eISSN 2255-0569

ORIGINAL

Postural analysis in flat-footed subjects

Análisis postural en sujetos de pie plano

Joel Marouvo[1,2], Nelson Azevedo[3,4], Filipa Sousa[5,6], Orlando Fernandes[7,8], Maria António Castro[1,2,9]

1. RoboCorp Laboratory, i2a, Polytechnic Institute of Coimbra, Coimbra, Portugal 2. Centre for Mechanical Engineering, Materials and Processes (CEMMPRE), University of Coimbra, Coimbra, Portugal 3. Instituto Superior de Saúde, ISAVE, Amares, Portugal 4. Faculty of Sports, University of Porto, Porto, Portugal 5. Porto Biomechanics Laboratory (LABIOMEP-UP), University of Porto, Porto, Portugal 6. Faculty of Sport (FADEUP), CIFI2D, University of Porto, Porto, Portugal 7. Departamento de Desporto e Saúde, Escola de Saúde e Desenvolvimento Humano, Universidade de Évora, Évora, Portugal 8. Comprehensive Health Research Center (CHRC), Universidade de Évora, Évora Portugal. 9. School of Health Sciences, Polytechnic Institute of Leiria, Leiria, Portugal.

Corresponding author
Maria António Castro
E-mail: maria.castro@ipleiria.pt

Received: 23 - VI - 2022
Accepted: 1 - VII - 2022

doi: 10.3306/AJHS.2022.37.05.48

Abstract

Background: Processing somatosensory input requires cognitive resources, any additional processing can decrease stability. Postural alignment of the feet has been linked to altered lower-limb movements and postural stability. The study aimed to determine whether there were differences in kinematics and kinetics between subjects with and without flat foot conditions, about postural stability.

Material and methods: The sample consisted of 31 participants comprising 62 feet, 15 of whom were in the experimental group with the flat foot condition, while 16 were in the control group with the neutral foot condition. The Navicular Drop Test and Resting Calcaneal Stance Position test were used to categorize each group of participants before posture analysis. All participants were subjected to a bipedal weight-bearing stance posture stability analysis, using a 3D-Motion Capture system and a force platform, both in eyes-open and closed conditions.

Results: Considering kinematics differences between groups, the only statistically significant results found were for the ankle joint namely in the sagittal (*p=.047*), coronal (*p=.013*), and transverse (*p=.001*) planes. Regarding Center of Pressure outcomes, no statistically significant results were found (*p>.05*) regarding group differences. Statistically significant results were found regarding Total and Antero-Posterior excursion (*p=.027/.016*), Total and Antero-Posterior Total velocity (*p=.027/.016*), and Antero-Posterior and Medio-lateral Amplitude (*p=.011/.039*).

Conclusion: In both conditions, flat-footed subjects present few alterations compared to neutral foot participants, in bipedal weight-bearing stance. Due to the methodological deficiency regarding influencing factors, further research should also address methodological variables to focus only on the foot.

Key words: Foot Posture; linear analysis, flat feet, plantar pressure.

Resumen

Introducción: el procesamiento de información somatosensorial requiere recursos cognitivos, cualquier procesamiento adicional puede disminuir la estabilidad. La alineación postural de los pies se ha relacionado con movimientos alterados de las extremidades inferiores y estabilidad postural. El estudio tuvo como objetivo determinar si había diferencias en la cinemática y la cinética entre sujetos con y sin pie plano, sobre la estabilidad postural.

Métodos: La muestra estuvo compuesta por 31 participantes de 62 pies, de los cuales 15 estaban en el grupo experimental con condición de pie plano, mientras que 16 estaban en el grupo control con condición de pie neutro. La prueba de caída del navicular y la prueba de posición de la postura del calcáneo en reposo se utilizaron para categorizar a cada grupo de participantes antes del análisis de la postura. Todos los participantes fueron sometidos a un análisis de estabilidad de la postura de la postura con soporte de peso bípedo, utilizando un sistema de captura de movimiento 3D y una plataforma de fuerza, tanto en condiciones de ojos abiertos como cerrados.

Resultados: Considerando las diferencias cinemáticas entre los grupos, los únicos resultados estadísticamente significativos encontrados fueron para la articulación del tobillo en los planos sagitais (p=0,047), coronal (p=0,013) y transversal (p=0,001). En cuanto a los resultados del Centro de Presión, no se encontraron resultados estadísticamente significativos (p>.05) con respecto a las diferencias de grupo. Se encontraron resultados estadísticamente significativos en cuanto a Excursión Total y Antero-Posterior (p=.027/.016), Velocidad Total y Antero-Posterior Total (p=.027/.016), Amplitud Antero-Posterior y Medio-lateral (p =.011/.039).

Conclusión: En ambas condiciones, los sujetos con pie plano presentan pocas alteraciones en comparación con los participantes con pie neutro, en la postura de carga bípeda. Debido a la deficiencia metodológica con respecto a los factores que influyen, la investigación adicional también debe abordar las variables metodológicas para centrarse solo en el pie.

