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What are the differences between subjects with and without flatfoot condition, with the aid of ultrasonography, kinematics, and kinetics in posture and gait?

Academic thesis submitted in partial fulfillment of the requirements for obtaining a doctoral degree in Physiotherapy according to the Decree-Law nº. 74/2006 March 24th.

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Dedications

To all involved in this adventured

“It always seems impossible until it's done.”

Nelson Mandela

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ABSTRACT

The foot complex has an important role in posture, balance, stability, and movement, during the static positions and in overall movements' patterns. Structural or functional alteration in the foot complex and foot posture may have an impact on posture and movement on distal and proximal structures. Commonly, subjects with flatfoot develop neurological or muscular restrictions, ligament or joint laxity, excessive motion, and muscle activity. This condition leads to higher risks of developing mechanical overloading injuries on adjacent lower-limb joints. The aim of this study is to determine if there are differences between flatfoot subjects compared to neutral foot subjects, regarding posture and gait pattern analysis. The sample was constituted by subjects with a flat and neutral foot, allocated in two groups. All subjects were submitted to assessment procedures to be allocated in one of the groups. Therefore, each participant was submitted to gait pattern and posture assessment, with the aid of a MOCAP system, and to muscle stiffness assessment with an ultrasound-based Shear-Wave Elastography and, finally to plantar pressure assessment with a baropodometric platform. Flatfoot subjects showed several alterations and differences when compared to neutral foot participants considering all principal outcomes along with posture and gait pattern. Considering all studies realized and included in this thesis, several differences were found in flatfoot subjects. Thus, most of those results are contradictory to those found in the literature, giving a growth of evidence relatively to foot posture condition and influence in posture and gait pattern. However, regarding the lack of consensus about the outcomes and assessment conditions, further studies need to be performed to create a more robust body of evidence. Although, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus on an overall evaluation of the condition and not only on the foot complex.

KEYWORDS: FOOT POSTURE, MOVEMENT PATTERNS, PES PLANUS, BIOMECHANICS.

RESUMO

O complexo do pé tem um papel importante na postura, equilíbrio, estabilidade e movimento, durante as posições estáticas e nos padrões gerais de movimento. Alterações estruturais ou funcionais no complexo do pé e no seu posicionamento podem afetar a postura e o movimento das estruturas distais e proximais. Comumente, indivíduos com pé plano desenvolvem restrições neurológicas ou musculares, frouxidão ligamentar ou articular, movimento excessivo e atividade muscular. Essa condição leva a maiores riscos de desenvolver lesões por sobrecarga mecânica nas articulações dos membros inferiores adjacentes. O objetivo é determinar se existem diferenças entre indivíduos com pé plano em comparação com indivíduos com pé neutro, em relação à postura e à análise do padrão de marcha. A amostra foi constituída por sujeitos com pé plano e neutro, alocados em dois grupos. Todos os sujeitos foram submetidos a procedimentos de avaliação para serem alocados em um dos grupos. Cada participante foi submetido à avaliação do padrão de marcha e postura, com auxílio de sistema MOCAP, e à avaliação da rigidez muscular com Ultrassonografia e, por fim, à avaliação da pressão plantar com uma plataforma de pressões. Os sujeitos com pé plano mostraram várias alterações e diferenças quando comparados aos participantes com pé neutro, de acordo com os principais resultados da análise da postura e do padrão de marcha. Considerando todos os estudos realizados e incluídos nesta tese, várias diferenças foram encontradas em indivíduos de pé plano. Porém, a maioria desses resultados são contraditórios com os resultados presentes na literatura, dando um crescimento da evidência científica sobre a condição de pé plano e a sua influência na postura, e no padrão de marcha. No entanto, em relação à falta de consenso sobre os resultados e condições de avaliação, vários estudos necessitam ser realizados para criar uma maior robustez da evidência científica. Porém, no que se refere ao rigor metodológico em relação a diferentes parâmetros, novos estudos precisam de abranger variáveis que foquem a avaliação geral da condição e não apenas do complexo do pé.

Palavras-chave: POSTURA DE PÉ, PADRÕES DE MOVIMENTO, PÈ PLANO, BIOMECÂNICA.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AA Arch Angle

AI Arch Index

ApEn Approximate Entropy

CD Correlation Dimension

CSI Chippaux-Smirak Index

FD Fractal Dimension

FF Flatfoot

FPI FootPrint Index

LyE Lyapunov Exponent

NDT Navicular Drop Test

NF Neutral foot

RCSP Resting Calcaneal Stance Position

SI Staheli Index

CHAPTER I

GENERAL INTRODUCTION

Foot problems are related to impaired mobility and postural stability, which have a detrimental impact on life quality and are reported as a common community apprehension (Buldt et al., 2013; Sung, 2016; Sung et al., 2017). FF condition is a foot deformity, characterized by plantarflexion and eversion of the calcaneus relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Angin et al., 2014; Buldt et al., 2013; Caravaggi et al., 2018; Kosashvili et al., 2008). This condition can be triggered by several causes, namely, neurological or muscular restrictions, ligament laxity, joint laxity, excessive motion, muscle activity (Farokhmanesh et al., 2014; Hunt & Smith, 2004; Tahmasebi et al., 2015). It is present among children, affects 10-25% of adults, and is associated with several injuries like knee and back pain (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008; Sung, 2016; Sung et al., 2017). Also, the prevalence of FF varies between 5.2 to 13.9% in the young adult population according to different studies and sample size (Aenumulapalli et al, 2017). It is often accompanied by pain and affects walking speed, balance, and function, which increases fall risks (Sung, 2016; Sung et al., 2017). Alongside FF condition, alterations like tibial internal rotation, increase forefoot abduction, and ankle inversion are considered biomechanical risk factors for lower-limbs pathological conditions or foot dysfunction (Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Sung, 2016; Twomey et al., 2010) and FF condition can be recognized as an intrinsic risk factor for kinetic stability (Sung, 2016). These were related to asymmetrical forces distribution across subtalar joint and knee transverse and frontal plane loads that can lead to spinal column pathologic conditions (Douglas Gross et al., 2011; Eslami et al., 2014; Farokhmanesh et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Tahmasebi et al., 2015; Twomey et al., 2010).

