment. The study protocol was conducted according to the ethical principles of the Declaration of Helsinki and was approved by the institution's ethics committee (SEK 01-09/2020).

Before measurement, each participant had Tabata's workout that lasted four minutes. Participants did eight rounds of 20 seconds of exercises followed by 10 seconds of rest. The motions included: running in place, skip A, jumping jacks, squat jumps. Each exercise was repeated in two rounds. After the warm-up, the participants were instructed how to perform the squats. They were allowed to perform a few squats without measuring as instructed. All subjects performed three different types of squats, depending on stance widths (Fig. 1a–c). Each squat was barefoot with the arms crossed over the chest (each hand was on the opposite shoulder) (Fig. 1d).

The following feet settings were taken into account: narrow stance (NS), hip stance (HS), and wide stance (WS), with foot angle always placements set at 0 degrees. Narrow stance (NS) – meant that the squat was performed with the feet pressed together (Fig. 1a). Hip stance (HS) – meant that the squat was performed with the feet positioned on the width of the subject's hips (Fig. 1b). The wide stance (WS) – meant that the squat was performed with the feet 3 feet apart (Fig. 1c). It is worth noting that the squats described were consistent with those listed in the paper of Lorenzetti et al. [23] as NS-0°, HS-0° and WS-0°.

Each participant performed each type of squat once (duration: 15 sec) (Fig. 1d). Time was measured using a metronome 60 BPM (Beats per Minute Metronome click). Participants knew they had a time of 15 metronome beats. A single squat cycle was defined with participants starting in an upright position (duration of 5 sec = 5 metronome beats), moving downwards to the lowest point possible and returning to the upright position (remaining time). During the squat, the heels could not leave the floor. Before each trial (squat), the system was calibrated according to the manufacturer's recommendations. The platform was properly level and set on a hard floor in the laboratory. During measurement, the stance analysis FDM module was used. Between each squat, the participants received a two-minute rest to minimize the possible effects of fatigue [24] and calibrate the system. For all conditions, standardized instructions were provided as follows: (1) Stand upright and place feet according to the squat's type. Keep your back straight and your arms on the opposite shoulders. Keep this position 5 seconds; (2) Perform the squat at the same speed in the downward and upward movements; (4) Go as far downward as possible, at least bringing your thigh parallel to the floor; (5) Get down in 5 seconds; (6) Go up in 5 seconds; (7) Do not get your heels up.

Center of pressure (CoP) trajectories in the anterior-posterior (AP) and medio-lateral (ML) directions were measured using the Zebris FDM at a sampling rate of 100 Hz. The study used three nonlinear measures to assess CoP dynamics: sample entropy (SampEn), the largest Lyapunov exponent (LyE), and fractal dimension (FD). The nonlinear coefficients were counted using MatLab software separately for AP and ML direction.

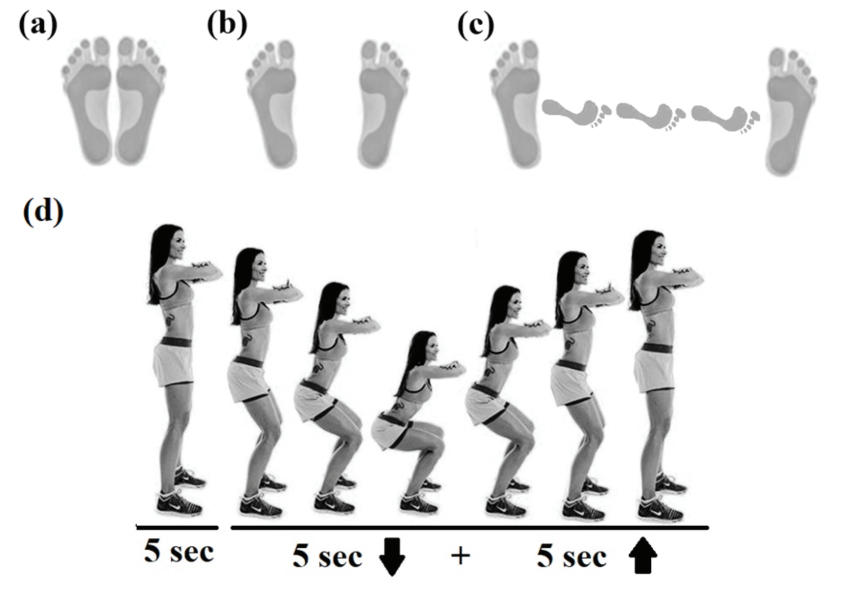

Fig. 1. The foot placement during squats: (a) narrow stance (NS), (b) hip stance (HS), (c) wide stance (WS) with the feet 3 feet apart and (d) the squat phase over time