Palabras clave: Postura del Pie; análisis lineal, pies planos, presión plantar.

Introduction

Incorrect range of motion, ligament/joint laxity, neurological restrictions, and altered muscle activity can all contribute to flat feet (FF)[1]. Mechanical overloading injuries are more likely to occur in FF subjects than in subjects without this condition. Knee pain, cartilage damage, medial tibial stress syndrome, sacroiliac dysfunction, metatarsal stress fractures, plantar fasciitis, Achilles tendinitis, tibialis anterior inflammation, or patellofemoral pain can result from this alteration[1-4]. Patients with musculoskeletal pathologies exhibit different postural patterns regarding functional activity. In daily living activities, both static and dynamic postural controls are required to maintain the Center of Mass (CoM) above the Base of Support (BoS)[5]. Alterations in BoS, such as a larger area, will result in an increase in sensorimotor adaptation resulting in increased postural stability, thus preventing fall risks[6,7]. BoS changes induce body sway, thereby increasing intrinsic stiffness[6,7]. Additionally, to maintain postural stability, the body requires the lower limb's proprioceptive receptors to respond effectively to environmental changes[7-9]. Plantar pressure, proprioceptive feedback, visual and oculomotor information, and vestibular information contribute to posture stability[8,10-12]. Through its unique sensory capacity, the visual and oculomotor system contributes to balance, not only by estimating distance but also by providing information about body motion and sway[9,10,13]. Any additional cognitive processes can reduce stability sustaining because somatosensory input requires cognitive processing to sustain stability. This information is processed in the Central Nervous System (CNS) to create neuromotor necessary output commands to maintain stability[14,15].

Foot posture induces altered plantar pressure patterns and proximal joint motion. In response to altered sensory afferent signals, the CNS modulates joint stiffness and postural stability through muscle coactivation, thus affecting muscle function, foot biomechanics, and lower-limb biomechanics[16]. These occur globally and locally through postural and functional joint stabilization[4,14,15,17-20]. Thus, foot posture, through altered lower-limb motion pattern can induce injuries[21,22] and it has been associated with abnormal foot motion during gait[1,4,23-26]. In addition to being a sensitive map, the foot contains many cutaneous mechanoreceptors that provide important information about balance, posture, movement, and muscular sensitivity[27]. Moreover, afferent input from the foot sole can affect postural awareness, while FF increase can be triggered by neurological and muscular restrictions, ligament and joint laxity, excess motion, and muscle activity[1]. It is difficult to assess the postural stability of FF subjects without assessing plantar pressure patterns that can influence negatively the results[10]. On the other hand, in FF subjects, the plantar foot area increases compared to the neutral foot which can impair the plantar pressure feedback, resulting in the other receptors' compensation for maintaining postural stability[8,11]. Consequently, an imprecise assessment of plantar pressure results from reduced accuracy in sensory integration[8].

According to biomechanical principles, the body can be conceptualized as a network of segments connected worldwide by main forces interactions[28]. A combined effect of rotational alignment between segments and the cumulative effect of foot hyperpronation induced a postural re-alignment to conserve the Center of Pressure (CoP) in the subject BoS, with repercussions on both distal and proximal joints[29,30]. Any variation in lower-limbs joints can influence both positively or negatively the whole lower extremity kinematic and kinetic chain[31]. In previous research, authors stated that during excessive subtalar pronation, the calcaneus performs an eversion movement, producing medial and inferior talus slide motion along with internal rotation, provoking thereby an internal shank rotation[28-32]. Thus, this biomechanical modification results in an increase in medial rotation of the femur, which in turn increases the pressure between the femoral head and the posterior portion of the acetabulum[29,33]. Consequently, this will produce an anterior pelvis tilt[28-30]. Finally, due to the pelvis/lumbar spine relationship at the sacroiliac joint by widespread fibrous connection, the anterior pelvic tilt increases lumbar lordosis[28,29], spine instability, balance disorder, and structural abnormalities[29]. Exposing subjects to induced hyperpronation emphasizes an immediate effect on the intersegmental relationship and not necessarily a prolonged adaptive effect[28].

The purpose of this study was to see if there is a difference in kinematics and kinetics between subjects with and without FF conditions, regarding postural stability.

Methods

1. Participants

This observational descriptive study was carried out at *RoboCorp Laboratory*, at the *Polytechnic Institute of Coimbra* after approval of the *Ethics Committee of Polytechnic Institute of Coimbra* (13_CEPC2/2019) based on the revised version of the 2013 *Declaration of Helsinki*[34,35]. Additionally, the recommendations for the communication of observational studies recommendations were followed (Strengthening the Reporting of Observational Studies in Epidemiology-STROBE)[35]. The sample size was calculated with the aid of the *G*power 3.1.9* software (*G*power 3.1.9*, Kiel, Germany) based on the previously published paper of *Kim et al.* (2015). The sample size was determined as the number of participants necessary to reach a statistical power of 95%, an estimated alpha level of 0.05, considering a moderate effect size (d = 0.6) (ref *Kim et al.* (2015). Therefore, a required sample size of 18 was determined and, consequently, forty-three volunteers were recruited for this study. All subjects were informed about the purpose of the study and the associated benefits, as well as any associated risks before any assessment was performed. Participants were guaranteed the right to withdraw at any time, and they were required to read and provide informed consent before participating. A total of thirty-one subjects aged between 18 and 35 years old met the eligibility criteria (13 women / 18 men – 23.26 yo ± 4.43 SD) (**Table I**). The inclusion criteria for the study were limited to subjects who presented bilateral FF or neutral foot (NF) who were aged between 18 to 40 years old.