Since lower-limbs postural alterations can lead to pelvic girdle postural changes and enhance low back pain risk, foot alignment should be considered as an important and effective factor (Buldt et al., 2013; Farokhmanesh et al., 2014). Subjects with FF condition have higher risks of developing mechanical overloading injuries triggered on either ankle, knee, or hip joints, due to lower limbs misalignment causing several injuries (Hösl et al., 2014; Hunt & Smith, 2004; Kim et al., 2015; Levinger et al., 2016; Lotito et al., 2011; Tahmasebi et al., 2015), which can represent several days without being able to carry out their professional activity. This can cause structural and functional deficits in standing and walking (Farokhmanesh et al., 2014). Those are due to skeletal system interactions, muscular system, and Central Nervous System, joint or muscle dysfunction that are reflected in the functionality of others, not locally but globally (Feldman, 2016).

Foot posture is generally characterized by foot skeleton alignment and varies between individuals (Angin et al., 2018; Buldt et al., 2013). Foot alignment, as the most distal part of the lower extremity kinematic chain as well as providing support to maintain the body's balance, has an important role in standing and walking and foot alignment changes affect the spine biomechanics that leads to spine instability, muscle imbalance, and structural modifications. When the body's center of gravity deviates from its ideal alignment, postural compensation strategies are employed to achieve stable posture (Farokhmanesh et al., 2014). In posture analysis, in a closed kinematic chain, FF condition causes internal tibial and femur rotation resulting in an increased pelvic anteversion that leads to hyperlordosis and associated pathologic alterations (Farokhmanesh et al., 2014; Tahmasebi et al., 2015). Various foot postural alignments have been theoretically associated with abnormal foot motion during gait (Douglas Gross et al., 2011; Eslami et al., 2014; Farokhmanesh et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Tahmasebi et al., 2015; Twomey et al., 2010). Those pathological modifications are compensatory patterns between the spine and lower limbs occurring in dynamic balance strategies to equalize several kinematic and kinetic imbalances (Sung et al., 2017). Besides, foot posture changes induce alterations of plantar pressure patterns. Neuromotor responses to altered sensory afferents signals affect muscle function and foot mechanics associated (Angin et al., 2018). Those patterns are higher pressure, force, and contact area values in the medial arch, central forefoot, and hallux, while these variables are lower in the lateral and medial forefoot (Buldt et al., 2013, Levinger, et al., 2018). The foot position during posture and gait is considered a risk factor for lower-limbs injuries.

Previous assessments have focused on the ankle joint and the foot complex without much adjacent joint analysis. However, authors have attributed to the ankle the cause of alterations in the lower-limb movement pattern. Those altered patterns can impact subjects' quality of life, influencing negatively for example their health, Laboral occupation, recreational activity, costing millions on healthcare treatment instead of focusing on injury prevention. This set of reasons raises the question of the analysis of gait and posture, including remaining joints.

To search for the best evidence of foot posture differences regarding gait and posture analysis, a systematic review was first carried out (**Chapter II**) with the application of the Newcastle-Ottawa scales, which were used to evaluate the methodological quality and to determine the level of scientific evidence regarding foot posture changes on dynamic and static posture. We found several outcomes and methods which investigate FF differences when compared to NF subjects. However, no consensus was found between the selected papers and authors. Secondly, based on the lack of evidence, study limitations, and lack of methodological procedure criteria, reviewed in the systematic review, an observational descriptive study was conducted to analyze static posture through a linear analysis (**Chapter III** and **Appendix F-G**). We investigated both kinematic and kinetic outcomes comparing FF and NF condition subjects. The raw data were extracted using a Motion Capture Analysis System and a force platform, where several significant differences were found between groups. Those methods are considered Linear methods as we analyzed Center of Pressure characteristics and kinematics through traditional ways to assess potential alterations. Following this, we explored the Center of Pressure characteristics differences among groups throughout Non-Linear methods (**Chapter IV** and **Appendix D-H**). For this, we used the *LyE*, *ApEn*, *FD,* and the *CD*. With the use of those different methods, we studied the postural stability variability of the different conditions and alongside the influence of the eyes-open and -closed condition. We, therefore, assessed several specificities of the stability process behavior among those participants, where only one parameter was significantly different among groups. Furthermore, we also investigated the gait pattern differences regarding foot posture, focusing primarily on kinematics changes (**Chapter V**) as we intend to verify if static differences were also present during the gait task. We found several kinematics differences between the FF group and the NF group. Besides, we intended to investigate more specifically structure modifications in FF subjects. Along with the poor understanding of different methods and the lack of evidence, we felt the need to understand more specifically shank and lower limb muscle alterations, more specifically stiffness differences in FF subjects. We investigated Tibialis Posterior muscle stiffness concerning foot posture condition as this muscle is one of the most affected muscles concerning FF condition that can further lead to developing medial tibial stress syndrome (Kohls et al., 2004; Ohya et al., 2017; Bowring et al., 2010). (**Chapter VI** and **Appendix I-J**) and the overall muscle stiffness relationship along with the lower limbs. There is a need for in-depth knowledge of specific muscle stiffness research and relationships among these populations (**Chapter VII** and **Appendix K**). Finally, based on the systematic review results, the assumption was made that an important factor was the foot posture assessment and characterization. As there are several methods for diagnosis, an observational, correlational, and descriptive study was performed to acknowledge those methods where controversial results were found when compared to other authors' findings (**Chapter VIII** and **Appendix A-B-C-E**).

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CHAPTER II

STUDY I · DIFFERENCES BETWEEN SUBJECTS WITH AND WITHOUT FLATFOOT ON STATIC AND DYNAMIC POSTURE: A SYSTEMATIC REVIEW

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Abstract

Background: Structural or functional alteration in the foot complex may have an impact on, posture and movement on distal and proximal structures. The foot complex has an important role in posture, balance, stability, and movement, during static positions and in overall movement patterns. Flatfoot can be triggered by several risk factors and lead to several injuries, functionally or pathologically. This condition leads to higher risks of developing mechanical overloading injuries on adjacent lower limb joints. The systematic review aim was to investigate the used variables to assess subjects with flatfoot regarding static and dynamic posture. ***Methods:*** A computerized database search of MEDLINE, PEDro, and CENTRAL was realized until March 2020. Reviewer applied inclusion criteria to selected articles for review and quality assessment which was evaluating subjects with and without flatfoot differences regarding different postures assessment. Outcomes assessment were divided into both kinematics and kinetics outcomes. All studies reported specific kinematics and/or kinetics outcomes in subjects with and without flatfoot. A final selection of 15 articles was reviewed. ***Results:*** Selected articles focused on analyzing kinetic and kinematics effects on static and dynamic posture. Nine articles analyzed the differences in static posture in subjects with and without flatfoot – 7 articles analyzed kinematic outcomes while 2 articles analyzed kinetic outcomes, and there was low overall evidence of alteration between subjects. Six studies analyzed the same condition however on dynamic posture – 1 article analyzed kinematic outcomes while 6 articles analyzed kinetic outcomes, and there was low evidence regarding kinematics and strong evidence of alteration between subjects on kinetics outcomes. ***Discussion:*** Literature provides evidence of several kinetic and kinematics differences between subjects with and without flatfoot, specifically on dynamic and static posture while regarding several limitations and lack of methodological procedure.