Sample entropy (SampEn)

Using sampEn makes it possible to calculate the probability that a sequence of N-data points, having repeated itself within a tolerance r for m points, will also repeat itself for $m + 1$ points, without allowing self-matches: SampEn(m, r, N) = $-\ln\left(\frac{A^m(r)}{B^m(r)}\right)$. B represents the total number of matches of length m while A represents the subset of B that also matches for $m + 1$. Thus, a low SampEn value arising from a high probability of repeated template sequence in the data, hence, greater regularity. For calculating the SampEn, we used the MatLab codes obtained from Physionet tool [11] and the "default" parameters: $m = 2$, $r = 0.2*\mathrm{SD}$, where SD is standard deviation.

The largest Lyapunov exponent (LyE)

This measure is a gauge of the local stability of a system, i.e., its resistance to small internal perturbations, such as the natural fluctuations that occur while maintaining an upright stance [36]. The idea of using LyE to identify chaos in a system is based on the assumption that if the average distance between two points increases at the exponential rate, then, the system is sensitive to a change in initial conditions and the value of LyE is greater than zero. Thus, LyE can be defined using the following equation: $d(t) = Ce^{\mathrm{LyE}t}$, where: $d(t)$ is the average divergence at time t and C is a constant that normalizes the initial separation [16]. Therefore, the existence of a positive LyE is often considered a necessary and sufficient condition for the presence of chaos in the system.

Fractal dimension (FD)

It can be used to estimate the dimensional complexity of time-series. The FD was calculated using Higuchi's algorithm [14], which was written in Matlab. Higher FD values are associated with greater complexity of the CoP path, with lower FD values indicative of a less complex (or 'straighter') CoP path.

Additionally, parameters that assess the stability and feet loading were exported. The parameters evaluating the stability included: CoP path length, the area of the 95th percentile ellipse (Area95) and CoP velocity. However, the parameters assessing the feet loading included: left and right forefoot loading [%], left and right back foot loading [%] and total foot loading separately for left and right foot [%]. For loading parameters the symmetry index (SI) was calculated according to the following formula [1]: $SI = \frac{|X_L - X_R|}{0.5\cdot(X_L + X_R)}\cdot 100\%$. The SI factor is a method of percentage assessment of the differences between the parameters for both lower limbs during squats. The value of $SI = 0$ indicates full symmetry, while $SI \geq 100\%$ indicates its asymmetry [1].

2.2. Data analysis

Statistical analyses were performed using Statistica v.12 (StatSoft, Tulsa, USA), with the significant p-value set at 0.05. All coefficients were tested for normal distribution, using the Shapiro–Wilk test. The two-way ANOVA and post-hoc Tukey's HSD test were used to explore the influence of sex and feet width (NS, HS, WS) and their interaction on all linear (Area95, CoP path length and average CoP velocity), nonlinear parameters (SampEn, FD, LyE) and feet loadings (forefoot pressure [%], back foot pressure [%] and total pressure [%]). Next, to assess the differences within the type of squats for feet loading (left vs. right), the t-test for independent samples was used.

3. Results

All of the analyzed parameters had a normal distribution. There was no statistically significant influence of sex on the linear and non-linear parameters within squats.

3.1. Body balance parameters

The two-way ANOVA results showed the existence of a statistically significant influence of the type of squat on the following linear parameters: CoP path length, Area95 and average CoP velocity. After conducting the post-hoc Tukey's HSD test, the significantly lower values were noted for NS ($p = 0.0001$) and HS ($p = 0.0001$) squats in comparison to WS squat (Figs. 2a–c).

For nonlinear parameters, significant differences were found for all nonlinear parameters in the AP direction between NS, HS and WS squats (Figs. 2d–f): (1) SampEn_AP, $p = 0.0003$; (2) FD_AP, $p = 0.0001$; (3) LyE_AP, $p = 0.0001$. The highest values were noted for the WS squat in the AP direction. It is worth adding that the values of all nonlinear parameters were significantly higher in the AP direction in relation to the ML direction for each type of squat.