Inclusion criteria in the FF group encompassed subjects that presented a >9mm Navicular Drop Test (NDT) and >4° Resting Calcaneal Stance Position (RCSP) scores. However, the inclusion criteria in the NF group involved participants with <9mm NDT and <4° RCSP scores. All participants were submitted to the NDT and RCSP to identify whether they had a FF or an NF as this test is clinically used by practitioners worldwide. The procedures were all performed by one practitioner who had more than six years of experience using these techniques. Following this, participants who presented the following criteria were not excluded from this study: (a) any disturbance that might affect posture analysis like orthopaedic, neurological, or visual impairment; (b) participation in a physiotherapy treatment program; (c) bone fracture or an ankle sprain in the last 6 months; (d) injury or surgery to the spine, hip, knee, or ankle; (e) aged less than 18 and more than 40 years old. Subsequently, 15 bilateral FF participants were assigned to the FF group, comprising a total of 30 feet, and 16 bilateral NF subjects were assigned to the NF group, comprising a total of 32 feet.

2. Procedures

2.1 Assessment

Foot posture was diagnosed based on clinical procedures including the Navicular Drop Test and the Resting Calcaneal Stance Position test, as those are clinically used by practitioners worldwide[29-31]. Both NF and FF conditions were evaluated bilaterally using the same assessment procedure in a weight-bearing barefoot stance position. They were performed by a single physiotherapist with more than 6 years of experience in the use of these techniques. The same procedure was used for both groups. In the first step, the navicular drop severity was evaluated using the NDT, where three measurements are summed up to determine its severity. The practitioner holds a plastic ruler perpendicularly to the ground and records the ground-navicular bone distance (millimeters). Then, the practitioner inverts the talus into a neutral position and repeats the procedure. The difference between both assessment positions quantifies the navicular drop severity[8]. Afterward, the angle between the rearfoot and the leg was assessed by the same practitioner using the Resting Calcaneal Stance Position test, where the mean of three measurement values defines the angle. This angle is formed by the longitudinal bisecting line of the calcaneus and the longitudinal bisecting line of the distal third of the leg, which was drawn by the investigator in a prone position, regarding the methodology previously used by *Tsai et al.* (2006). A rigid goniometer was used to measure this angle (Enraf-Nonius B.V, Rotterdam, The Netherlands).

Following the aforementioned tests, a three-dimensional computerized posture analysis was performed on both the FF and NF groups to assess movement characteristics such as joint angular kinematics and Center of Pressure parameters. A bilateral weight-bearing stance position was measured with a 10-camera Qualisys® 3D Motion Capture System (Qualisys AB, Götebor, Sweden) with a predictive error of 25 mm and a maximum residual set at 6 mm. This last one was coupled with a force platform *Bertec® FP4060* (Bertec Corporation, USA). A full-body marker setup based on the IOR model[36] comprising fifty-three reflective kinematic markers was used on specific anatomical positions of the participants, namely on the thorax, the head, and the lower limbs. Tracking markers, i.e., four marker clusters, were placed over the thighs and shanks to improve segment tracking accuracy. Therefore, kinematic data were collected in a previously calibrated volume, with a calibration error below 0.7 mm and recorded at a 200 Hz sampling frequency for the kinematics and a 1000 Hz sampling frequency for CoP characteristics.

Before posture acquisition, subjects were asked to perform a bilateral stance posture assessment regarding model creation processing. Therefore, subjects were instructed to stay upon a force platform for 60 sec with eyes open (EO) and repeated it with eyes closed (EC). There was a ten-second rest period between trials. The assessment was done with subjects in a quiet, comfortable barefoot posture upon the force platform while keeping their arms at the side and they were asked to look at a reference point for 5 seconds to stabilize the position before recording the data[37]. No other restrictions were placed on participants. Trials in which all of the markers were clear and possible to identify were defined as valid and if any participants failed to maintain their position, the trial was repeated.

2.2 Data processing and analysis

Initially, the recorded kinematic data were pre-processed using the Qualisys Track Manager v2.15 (Qualisys AB, Götebor, Sweden) software. The resulting data were then exported to Visual3D (C-Motion, Germantown, MD, USA) for further analysis. The marker's trajectories were then filtered with a *6-Hz Butterworth* low-pass filter and a 3-D model was created to analyse the relative angles of ankle, knee, and hip joints and, pelvis[38]. A 3D model was created to analyse the relative angles of the ankle, knee, and hip joints. Finally, Visual 3D (C-Motion, Germantown, MD, USA) software commands were computed and identically replicated for each subject to identify outcomes measures, namely joint angular kinematics (ankle, knee, hip, and pelvis angle). Also, the CoP excursion, velocity, and area were evaluated. Alongside, the *Matlab-R2020b* (MathWorks Inc., USA) software was utilized for the CoP data processing. Initially, all CoP data were downsampled to a 200Hz frequency and, then filtered with a *7th-order Butterworth 50-Hz low-pass filter* to reduce some high-frequency parasitic signals. Finally, a routine was created to identify CoP outcomes.