Keywords: Foot posture, movement patterns, kinetics, kinematics, posture assessment

Introduction

Foot problems are related to impaired mobility and postural stability, having a detrimental impact on life quality, and are reported as a common concern in the community (Sung, 2016; Sung et al., 2017). FF is characterized by calcaneus plantarflexion and eversion relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008). This is triggered by several causes, namely, neurological, or muscular restrictions, ligament laxity, joint laxity, excessive motion, and muscle activity (Farokhmanesh et al., 2014; Hunt & Smith, 2004; Tahmasebi et al., 2015). This condition is present in children, targets 10-25% of adults, and is associated with several injuries (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008; Sung, 2016; Sung et al., 2017). It is often accompanied by pain and frequently affects walking speed and gait pattern, balance, and decreased function, which increases fall risk (Farokhmanesh et al., 2014; Sung, 2016; Sung et al., 2017). Alongside FF, tibial internal rotation, increased forefoot abduction, and ankle inversion is considered biomechanical risk factors for pathological conditions (Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Sung, 2016; Twomey et al., 2010), and FF is considered an intrinsic risk factor for kinetic stability(Sung, 2016a). Those are related to force asymmetrical distribution across the subtalar joint and transverse and frontal plane loads on the knee that can lead to pathologic conditions in the spinal column (Douglas Gross et al., 2011; Eslami et al., 2014; Farokhmanesh et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Tahmasebi et al., 2015; Twomey et al., 2010).

Since lower extremities postural alterations lead to postural changes in the pelvic girdle and enhance low back pain risk, foot alignment should be considered an important and effective factor (Farokhmanesh et al., 2014). FF subject has higher risks of developing mechanical overloading injuries triggered on either ankle, knee, or hip joints (Hösl et al., 2014; Hunt & Smith, 2004; Kim et al., 2015; Levinger et al., 2016; Lotito et al., 2011; Tahmasebi et al., 2015). Those are due to skeletal system interactions, muscular system, and Central Nervous System (CNS), joint or muscle dysfunction, that are reflected in others functionality, not locally but globally (Feldman, 2016; Ghasemi et al., 2016). Foot posture is generally characterized by the alignment of the foot skeleton and varies considerably between individuals (Angin et al., 2018). Foot alignment, as the most distal part of the lower extremity kinematic chain as well as providing support to maintain the body's balance, has an important role in standing and walking (Douglas Gross et al., 2011; Eslami et al., 2014; Farokhmanesh et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Tahmasebi et al., 2015; Twomey et al., 2010) and foot alignment alterations affect the spine biomechanics that can lead to spine instability, muscle imbalance and structural alterations (Farokhmanesh et al., 2014). When the body's center of gravity deviates from its ideal alignment, postural compensation strategies are employed to achieve a stable posture. Besides, alterations in foot posture induce altered plantar pressure patterns, which consequently alter the proximal lower limb joints (Angin et al., 2018). Neuromotor responses to the altered sensory afferents signals affect muscle function and foot mechanics associated (Angin et al., 2018). Those patterns show higher pressure, force, and contact area values in the medial arch, central forefoot, and hallux, while these variables are lower in the lateral and medial forefoot (Buldt et al., 2018, Levinger, et al., 2018). Pathological alterations are consequences of compensatory patterns between the spine and lower limbs during dynamic balance strategies and equalize several kinematic and kinetic imbalances (Sung et al., 2017). Therefore, this systematic review aims to appraise the variables used to assess subjects with FF on static (SP) and dynamic posture (DP).

Methods

Design

This systematic review was established after the Ethics Committee approval of Polytechnic Institute of Coimbra (*13_CEPC2/2019*) and using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (*PRISMA*) guidelines. PRISMA statement (http://www.prisma-statement.org) includes a 27-item checklist that is designed for reporting systematic reviews.

Search Strategy

Searches encompassed three electronic databases which were Medline (Pubmed), Physiotherapy Evidence Database (PEDro), CENTRAL (Cochrane

Controlled Register of Trials) for relevant full-text studies, written in English with no data restrictions and concluded on 2nd of March 2020. This review protocol was not registered a priori. All authors independently performed searches until 30 Jun 2020 and matched results for duplicate studies.

All data extraction and bias assessment risk were performed by the principal investigator, and reviewed by 3 others, with consensus achieved through discussion. Reference lists of the most relevant selected publication were screened for additional information or relevant publications that were not identified through computerized search. The database search strategy combined the following search terms along and in combinations: *"Ankle eversion", “Flatfoot”, “Plano valgus foot”, “Over-pronated foot”, “Hyperpronation”, "Posture", “Standing position”, "Kinematic" and "Kinetic".*

Study Selection

All searches were screened to remove duplicates and non-suitable publications by the principal investigator. The remaining titles and abstracts were screened for relevant articles and pertinent full-text studies were selected for further analysis. Full-texts were analyzed by the main investigator following several specific inclusion criteria: (a) all subjects must be at least 18 years old with no age restriction; (b) all studies must report subjects with and without FF; (c) all studies must report kinematic and/or kinetic variables assessed on SP and DP; (d) all studies cannot report comparison treatment inclusion; (e) study designs included were observational cohort and case-control studies; We excluded studies that (a) full text wasn’t available; (b) investigate acute or ankle fractures history and (c) case reports, reviews and editorials.

Data Extraction and Summary

Data collection and extraction were realized by the principal investigator and checked by 3 others. All documents related to selected studies (full-text document, appendices, and supplementary material) were collected for further analysis. Authors extracted and summarized included studies characteristics and recommendations regarding specific study design, participants feature, condition characteristics, assessment components, outcomes measures, and results (***Table 2.1***).