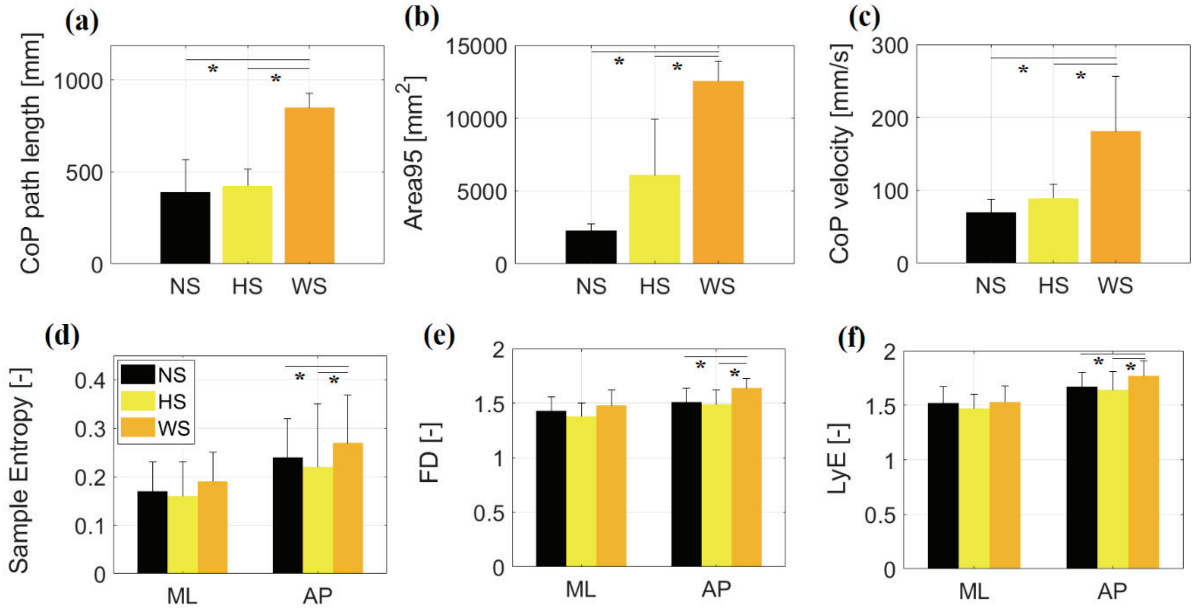

Fig. 2. The mean and standard deviation values of linear: (a) CoP path length, (b) the area of the 95th percentile ellipse (Area95), (c) average CoP velocity and nonlinear parameters: (d) sample entropy, (e) fractal dimension (FD), (f) Lyapunov exponent (LyE), where: AP – anterio-posterior direction, ML – medio-lateral direction, * marks statistically significant differences ($p \leq 0.05$)

3.2. Symmetry of foot pressure while squating

In this group, all parameters had normal distributions. Within the group (women and men) comparing the left and right sides showed a significantly higher ($p < 0.0031$) load on the left foot in the HS and WS squat (Figs. 3a–c). This tendency was for the following parameters: forefoot pressure [%], backfoot pressure [%], and total pressure [%]. For the total pressure parameter, there were additionally significantly ($p = 0.0001$) higher values for the NS squat.

The two-way ANOVA showed statistically significant ($p = 0.0015$) differences between squats for the symmetry parameters. In each case, the asymmetry was significantly higher for WS squat compared to those calculated for NS (Fig. 3d).