3. Statistical analysis

The data were statistically processed with the *IBM SPSS Statistics 27.0* software (IBM Corporation, New York, USA). In this observational descriptive study, the appropriate summary statistics were applied to the descriptive analysis of the sample. Before any further statistical procedure, the normality of the distribution was explored. The samples presented a normal distribution based on the *Shapiro-Wilk* test regarding kinematic variables (*p>.05, t>0.074*) and several CoP variables (*p>.725, t>0.976*). For the remaining CoP variables, the sample presented a non-normal distribution using the *Shapiro-Wilk* test (*p<.001, t>0.617*). Continuous variables were described using the median/variance and mean/standard deviation based on the sample distribution. The differences between the groups were assessed according to the *T-test for independent samples* and *U-Mann Whitney* in the comparison between the experimental and control group. Then, the differences between both condition assessments, EC and EO were assessed according to the *T-test for paired samples* and the *Wilcoxon test*.

The level of significance was set at 5% (*p<.05*) for all hypothesis tests.

Results

1. Sample and Groups characteristics

The sample characteristics are specified in **table I** alongside the mean values of the different tests for both groups. In the procedure, 30 FF and 32 NF were identified through inclusion criteria. Both subjects were identified and allocated to different groups using the NDT and RCSP score assessment.

2. Kinematics Analysis

Considering the result kinematics values regarding the differences between groups, the only statistically significant results found were all concerning the ankle joint namely in the sagittal (*diff=1.93°, p=.047*), coronal (*diff=2.62°, p=.013*), and transverse (*diff=5.02°, p=.001*) planes. The other joints did not show statistically significant differences between groups (*p>.05*). All the results those results are presented in **table II**.

3. CoP analysis

No statistically significant results were found (*p>.05*) regarding CoP between groups, both in the EO and EC conditions. Between conditions, statistically significant results were found regarding several outcomes, namely the Total CoP excursion (*p=.027*), Antero-Posterior Total excursion (*p=.016*), Total CoP velocity (*p=.027*), Antero-Posterior Total velocity (*p=.016*), Antero-Posterior and Medio-lateral Amplitude (*p=.011/.039*). **Table III** presents all of the results over the CoP characteristics along with **Figures 1** and **2**, which show examples of Statokinesigram and phase plane analysis.

Table I: Sample characteristics.

Group	n	NDT *(mm)*	RCSP *(°)*	Age *(years)*	Height *(m)*	Weight *(kg)*
NF	*16*	5.06 ± *2.42*	1.44 ± *1.19*	21.69 ± *2.98*	1.72 ± *0.09*	75.92 ± *17.03*
FF	*15*	11.35 ± *1.43*	5.52 ± *2.22*	24.93 ± *5.17*	1.68 ± *0.10*	74.32 ± *12.90*
Total	*31*	-		23.26 ± *4.43*	1.70 ± *0.98*	75.14 ± *14.94*

Mean ± Standard Deviation; NF = Neutral Foot; FF = Flatfoot.

Table II: Groups kinematics characteristics in Eyes Open assessment.

		NF	FF	*p-value*
Ankle *(°)*	*Dorsiflexion - Plantarflexion*	-3.77 ± *3.91*	-1.83 ± *3.54*	*0.047*
	Abduction - Adduction	-8.38 ± *3.63*	-5.75 ± *4.34*	*0.013*
	Internal – External rotation	-13.31 ± *6.15*	-8.29 ± *4.96*	*0.001*
Knee *(°)*	*Flexion - Extension*	-2.07 ± *5.88*	-3.88 ± *4.98*	*0.198*
	Abduction - Adduction	1.42 ± *4.26*	0.65 ± *5.44*	*0.536*
	Internal - External rotation	18.05 ± *10.57*	16.10 ± *6.62*	*0.393*
Hip *(°)*	*Flexion - Extension*	-1.48 ± *9.40*	-1.08 ± *7.67*	*0.856*
	Abduction - Adduction	-0.62 ± *3.68*	-1.93 ± *5.29*	*0.268*
	Internal - External rotation	3.24 ± *9.71*	-0.77 ± *7.21*	*0.071*
Pelvis *(°)*	*Anterior – posterior Tilt*	-9.13 ± *7.93*	-9.47 ± *5.97*	*0.894*
	Lateral Tilt	-0.66 ± *2.34*	-1.09 ± *2.64*	*0.635*
	Rotation	-0.28 ± *5.69*	-0.05 ± *2.64*	*0.889*

Mean ± Standard Deviation; NF = Neutral Foot; FF = Flatfoot; Negative value = extension / internal rotation / adduction / anterior tilt; Positive value = flexion / external rotation / abduction / posterior tilt.