Assessment of risks of bias

Studies' methodological quality was assessed using the *Newcastle-Ottawa scale* (NOS). However, the *NOS – Case-control* studies version was used for eight studies while the *NOS – Cross-sectional* studies version was used for the remaining seven. The principal investigator assessed all studies' quality. For both scale versions, qualitative assessment criteria encompass 3 main categories: sample selection, comparability, and exposure. Each factor had questions that could be assigned 1 or 2 points (stars) if analyzed studies met specific criteria which can generate a potential maximum value of 9 and 10 points, respectively. In our analysis, studies with *NOS* scores of 1-3; 4-6, and 7-9/10 were considered as low, intermediate, and high-quality studies (***Table 2.2****)*.

Table 2.1*: Quality assessment of individual trials.*

NOS – Case-control studies

	Selection				***Comparability***	***Outcome***			***Total Score (0-9)***
Authors	Is the case definition adequate?	Representativeness of the Cases	Selection of Controls	Definition of Controls	Comparability of Cases and Controls on the Basis of the Design or Analysis	Ascertainment of Exposure	Same method of ascertainment for cases and controls	Non-Response Rate	
Kim et al. (2015)	*	*	-	*	**	-	*	*	7
Prachgosin et al. (2015)	*	-	-	*	**	-	*	*	6
Sung et al. (2016)	*	-	-	*	**	-	*	*	6
Sung et al. (2017)	*	-	-	*	**	-	*	*	6
Sung et al. (2018)	*	-	-	*	**	-	*	*	6
Tahmasebi et al. (2014)	*	-	-	-	**	-	*	*	5
Hertel et al. (2002)	*	-	-	*	**	-	*	*	6
Tsai et al. (2006)	*	-	-	*	**	-	*	*	6

NOS – Cross-sectional study

	Selection				***Comparability***	***Outcome***		***Total Score (0-10)***
Authors	Representativeness of the sample	Sample size	Non-respondents	Ascertainment of the exposure	Comparability of Cases and Controls on the Basis of the Design or Analysis	Assessment of the outcome	Statistical test	
Duval et al. (2010)	-	-	*	*	--	-	*	3
Farokhmanesh et al. (2014)	*	*	*	**	--	-	*	6
Ghasemi et al. (2016)	-	-	*	**	--	-	*	4
Khamis et al. (2007)	-	-	*	**	--	-	*	4
Khamis et al. (2015)	-	-	*	**	--	-	*	4

Pinto et al. (2008)	*	*	*	**	--	-	*	6
Tateuchi et al. (2011)	-	-	*	**	--	-	*	4

Table 2.2: *Summary of included studies*

Study	**Design**	**Participants**	**Condition**	**Assessment**	**Outcomes measures**	**Results**
Duval et al. (2010)	*Cross-sectional study*	n = 15 Exp age *(yr)* = 25.4 (SD 1.7) 66% Female	Exp • Induced bilateral excessive ankle eversion	Flat surface, 5º, 10º, and 15º wedges upright standing (30sec each)	*Kinematic assessment:* • Lumbar lordosis ROM • Knee ROM • Hip ROM • Pelvis ROM *Follow up* = baseline	Increase hip and knee ROM ($p<.001$)
Farokhmanesh et al. (2014)	*Cross-sectional study*	n = 35 males Exp age *(yr)* = 22.8 (SD 2.89)	Exp • Induced bilateral excessive ankle eversion	Flat surface, 10º, 15º, and 20º wedges upright standing	*Kinematic assessment:* • Lumbar lordosis ROM • Thoracic kyphosis ROM *Follow up* = baseline	Increase lumbar lordosis and thoracic kyphosis ($p<.008$)
Ghasemi et al. (2016)	*Cross-sectional study*	n = 35 males Exp age *(yr)* = 22.8 (SD 2.89)	Exp • Induced bilateral excessive ankle eversion	Flat surface, 10º, 15º, and 20º wedges upright standing	*Kinematic assessment:* • Sacral angle • Pelvic inclination • Lumbar lordosis ROM • Thoracic kyphosis ROM *Follow up* = baseline	Increase ($p<.001$) sacral angle, pelvic inclination, lumbar lordosis, and thoracic kyphosis variables
Hertel et al. (2002)	*Case-control study*	n = 30 Age *(yr)* = 21.9 (SD 2.0) 50% Female	Exp 1 • Cavus foot group Exp 2 • Flatfoot group Con • Neutral foot group	Single-leg stance (3x 10sec)	*Kinetic assessment:* • CoP excursion area • CoP velocity *Follow up* = baseline	No significant differences between the flatfoot group and control group

			Goniometric rearfoot and forefoot measurement			
Khamis et al. (2007)	*Cross-sectional study*	n = 35 Exp age*(yr)* = 23 - 33 (SD NR) 57% Female	Exp • Induced bilateral excessive ankle eversion	Flat surface, 10º, 15º, and 20º wedges upright standing (3x 10sec for each)	*Kinematic assessment:* • Calcaneal eversion angle • Shank rotation angle • Thigh rotation angle • Pelvic tilt angle *Follow up* = baseline	Increase internal shank rotation (*p<.001*), internal hip rotation (*p<.001*), and anterior pelvic tilt (*p<.001*)
Khamis et al. (2015)	*Cross-sectional study*	n = 35 Exp age *(yr)* = 27.68 (SD 2.6) 57% Female	Exp • Induced bilateral excessive ankle eversion	Flat surface, 10º, 15º, and 20º wedges upright standing (3x 10sec for each)	*Kinematic assessment:* • Calcaneal eversion angle • Shank rotation angle • Pelvic tilt angle Follow up = baseline	Significant (*p<.05*) bi-variate relationship between the anterior pelvic tilt and thigh internal rotation, in all standing positions.
Kim et al. (2015)	*Case-control study*	n = 28 Exp age *(yr)* = 22.8 (SD 1.9) Con age *(yr)* = 23.6 (SD 4.0) 55% Female	Exp • Flatfoot group 5-9mm NDT and 2º RCSP Con • Neutral foot group >10mm NDT and >4º RCSP	• Single leg standing with eyes open and closed (3x 7sec) • Y Balance Test	*Kinetic assessment:* • CoP excursion (Anteroposterior – Mediolateral) • Y Balance Test *Follow up* = baseline	Greater CoP speed: • Anteroposterior with eyes open (*p=.007*) and closed (*p=.005*) • Mediolateral with eyes open (*p=.004*) and eyes closed (*p=.019*)
Pinto et al. (2008)	*Cross-sectional study*	n = 14 Exp age *(yr)* = 22.85 (SD 2.47) 50% Female	Exp • Induced bilateral and unilateral excessive ankle eversion	Flat surface and 10º upright standing (3x 10sec for each)	*Kinetic assessment:* • Pelvic posture (sagittal) • Pelvic posture (frontal) *Follow up* = baseline	Increase pelvic anteversion on both bilateral (*p=.003*) and unilateral (*p=.021*).