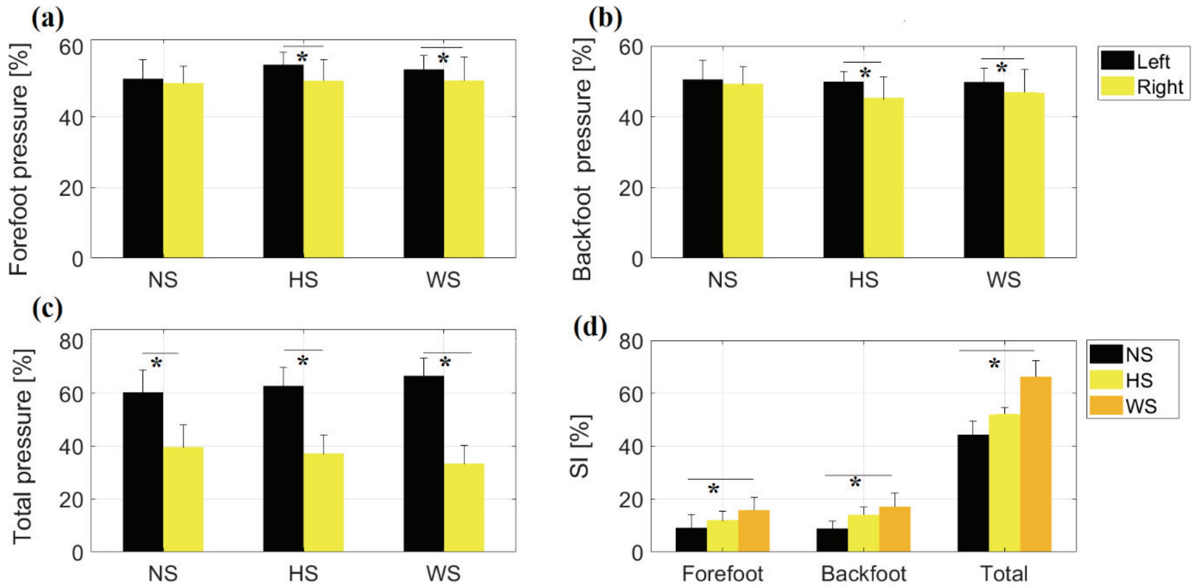

Fig. 3. The left and right foot plantar pressure distribution during narrow stance (NS), hip stance (HS), and wide stance (WS) squats for: (a) forefoot pressure [%], (b) backfoot pressure [%], (c) total pressure [%]; (d) symmetry indices for feet loading for each type of squat, where: * marks statistically significant differences ($p \leq 0.05$)

Analyzing the forefoot and backfoot plantar pressure, we can see that only for NS type of squat the foot pressure is distributed symmetrically on the left and right foot (Figs. 3a, b). When comparing the total foot pressure within squats, the left foot was loaded significantly more (Fig. 3c). In the case of the WS squat, the total plantar pressure on the left foot was almost twice (1.99) higher than that on the right foot. For HS – the left foot plantar pressure was 1.68 times higher, and in the case of NS – 1.52 times. It is worth emphasizing that the symmetry index was the lowest for the NS squat and the highest for the WS squat. The following relationship is observed that the asymmetry indicator increased with the increase in the support base.

4. Discussion

This study aimed to quantify the effect of various stance widths on postural control during squat and symmetry of feet loading. The squat is a closed kinetic chain movement task. It is an important element of physiotherapy and sports training programs. The selection of the appropriate body position for squatting, placement of the feet, location of the lifted weight and observation of the course of CoP movement, as well as feet loading, guarantee safe squat performance.

In this paper, three stance widths were examined: narrow stance (NS) described a stance where feet were pressed together; hip stance (HS) was a distance between the two anterior superior iliac spines and a wide stance (WS) was the distance of feet 3 feet apart. The HS and WS equaled the two stance widths analyzed by McKean, Dunnand Burkett [25]. On the other hand, Lorenzetti et al. [23] analyzed squats in 9 different foot settings. Three of these were selected for this article. It was shown that the wide squat (WS) has significantly higher values of CoP path length, surface area, and CoP velocity compared to other types of the squat (NS and HS). Similar relationships were obtained for non-linear parameters, but only for the AP direction. This result is probably generated by the greater freedom of movement in the knee and hip joints and especially of the trunk for the wide setting of the feet [10], [25]. High values of Lyapunov's exponent confirm this interpretation. It was also shown that in each position of the feet, the non-dominant (left) leg was loaded significantly more. Moreover, as the distance between the feet increased, the asymmetry of loads increased for each of the tested parts of the foot.

Linear parameters

According to Kohn [21], individuals with large displacements in CoP have less postural control and, therefore, worse balance. On the other hand, increasing the base support should improve the stability results. In the case of this study, despite the area surface's enhancement, the results were the opposite. For all linear parameters, the wide squat was the exercise in which the values were the highest. Both Comfort [4] and Paoli, Marcolinand Petrone [32] highlighted that the width base of support during squat alter muscle recruitment patterns increasing the activity of the adductor longus. This different activity could be the explanation, that WS squat has the highest values of linear and also nonlinear measures. Kim et al. [18] investigated how age and gender affect the postural sway during dynamic squat and stand-up movements. The main finding of this study was that the postural sway during squat increases with age only for females. Mehls, Grubbs, Jinand Coons [26] pointed out differences in muscle activity between women and men in squat exercises. Also Riis et al. [35] proved statistically significant differences between CoP path length for sex in upright standing position. It is worth noting that, in our study, no differences were found between men and women for the studied parameters. Kohn [21] checked how the gaze direction affects CoP displacements during barbell back squat exercise. The down direction had the smallest CoP displacements. There were significantly larger displacements in the upward gaze direction.