Table III: Center of Pressure characteristics.

		EO			EC			EO vs EC
		NF	FF	*p-value*	NF	FF	*p-value*	*p-value*
Excursion *(mm)*	*Total*	2476.82 ± *468.21*	2492.82 ± *414.32*	*0.922*	2457.15 ± *451.55*	2570.49 ± *425.14*	*0.508*	*0.027*
	Antero-Posterior	1871.44 ± *352.55*	1908.29 ± *314.98*	*0.766*	1876.18 ± *334.31*	1975.31 ± *337.02*	*0.450*	*0.016*
	Medio-Lateral	1247.68 ± *239.55*	1229.89 ± *212.08*	*0.832*	1218.89 ± *243.16*	1256.04 ± *199.83*	*0.667*	*0.210*
Velocity *(mm/s)*	*Total*	495.41 ± *93.65*	498.61 ± *82.87*	*0.922*	491.47 ± *90.32*	514.14 ± *85.03*	*0.508*	*0.027*
	Antero-Posterior	374.32 ± *70.52*	381.69 ± *63.00*	*0.766*	375.27 ± *66.87*	395.09 ± *67.41*	*0.450*	*0.016*
	Medio-Lateral	249.56 ± *47.91*	245.99 ± *42.42*	*0.832*	243.80 ± *48.63*	251.23 ± *39.97*	*0.667*	*0.210*
Amplitude *(mm)*	*Antero-Posterior*	30.33 ± *12.80*	27.64 ± *11.03*	*0.637*	38.85 ± *20.58*	38.58 ± *26.01*	*0.793*	*0.011*
	Medio-Lateral	17.09 ± *7.91*	17.30 ± *12.27*	*0.759*	19.84 ± *12.48*	17.75 ± *11.48*	*0.867*	*0.039*
Area *(mm²)*		284.47 ± *250.93*	221.37 ± *165.93*	*0.498*	379.09 ± *453.38*	376.25 ± *557.17*	*1.000*	*0.486*

Mean ± Standard Deviation; NF = Neutral Foot; FF = Flatfoot; EO = Eyes Open; EC = Eyes Closed

Figure 1: Statokinesigram.

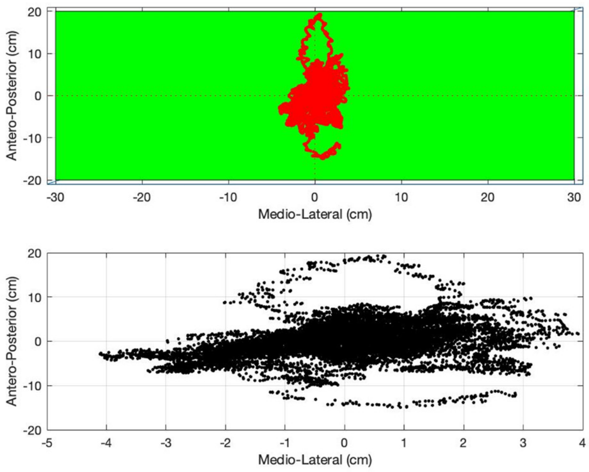
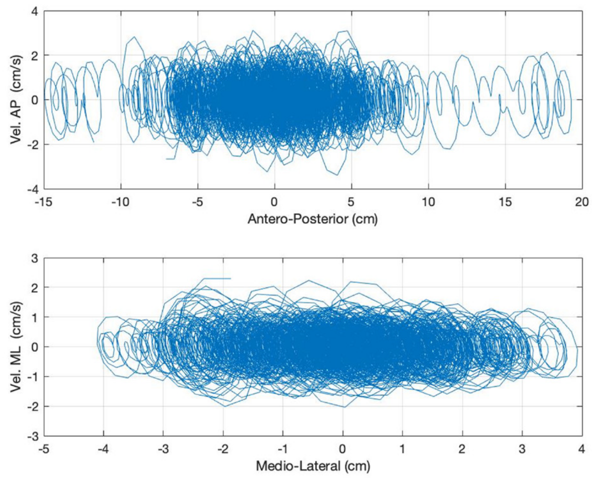


Figure 2: Phase Plane graphs.



Discussion

The current study is the first of its kind to investigate differences between FF and NF in terms of overall lower-limb kinematics, CoP characteristics, and eligibility criteria, such as NDT and RSCP testing. Studies have previously investigated kinematics and postural stability variations using different inclusion criteria and conditions, such as bilateral FF or induced bilateral excessive ankle eversion.