Prachgosin et al. (2015)	*Case-control study*	n = 28 Exp age *(yr)* = 24.9 (SD 3.3) Con age *(yr)* = 32.7 (SD 8.9) 85% Female	Exp • Flat feet group Footprint AI >0.32 Con • Neutral feet group 0.20<Footprint AI<0.28	Static capture in a relaxed position	*Kinematic assessment:* • Medial longitudinal arch angle (º) *Follow up* = baseline	Greater Medial longitudinal arch angle (*p=.002*).
Sung et al. (2016)	*Case-control study*	n = 64 Exp age *(yr)* = 33.1 (SD 14.5) Con age *(yr)* = 27.5 (SD 12.1) 50% Female	Exp • Flatfoot group >9mm NDT on dominant side Con • Neutral foot group 5-9mm NDT	Single leg standing for 25sec	*Kinetic Assessment:* • Kinetic Stability Index (Ground reaction force thresholds) • Standing time *Follow up* = baseline	Differences between groups in for 3N (*p<.01*) and 7N (*p<.03*) with the use of Kinetic Stability Index.
Sung et al. (2017)	*Case-control study*	n = 44 Exp age *(yr)* = 44.50 (SD 9.79) Con age *(yr)* = 42.33 (SD 2.56)	Exp • Flat foot group >9mm NDT on right foot Con • Neutral feet group 5-9mm NDT	Single leg standing for 25sec with eyes-open and closed, with the contralateral hip and knee flexed approximately 90°.	*Kinetic and Kinematic Assessment:* • Kinetic Stability Index • Kinematic Stability Index *Follow up* = baseline	Decrease kinetic stability index score in Exp group in the eyes-closed condition (*p=.001*). Lower kinematic stability index score in: ▪ Eyes-closed condition for the head, upper thorax, lower thorax, and lumbar spine (*p=.001*) ▪ Eyes-open condition for the upper thorax and lower thorax (*p=.02*)
Sung et al. (2018)	*Case-control study*	n = 64 Exp age *(yr)* = 33.1 (SD 14.5) Con age *(yr)* = 27.5 (SD 12.1) 39% Females	Exp • Flatfoot group >9mm NDT on dominant side Con • Neutral foot group	Single leg standing for 30sec with eyes-open and closed, with the contralateral hip and knee flexed approximately 90°.	*Kinetic Assessment:* • Postural Stability Index (Various Ground Reaction Force thresholds) *Follow up* = baseline	Decrease postural stability index score in Exp group for thresholds: ▪ 3N (*p=.01*) and 7N (*p= .03*) in the eyes-closed condition;

			5-9mm NDT			▪ 3N (*p=.01*), 7N (*p=.01*) and 15N (*p=.02*) in the eyes-open condition.
Tahmasebi et al. (2014)	*Case-control study*	n = 30 Exp age *(yr)* = 22.3 (SD 2.3) Con age *(yr)* = 21.6 (SD 3.2)	Exp • Flatfoot group AI > 0.26 and Footprint Angle >42º Con • Neutral foot group 0.21 < AI < 0.26 and Footprint Angle <29.9º	One-minute standing posture	*Kinetic Assessment:* • CoP excursion (anteroposterior/mediolateral) • CoP velocity (anteroposterior/mediolateral) *Follow up* = baseline	Increase anteroposterior and mediolateral CoP velocity in Exp group (*p=.000*). Increase in anteroposterior CoP excursion in Exp group (*p=.034*).
Tateuchi et al., (2011)	*Cross-sectional study*	n = 28 males Exp age *(yr)* = 23.4 (SD 2.7)	Exp • Induced unilateral excessive calcaneus eversion	Flat surface, 5º, 10º wedges upright standing (3x 10sec for each)	*Kinematic assessment:* • Pelvic angle • Hip angle • Thorax angles *Follow up* = baseline	Increase angle ROM (*p=.016*): ▪ Hip joint flexion ▪ Medial rotation ▪ Pelvic anterior tilt ▪ Thoracic lateral tilt ▪ Thoracic Axial rotation
Tsai et al. (2006)	*Case-control study*	n = 45 Exp 1 age *(yr)* = 21.9 (SD 3.5) Exp 2 age *(yr)* = 23.9 (SD 3.2) Con age *(yr)* = 26.1 (SD 3.6) 46% Females	Exp 1 • Flatfoot group > 9° RCSP < 134° MLA Exp 2 • Cavus group <3° RCSP >150 MLA Con • Neutral foot group	Single-limb stance with eyes closed (3x 10sec for each)	*Kinetic assessment:* • CoP average speed (AP/ML) • CoP maximum displacement (AP/ML) *Follow up* = baseline	The pronated group had a significantly greater maximum displacement (*p=.05*) in the AP direction than subjects in the neutral group.

			3-9° RCSP 134-150º MLA			

SD = Standard Deviation, Exp = experimental group, Con = control group, Pla = placebo group, NR = not reported, ROM = Range of motion, MLA = Medial longitudinal arch, AP = anteroposterior, ML = mediolateral, CoP = Centre of Pressure.

Results

Study Selection

Through all database and hand searches, 298 titles and abstracts were found after duplicates removal. After analysis, 268 articles were screened based on titles and abstract reading whose provided 62 studies. Those were assessed for full-text evaluation and meeting eligibility criteria resulting in 15 studies (***Figure 2.1***).