Nonlinear parameters

Similar relationships were observed for both nonlinear and linear parameters. The complexity of the human system allows researchers to use nonlinear methods. Sample entropy and other nonlinear parameters can play an important role and evaluating the complexity of movement and thus complex muscle behavior [16]. The highest sample entropy values were in both directions for wide stance squat. The lowest SampEn values were for hip stance squat. For AP direction, SampEn values were higher for each type of squat. This result appears due to the squat motor pattern, which is characterized by greater ranges of motion in joints and bigger trunk flexion in the anterior-posterior direction, rather than for medio-lateral.

High sample entropy values during wide squats may indicate that this movement is more irregular, requiring more muscle activation than squats in narrow or hip-width [23]. The values of the fractal dimension were presented similarly. For WS, the FD was higher in the AP direction, which probably indicates a change in the squats control strategy as more complex [17]. This result could be confirmed by Kitamura et al. [19], who measured muscle activities in narrow squat posture and squat with CoP intentionally shifted forward as far as possible. The forward shift in CoP occurred in higher loads for posterior muscles groups (semitendinosus and gastrocnemius lateral head). In [28], sample entropy was used to assess force variability during squats performed on stable and unstable surfaces. Contrary to our study, in [28], sample entropy for forces showed no differences between conditions. The Lyapunov exponent results presented associated relationships. The highest LyE values were also for wide stance squat in the AP direction. According to interpretation for postural stability trials [17], high LyE values for AP direction and wide squat mean that participants maintained a stable posture, had a strong ability to respond to disturbance or destabilization, and had high body flexibility. Lower values for narrow stance could be interpreted as decreased range of motion and higher rigidity (immobility) in the joints during the movement.

Symmetry of foot pressure

Researchers use different foot regions for plantar pressure assessment. Some of them divided the foot into 10 regions, others for 7 or 4 [5]. In our study, we reduced them to two regions: forefoot and backfoot. For each type of squat, there were statistically higher values for total load for the left foot, compared to the right foot. The comparison of load between the forefoot and backfoot between sides showed that statistically significant differences occurred only for hip-width squat. Da [5] showed that during half squat, subjects with pronated feet exhibited a higher plantar pressure in the forefoot medial region than for the control group. Teh [40] showed that for all types of squats, a statistically higher load for the left foot was noticed. Dionisio, Almeida, Duarte and Hirata [6] assessed CoP displacements during the squat's descending phase. They observed that the CoP shifted towards the heel. On the other hand, when the body is in the squat position, the CoP shift towards the forefoot. The papers presented above emphasize that the squat and the feet loads are not symmetrical. It is also worth emphasizing that the asymmetry increases with increasing support surface area. The test subjects put a higher load on the supporting limb (left limb). There were no significant differences between sex for plantar pressure beside the fact that men were significantly taller than women. This is the opposite result to papers where authors reported that females have a strong trend toward one-leg dominance with greater bilateral asymmetry during landing tasks [12].

A limitation of this study was the small number of participants. Additionally, the people selected for the research were not random. They were young, physically active people, able to perform selected squats correctly. However, their joint mobility was assessed only visually. Data from kinematics and kinetics measurements may be important in describing the squat movement pattern and observing asymmetry. Clinical examination of feet arches should be performed to exclude feet with pronation. It is worth adding the EMG analysis for major muscle groups. An additional limitation of the present study ways that the entire movement included not only a squat but also a 5-second standing position. That certainly affected the results of the linear and nonlinear parameters. Admittedly, if this part was removed, the time series would be significantly shortened. Nevertheless, it is worth noting that standing is always present in this activity because it contains an element of preparation and some muscle pre-activation.

5. Conclusions

The use of linear and nonlinear measures allows for a comprehensive analysis of posture control. The wide squat requires complex posture control behavior and is less symmetrical for total foot pressure. An important factor in physical therapy or training programs is to start the exercise with tight squats or hip squats, not wide squats. Wide squats can be difficult for patients to perform. It requires proper posture control and an adequate range of motion. This research showed that the greater the distance between the feet, the greater the feet load asymmetry. This knowledge is crucial for people with the lower arch of the foot or flat feet. Performing wide squats can affect the soft tissue of the sole and cause pain.

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