In our observational study not all results present statistically significant differences between the NF and FF group concerning kinematics outcomes. In our overall lower-limb analysis, only the ankle joint presents variation between groups in all planes. In the FF group, subjects presented higher dorsiflexion (*p=.047*), abduction (*p=.013*), and external rotation (*p=.001*) ROM compared to the control group. The results can be translated into a drop of the navicular bone and a collapse of the entire medial longitudinal arch, i.e., alterations that are present in FF subjects. These findings are also in agreement with the results of clinical tests used to evaluate FF conditions, namely the NDT and RCSP. Many authors analyzed the kinematic outcomes in FF subjects concerning several posture assessment conditions. However, those investigated mainly the correlations between joint motion and differences between groups. Others analysed the induced hyperpronation effect using a few wedges. *Duval et al.* (2010) found differences between subjects, yet not all those were statistically significant[39]. Subtalar pronation, relative to neutral position increases internal knee and hip rotation. Though, the authors found only a significant association between subtalar angle and knee and hip rotation (*p<.001*) which follows *Khamis et al.* (2007-2015) results. However, foot pronation and supination did not statistically significantly correlate with pelvic tilt and lumbar lordosis (*p=.074*). These results are in contradiction with those found by *Farokhmanesh et al.* (2014), Ghasemi et al. (2016), Khamis et al. (2007-2015) who established a statistically significant increase in lumbar lordosis (*p<.05*). These differences may arise from the fact that the authors examined functional changes created by the wedges rather than structural changes occurring continuously in bilateral flatfoot subjects. Despite this, more research is needed due to differences in samples, setups, and quality of the studies.

Also, *Duval et al.* (2010) found that thigh internal rotation produced an anterior pelvis tilt (*p<.001*)[39]. Although, in the same condition, *Farokhmanesh et al.* (2014) found alterations between subjects, with a statistically significant increase in thoracic kyphosis (*p<.008*) related to subtalar pronation that accords with *Ghasemi et al.* (2016) findings (*p<.001*). Finally, this last one analyzed sacral angle related to foot pronation and noticed a statistically significant increase in induced hyperpronation conditions (*p<.001*). No paper relating differences between groups using the combination of NDT and RCSP to assess FF condition was found. The difference between results can be explained by the selection of the inclusion and exclusion criteria, specifically the NDT-RCSP combination. Both tests are considered clinical tests, used to assess foot complex mobility[40,41]. They were considered user-friendly but presented few limitations. Instead, several authors used Footprint parameters, namely using a few indexes to quantify and characterize foot posture FF, NF, and cavus foot[42]. However, NDT and Footprint parameters present good association and reliability based on the few published papers[40-42]. Nevertheless, those contradictions made unclear the emergence of a posture pattern often described in FF subjects. Nonetheless, more studies need to incorporate methodological variables to only focus on foot alteration based on methodological variations.

In our study, CoP characteristics were also investigated and analyzed. We did not find any statistically significant results between groups, in both assessment conditions, regarding CoP total, anteroposterior or mediolateral excursion, amplitude, and area (*p>.05*). Those are contradictory to the found results by *Tahmasebi et al.* (2014), who stated a statistically significant increase in anteroposterior CoP excursion (*p=.034*) in EO condition amongst FF subjects that can be due to group inclusion criteria where the authors utilized the FootPrint Arch Index and Arch Angle which is considered as a FootPrint parameter. Also, another published study by *Koshino et al.* (2020), find a statistically significant increase in Antero-Posterior and Medio-Lateral total excursion among FF subjects compared to NF subjects (*p<.023*). Likewise, we investigated the total, anteroposterior, and mediolateral CoP velocity where we did not find ether statistically significant differences (*p>.05*) between groups, which is contradictory to the result found by *Tahmasebi et al.* (2014). The authors related a statistically significant increase in total, anteroposterior and mediolateral CoP velocity in FF subjects compared to NF subjects (*p=.000*). However, along with the previous two mentioned articles, in our research, we did not find more published papers that related differences in CoP characteristics among FF subjects. In the literature research, none of the selected papers investigated the EC condition assessment nor the postural system modulation. Analysis of postural stability in FF subjects can be challenging without controlling or assessing the visual and oculomotor systems, which can adversely affect results[10]. In our study, contradictory to the postural stability system evaluation, we did not find any statistically significant differences between both conditions assessments, EO and EC. Additionally, the BoS area used to assess impairments in different foot posture conditions differs from previous searches, along with visual input assessment. Several studies used the unilateral stance position with Kinetic Stability Index, CoP excursion, and velocity outcomes analysis. They stated that a decreased kinetic sensitivity can increase postural sway and instability in that position[8,9,43] as long as Antero, Mediolateral CoP excursion, and speed increase in FF subjects with EC and EO[27]. BoS variations lead to stability adaptation. In a bipedal stance, the mediolateral Center of Mass (CoM) position is usually positioned above the BoS area while it is reduced in unilateral stance, and accompanied by postural corrections, using ankle, knee, or hip strategy, which increases postural instability and body sway[6,7]. When proprioception is limited, FF participants might be prone to kinetic instability since inaccurate body sway estimation can be caused by reduced accuracy in the sensory integration process[6,7]. In our study, we used a weight-bearing bipedal stance position. The subject needs information from all postural receptors to maintain stability in that condition. As the position provides a higher BoS area, there is little external stimulus influencing the position maintenance, i.e., the postural system is fully functional and without reporting CoP impairments, nor differences between various foot posture conditions. Finally, along with those conditions, in FF subjects, plantar foot area increases compared to NF subjects which impairs pressure feedback resulting in receptors' compensation for maintaining postural stability[8,11]. The method required to assess this parameter differs between authors according to the chosen test. In *Tahmasebi et al.* (2014) study, the authors used the combined method of Arch Index and the Footprint Angle, i.e., clinical methods. However, *Koshino et al.* (2020) used the Foot Posture Index (FPI-6), i.e., questionnaire evaluation, and finally the combined use of the NDT and RSCP was utilized in our study, i.e., mobility tests. Those represent three different methods to diagnose the FF condition, which can impair the results and comparation.