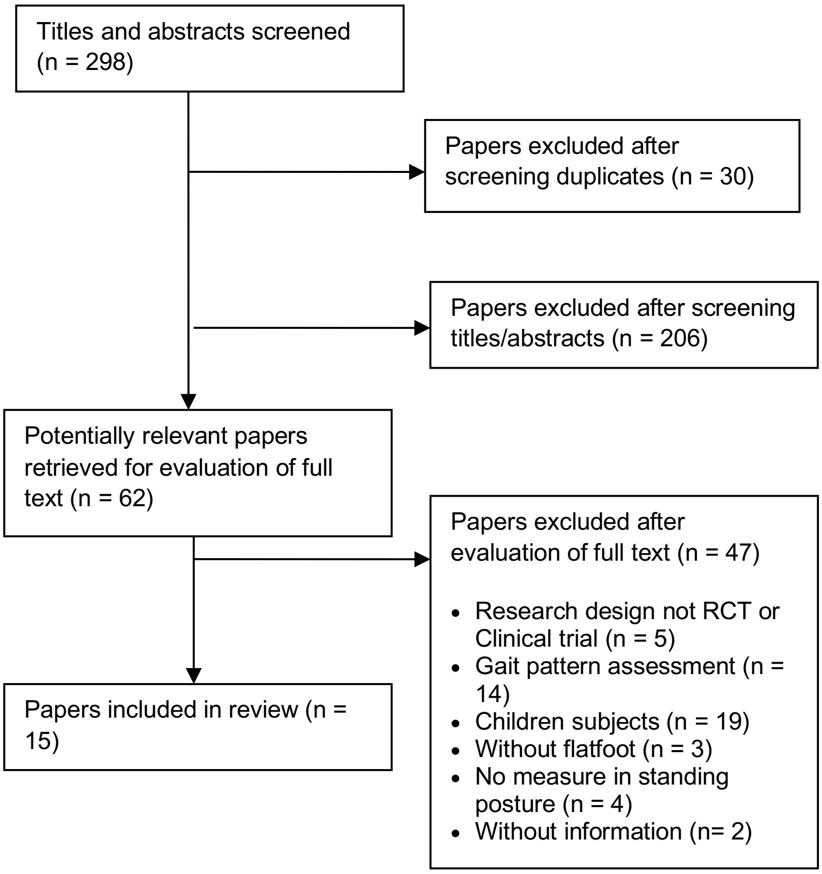

Figure 2.1: *Flow of studies through the review*

Studies characteristics

Most studies include a separate control group (Hertel et al., 2002; Kim et al., 2015; Prachgosin et al., 2015; Sung, 2016, 2018; Sung et al., 2017; Tahmasebi et al., 2015; Tsai et al., 2006); seven studies participants served as their control in cross-sectional studies (Duval et al., 2010; Farokhmanesh et al., 2014; Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Pinto et al., 2008; Tateuchi et al., 2011). Participants number in reviewed studies ranged from 14 (Pinto et al., 2008) to 64 subjects (Sung, 2016, 2018). No follow-up was considered for all studies (***Table 2.1***).

Risk of bias

All studies' risk of bias scores are presented in Table 2.2. The mean rating for the eight articles using *NOS – Case-control* studies was 6 out of 9 total points. The overall scoring difference was just one point between the highest (Kim et al., 2015) and the lowest (Tahmasebi et al., 2015). Respectively, the highest article (Kim et al., 2015) achieve a score of 7, representing a high-quality study, lowest article (Tahmasebi et al., 2015) achieved a score of 5 which correspond to intermediate quality, while the remaining 6 others achieved a score of 6 (Hertel et al., 2002; Prachgosin et al., 2015; Sung, 2016, 2018; Sung et al., 2017; Tsai et al., 2006) which correspond to intermediate quality. For the *NOS – Case-control* scale, the seven remaining articles' mean rating was 4.4 out of 9 total points. The overall scoring difference was three points between the lowest (Duval et al., 2010) and the highest (Farokhmanesh et al., 2014; Pinto et al., 2008). Those articles achieved respectively a score of 3 and 6 out of 10 total points, which correspond to low and intermediate quality while other studies achieved a score of 4 (Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Tateuchi et al., 2011), which correspond to low quality. Long-term follow-up was lacking in all studies.

Participants

Subjects' mean age across studies ranged from 21,6 (Tahmasebi et al., 2015) to 44,5 years (Sung et al., 2017). Within 15 articles, eight studies were performed in FF participants, while NF subjects served as the control group (333 participants) (Hertel et al., 2002; Kim et al., 2015; Prachgosin et al., 2015; Sung, 2016, 2018; Sung et al., 2017; Tahmasebi et al., 2015; Tsai et al., 2006). The remaining seven studies used NF subjects who were submitted to an induced bilateral or unilateral FF (197 participants) (Duval et al., 2010; Farokhmanesh et al., 2014; Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Pinto et al., 2008; Tateuchi et al., 2011). For FF individuals, researchers evaluate the condition using several tests. The NDT was utilized by *Sung et al.* (2016,2017,2018) and *Kim et al.* (2015) (FF group>9/10mm). *Tsai et al.* (2006) utilized the Medial Longitudinal Arch (MLA) angle to characterize each group (FF group<134º). Those two last authors, along with their previous test, used the RCSP, with values respectively higher than 4º and 9º. Also, *Hertel et al.* (2002) used Goniometric rearfoot and forefoot measurement to characterize each group in lying position. Finally, *Prachgosin et al.* (2015) used the *AI* (FF group>0.32), and *Tahmasebi et al.* (2014) used both *AI* and *Footprint Angle* (FPA) (AI>0.26 and FPA>42º).

Assessment

The experimental procedure was performed in two ways. For DP, the authors utilized the One-leg Standing test with the other knee and hip at 90º of flexion (Kim et al., 2015; Sung, 2016, 2018; Sung et al., 2017; Tateuchi et al., 2011) and the Y-Balance Test (Kim et al., 2015). Single-leg standing was divided into two types, with eyes open and closed on a flat surface (Kim et al., 2015; Sung, 2016, 2018; Sung et al., 2017; Tsai et al., 2006), while two studies were realized on several wedges' positions (Tateuchi et al., 2011). Regarding SP, authors utilized bipedal standing posture task in orthostatic position on a flat surface (Prachgosin et al., 2015; Tahmasebi et al., 2015) and repeated on several wedges' positions (Duval et al., 2010; Farokhmanesh et al., 2014; Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007). Assessment follow-up was identical in all studies. However, one study (Pinto et al., 2008) realized both bipedal and unilateral assessment on a flat surface and 10º wedge. Assessment duration was inconstant with static assessment total duration time range from 1 (Pinto et al., 2008) to 5 minutes (Tahmasebi et al., 2015) while for dynamic assessment range from 30 (Hertel et al., 2002; Khamis et al., 2015; Khamis & Yizhar, 2007) to 90 seconds (Sung, 2018). Three studies didn't report time (Farokhmanesh et al., 2014; Ghasemi et al., 2016; Prachgosin et al., 2015).

Outcomes measures

All studies investigated kinematic or kinetic differences between subjects with or without FF in DP or SP. In our research, kinematic outcomes were gathered in acquired and induced FF participants. Several studies assessed in induced FF subjects, lumbar lordosis (Duval et al., 2010; Farokhmanesh et al., 2014; Ghasemi et al., 2016), hip (Duval et al., 2010; Tateuchi et al., 2011), knee (Duval et al., 2010), thoracic kyphosis (Farokhmanesh et al., 2014; Ghasemi et al., 2016; Tateuchi et al., 2011) and pelvic (Duval et al., 2010; Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Pinto et al., 2008; Tateuchi et al., 2011) ROM and sacral (Ghasemi et al., 2016), maximum calcaneal eversion (Khamis et al., 2015; Khamis & Yizhar, 2007) and, shank and thigh rotation (Khamis et al., 2015; Khamis & Yizhar, 2007) angles. MLA deformation was assessed by *Prachgosin et al.* (2015). Finally, the *Kinematic Stability Index* was investigated by *Sung et al.* (2017). Moreover, kinetic outcomes were only obtained in participants with FF. *Center of Pressure* (CoP) excursion and velocity were investigated by *Hertel et al*. (2002), *Kim et al*. (2015), *Tahmasebi et al.* (2014), and *Tsai et al.* (2006). Authors like *Sung et al*. (2016,2018) analyzed *Ground Reaction Force* (GRF) variability, while *Sung et al.* (2016,2017) investigated the *Kinetic Stability Index*. This last one investigates both kinetic and kinematic outcomes using both indexes for DP assessment.

Discussion

This systematic review is, to our knowledge, the first to look at FF effects on SP and DP, regarding kinematics and kinetics aspects. A previous systematic review investigated the same condition considering gait pattern and running task.

Dynamic posture

Results didn’t have a consensus between all authors in different papers. All studies that evaluated FF in DP investigated kinetics outcomes that vary among authors. The *kinetic Stability Index* that was used to compare thresholds sensitivity, showed statistically significant differences between groups for 3N and 7N in open and closed eyes conditions (*p<.03*) (Sung, 2016, 2018). However, an interesting result is the differences found by *Sung et al.* (2018) for 15N threshold sensitivity that is contradictory to results found by *Sung et al.* (2016). Those results indicated that threshold settings lower than 15N are considered more suitable to detect kinetic stability. Thresholds lower than 15N (either 3N or 7N) were significantly higher in the NF group. Threshold sensitivity analysis from GRF needs to be considered by practitioners to acquire additional information about postural biomechanical mechanisms in FF participants. Thresholds higher than 15N can be considered sensitive enough to distinguish FF from NF (Sung, 2016, 2018).

One interesting result was the 15N threshold regarding visual input, which was significantly lower (*p<.02*) in the FF group due to possible foot mobility found by *Sung et al.* (2018). Plantar pressure variability alterations during unilateral stance might be trivial, although visual feedback produced a significant change on stability index at the 15N threshold (Sung, 2018). In the same population, *Sung et al.* (2017), found significant results in eyes-closed conditions, where the FF group demonstrated decreased kinetic stability. However, in the eyes-open condition, no significant differences between groups were found (*p=.27*) which is contradictory to results found by *Sung et al.* (2018). Considering those studies' intermediate quality (NOS-Score: 6) and the same used methodology setup, results could be extrapolated to the studied population. However, controversial results can be explained by possible visual input impairment between both samples.

FF participants might develop risk for kinetic instability when proprioception is limited since imprecise body sway estimation can be due to reduced accuracy in the sensory integration process. Further analysis regarding group differences for the 7N threshold is recommended, which might expand FF characteristics understanding for dynamic activities. Threshold sensitivity based on *Kinetic Stability Index* needs to be considered with a three-dimensional approach to produce valid and reliable results for foot stability (Sung, 2016).

In unilateral leg stand, *Kim et al.* (2015) analyzed CoP excursion and Y balance test scores in subjects with and without FF. CoP speed was statistically significantly greater in the FF group compared to the NF group both in anteroposterior and mediolateral with eyes-open (*p=.007*, *p=.004*) and closed (*p=.005*, *p=.019*). Besides, there are no statistically significant differences regarding Y scores (*p=.839*). Finally, no significant correlation was found between CoP and Y score (*p>.05*). These results contrast with two previous reports that investigated CoP speed in subjects with FF and NF where *Hertel et al.* (2002) reported no significant difference (*p=.91*) in average CoP speed among different foot types. Similarly, *Tsai et al.* (2006) reported no significant difference (*p>.05*) in CoP excursion velocity between FF and NF. Authors postulated that this might be due to subtalar joint instability in the FF group, supported by greater NDT and RCSP values. Subtalar joint controls the stability of the rear foot directly positions and distal joints, such as transverse tarsal joint, indirectly. When weight-loaded, excessive subtalar joint flexibility increases pronation, leading to an unstable base of support (BoS) and decreased foot stability (Kim et al., 2015). Regarding those studies' intermediate and high quality, discrepancies between results can be explained by different used methodology regarding different groups conditions, time assessment, and visual input.

Two authors investigated kinematic outcomes for the dynamic task. *Sung et al.* (2017) analyzed the *Kinematic Stability Index* in both open and closed-eyes conditions. They reported lower statistically significant differences between groups in an eyes-closed condition regarding the head, upper, lower thorax, and lumbar spine (*p=.001*). FF subjects presented lower stability during one-leg standing without visual input. Though, for the other condition, authors found lower significant differences only for upper (*p=.02*) and lower thorax (*p=.02*). The other study (Tateuchi et al., 2011) that investigated kinematic outcomes in DP found that induced FF moment, in different conditions affect three-dimensional kinematics of hip, pelvis, and thorax except for pelvic axial rotation (*p<.01*). Study findings highlight the need for clinicians to consider foot alignment when examining patients with malalignments, such as hip medial rotation, pelvic tilt, and thoracic axial rotation. Few studies examined these variables, thus showing a need for search in this area.

Static Posture

Few articles investigated kinematic outcomes while just one also investigated kinetic data. Several investigators analyzed the induced FF effect using a few wedges. *Duval et al.* (2010) found changes between subjects, yet not all those were statistically significant. Subtalar pronation, relative to neutral position increases internal knee and hip rotation. Though, the authors found only a significant correlation between subtalar angle and knee and hip rotation (*p<.001*) which follow *Khamis et al.* (2007,2015) results. However, foot pronation and supination did not have a significant relationship 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 significant increase in lumbar lordosis (*p<.05*). However, more search needs to be developed in this area because of sample differences, used setup, and low-intermediate studies quality. Also, *Duval et al.* (2010) found that thigh internal rotation produced an anterior pelvis tilt (*p<.001*). 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) result (*p<.001*). Finally, this last one analyzed sacral angle related to foot pronation and noticed a significant increase in induced FF subjects (*p<.001*). Though, *Prachgosin et al.* (2015) in FF subjects, where MLA deformation was assessed observed that FF subjects had significantly greater MLA angle (*p=.002*). In kinetic assessment, *Tahmasebi et al.* (2014) found that total, anteroposterior and mediolateral CoP velocity was statistically greater (*p=.000*) and a statistically significant increase in anteroposterior CoP excursion (*p=.034*) in FF subjects.