Considering the overall kinematic and CoP characteristics outcomes and assessed variables, we can state that FF subjects did present few alterations compared to NF participants, in bipedal weight-bearing stance, both in EC and EO conditions. However, considering the lack of consensus regarding utilized outcomes and assessment conditions, further studies need to be performed to create more robust evidence. Regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

Acknowledgments

The authors acknowledge RoboCorp, i2A, Polytechnic Institute of Coimbra. MAC and JM acknowledge the support of the Centre for Mechanical Engineering, Materials and Processes - CEMMPRE of the University of Coimbra, which is sponsored by Fundação para a Ciência e Tecnologia (FCT) (UIDB/00285/2020, LA/P/0112/2020).

Funding

This research was supported by the Mais Centro Program, Center Region Coordination Committee of EU through the European Regional Development Fund.

Interests conflict

The researchers declare that they have no conflict of interest.

References

1. Hunt AE, Smith RM. Mechanics and control of the flat versus normal foot during the stance phase of walking. Clin Biomech 2004;19:391-7.

2. Lotito G, Pruvost J, Collado H, Coudreuse J-M, Bensoussan L, Curvale G, et al. Peroneus quartus and functional ankle instability. Ann Phys Rehabil Med 2011;54:282-92.

3. Hösl M, Böhm H, Multerer C, Döderlein L. Does excessive flatfoot deformity affect function? A comparison between symptomatic and asymptomatic flatfeet using the Oxford Foot Model. Gait Posture 2014;39:23-8.

4. Levinger P, Zeina D, Teshome AK, Skinner E, Begg R, Abbott JH. A real time biofeedback using Kinect and Wii to improve gait for post-total knee replacement rehabilitation: a case study report. Disabil Rehabil Assist Technol 2016;11:251-62.

5. Nagai K, Yamada M, Uemura K, Yamada Y, Ichihashi N, Tsuboyama T. Differences in muscle coactivation during postural control between healthy older and young adults. Arch Gerontol Geriatr 2011;53:338-43.

6. Forbes PA, Chen A, Ebastien J. Sensorimotor control of standing balance 2018;159. https://doi.org/10.1016/B978-0-444-63916-5.00004-5.

7. Rogers MW, Mille M. Balance perturbations. vol. 159. 1st ed. Elsevier B.V.; 2018.

8. Sung PS. The Sensitivity of Thresholds by Ground Reaction Force and Postural Stability in Subjects With and Without Navicular Drop. J Foot Ankle Surg 2018;57:742-6.

9. Sung PS, Zipple JT, Andraka JM, Danial P. The kinetic and kinematic stability measures in healthy adult subjects with and without flat foot. Foot 2017;30:21-6.

10. Peterka RJ. Sensory integration for human balance control. Handb. Clin. Neurol., vol. 159. 1st ed., Elsevier B.V.; 2018, p. 27-42.

11. Mackinnon CD. Sensorimotor anatomy of gait , balance , and falls. vol. 159. 1st ed. Elsevier B.V.; 2018.

12. Young AS, Rosengren SM, Welgampola MS. Disorders of the inner-ear balance organs and their pathways. vol. 159. 1st ed. Elsevier B.V.; 2018.

13. Dakin CJ, Rosenberg A. Gravity estimation and verticality perception. vol. 159. 1st ed. Elsevier B.V.; 2018.

14. Colebatch JG, Govender S, Dennis DL. Postural responses to anterior and posterior perturbations applied to the upper trunk of standing human subjects. Exp Brain Res 2016;234:367-76.

15. Feldman AG. The Relationship Between Postural and Movement Stability. In: Laczko J, Latash ML, editors. vol. 957, Cham: Springer International Publishing; 2016, p. 105-20.

16. Angin S, Mickle KJ, Nester CJ. Contributions of foot muscles and plantar fascia morphology to foot posture. Gait Posture 2018;61:238-42.

17. Dicharry JM, Franz JR, Croce U Della, Wilder RP, Riley PO, et al. Differences in Static and Dynamic Measures in Evaluation of Talonavicular Mobility in Gait. J Orthop Sport Phys Ther 2009;39:628-34.

18. Bavdek R, Zdolšek A, Strojnik V, Dolenec A. Peroneal muscle activity during different types of walking. J Foot Ankle Res 2018;11:50.

19. Svoboda Z, Janura M, Kutilek P, Janurova E. Relationships between movements of the lower limb joints and the pelvis in open and closed kinematic chains during a gait cycle. J Hum Kinet 2016;51:37-43.

20. Kazemi K, Arab AM, Abdollahi I, López-López D, Calvo-Lobo C. Electromiography comparison of distal and proximal lower limb muscle activity patterns during external perturbation in subjects with and without functional ankle instability. Hum Mov Sci 2017;55:211-20.

21. Buldt AK, Murley GS, Butterworth P, Levinger P, Menz HB, Landorf KB. The relationship between foot posture and lower limb kinematics during walking: A systematic review. Gait Posture 2013;38:363-72.

22. Buldt AK, Levinger P, Murley GS, Menz HB, Nester CJ, Landorf KB. Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet. Gait Posture 2015;42:42-8.

23. Eslami M, Damavandi M, Ferber R. Association of Navicular Drop and Selected Lower-Limb Biomechanical Measures During the Stance Phase of Running. J Appl Biomech 2014;30:250-4.

24. Twomey D, McIntosh AS, Simon J, Lowe K, Wolf SI. Kinematic differences between normal and low arched feet in children using the Heidelberg foot measurement method. Gait Posture 2010;32:1-5.

25. Douglas Gross K, Felson DT, Niu J, Hunter DJ, Guermazi A, Roemer FW, et al. Association of flat feet with knee pain and cartilage damage in older adults. Arthritis Care Res 2011;63:937-44.

26. Buldt AK, Forghany S, Landorf KB, Levinger P, Murley GS, Menz HB. Foot posture is associated with plantar pressure during gait: A comparison of normal, planus and cavus feet. Gait Posture 2018;62:235-40.

27. Kim J, Lim O, Yi C. Difference in static and dynamic stability between flexible flatfeet and neutral feet. Gait Posture 2015;41:546-50.

28. Khamis S, Yizhar Z. Effect of feet hyperpronation on pelvic alignment in a standing position. Gait Posture 2007;25:127-34.

29. Ghasemi MS, Koohpayehzadeh J, Kadkhodaei H, Ehsani AA. The effect of foot hyperpronation on spine alignment in standing position. Med J Islam Repub Iran 2016;30.

30. Khamis S, Dar G, Peretz C, Yizhar Z. The Relationship between Foot and Pelvic Alignment while Standing. J Hum Kinet 2015;46:85-97.

31. Farokhmanesh K, Shirzadian T, Mahboubi M, Shahri MN. Effect of Foot Hyperpronation on Lumbar Lordosis and Thoracic Kyphosis in Standing Position Using 3-Dimensional Ultrasound-Based Motion Analysis System. Glob J Health Sci 2014;6:254-60.

32. Tahmasebi R, Karimi MT, Satvati B, Fatoye F. Evaluation of Standing Stability in Individuals With Flatfeet. Foot Ankle Spec 2015;8:168-74.

33. Lee H-C, Huang C-L, Ho S-H, Sung W-H. The Effect of a Virtual Reality Game Intervention on Balance for Patients with Stroke: A Randomized Controlled Trial. Games Health J 2017;6:303-11.

34. Holt GR. Declaration of Helsinki—The World's Document of Conscience and Responsibility. South Med J 2014;107:407.

35. Vandenbroucke JP, von Elm E, Altman DG, Gøtzsche PC, Mulrow CD, Pocock SJ, et al. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and elaboration. Int J Surg 2014;12:1500-24.

36. Wilken JM, Rodriguez KM, Brawner M, Darter BJ. Reliability and minimal detectible change values for gait kinematics and kinetics in healthy adults. Gait Posture 2012;35:301-7.

37. Janusz BW, Beck M, Szczepańska J, Sadowska D, Bacik B, Juras G, et al. Directional measures of postural sway as predictors of balance instability and accidental falls. J Hum Kinet 2016;52:75-83.

38. Winter DA. Biomechanics and Motor Control of Human Movement. 3rd editio. Wiley; 2008.

39. Duval K, Lam T, Sanderson D. The mechanical relationship between the rearfoot, pelvis and low-back. Gait Posture 2010;32:637-40.

40. Zuil-Escobar JC, Martínez-Cepa CB, Martín-Urrialde JA, Gómez-Conesa A. Evaluating the Medial Longitudinal Arch of the Foot: Correlations, Reliability, and Accuracy in People With a Low Arch. Phys Ther 2019;99:364-72.

41. Queen RM, Mall NA, Hardaker WM, Nunley JA. Describing the medial longitudinal arch using footprint indices and a clinical grading system. Foot Ankle Int 2007;28:456-62.

42. Zuil-Escobar JC, Martínez-Cepa CB, Martín-Urrialde JA, Gómez-Conesa A. Medial Longitudinal Arch: Accuracy, Reliability, and Correlation Between Navicular Drop Test and Footprint Parameters. J Manipulative Physiol Ther 2018;41:672-9.

43. Sung PS. The ground reaction force thresholds for detecting postural stability in participants with and without flat foot. J Biomech 2016;49:60-5.