Biomechanically, the body is considered as a multi-segmental structure linked globally together by main forces interactions between adjacent segments (Khamis & Yizhar, 2007). The combined effect of rotational alignment between segments and the cumulative effect of foot hyperpronation induced postural re-alignment to conserve CoP in subject support base to maintain postural stability with repercussion on both distal and proximal joints (Ghasemi et al., 2016; Khamis et al., 2015). Any variation in those joints can influence both positively and negatively the whole lower extremity kinematic and kinetic chain (Farokhmanesh et al., 2014). During excessive subtalar pronation, the calcaneus performs an eversion movement, producing medial and inferior talus slide motion along with internal rotation, provoking an internal shank rotation (Farokhmanesh et al., 2014; Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Tahmasebi et al., 2015). Then, femur medial rotation increases the pressure between the femoral head and acetabulum posterior portion (Ghasemi et al., 2016; Sung et al., 2017), inducing anterior pelvis tilt (Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007) and consequently, due to the pelvis/lumbar spine relationship at the sacroiliac joint by widespread fibrous connection, pelvis motion alteration increases lumbar lordosis (Ghasemi et al., 2016; Khamis & Yizhar, 2007), spine instability, balance disorder and structural abnormalities (Ghasemi et al., 2016). Exposing subjects to induced hyperpronation emphasizes immediate effect on the intersegmental relationship and not necessarily a prolonged adaptive effect (Khamis & Yizhar, 2007).

Besides, some results are in contradiction possibly because of the non-evaluation and postural system modulation. To maintain postural stability, the body requires sensitive inputs of lower limb proprioceptive receptors relative to several environmental alterations (Rogers & Mille, 2018; Sung, 2018; Sung et al., 2017). Postural stability rests on sensorimotor receptors feedback, namely plantar pressure, visual system, dental-occlusal and vestibular alterations (Mackinnon, 2018; Peterka, 2018; Sung, 2018; Young et al., 2018). The visual system contributes to balance, through sensorial capacity, estimating distances, and providing information about body motion and sway (Dakin & Rosenberg, 2018; Peterka, 2018; Sung et al., 2017). It is difficult to analyze postural stability in FF subjects without controlling this receptor that can influence negatively data results (Peterka, 2018). In FF subjects, the plantar foot area increases compared to NF subjects which impair pressure feedback resulting in receptors compensation for maintaining postural stability (Mackinnon, 2018; Sung, 2018). This follows the present review findings where decreased kinetic sensitivity increased postural sway and instability. Finally, one parameter that differs from previous searches is BoS used to assess alterations. BoS variations lead to stability adaptation. In a bipedal stance, mediolateral Center of Mass (CoM) position is usually positioned above BoS area while reduced in unilateral stance, accompanied with postural corrections, using ankle, knee, or hip strategy, increasing postural instability, and body sway, thereby increasing intrinsic stiffness (Forbes et al., 2018; Rogers & Mille, 2018).

Conclusion

Considering the overall quality, kinetic and kinematic outcomes, and assessed variables, there are several differences between subjects with and without FF, specifically regarding DP and SP. However, considering the lack of consensus regarding utilized outcomes and assessment conditions, both for static and DP, further studies need to be performed to create more robust evidence. Although, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER III

STUDY II · POSTURAL LINEAR ANALYSIS IN FLATFOOT SUBJECTS

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Abstract

Background: Stability requires cognitive resources to process somatosensory input, any additional process can reduce stability sustaining. Foot postural alignment has been associated with lower-limbs abnormal motion and altered postural stability. The study aimed to investigate if there are kinematics and kinetics differences between subjects with and without flatfoot condition, regarding postural stability. ***Material and methods:*** The sample consisted of 31 participants comprising a total of 62 feet, where 15 integrated into the experimental group with the flat foot condition and the remaining 16 in the control group with the NF condition. Subjects were screened, before posture analysis, using the NDT and RCSP test, to characterize each group. 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 condition. ***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***: Flat-footed subjects presents few alterations compared to NF participants, in bipedal weight-bearing stance, both conditions. However, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

Keywords: Foot Posture; linear analysis, pés planus, plantar pressure.

Introduction

A FF condition can be caused by neurological or muscular restrictions, ligament/joint laxity, inconsistent range of motion, and muscle activity alterations (Hunt & Smith, 2004). In FF subjects, the risk of developing mechanical overloading injuries is higher than in subjects who did not present this condition. This alteration can induce knee pain, cartilage damage, medial tibial stress syndrome, sacroiliac joint dysfunction, metatarsal stress fractures, plantar fasciitis, Achilles tendinitis, tibialis anterior inflammation, or patellofemoral joint pain (Hösl et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Lotito et al., 2011). 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) (Nagai et al., 2011). Modifications in BoS, namely a greater area will increase sensorimotor adaptation leading to an increase in postural stability, therefore, preventing fall risks (Forbes et al., 2018; Rogers & Mille, 2018). BoS alterations induce body sway, thereby increasing intrinsic stiffness (Forbes et al., 2018; Rogers & Mille, 2018). Alongside, to maintain postural stability, the body requires sensitive inputs of the lower limbs' proprioceptive receptors relative to several environmental alterations (Rogers & Mille, 2018; Sung, 2018; Sung et al., 2017). Postural stability is based on various sensorimotor receptor feedback, namely plantar pressure, proprioceptive, visual and oculomotor motion, and vestibular information (Mackinnon, 2018; Peterka, 2018; Sung, 2018; Young et al., 2018). Regarding visual input, the visual and oculomotor system contributes to balance, through their unique sensorial capacity, estimating distances, and also providing information about body motion and sway (Dakin & Rosenberg, 2018; Peterka, 2018; Sung et al., 2017). Because stability requires cognitive resources to process somatosensory input, any additional process can reduce stability sustaining. This information is processed in the Central Nervous System (CNS) to create neuromotor necessary output commands to maintain stability (Colebatch et al., 2016; Feldman, 2016).

Foot posture induces altered plantar pressure patterns and proximal joint motion. Neuromotor responses to the altered sensory afferents signals affect muscle function, foot, and lower-limb biomechanics, as the CNS uses muscle coactivation as a motor control mechanism to modulate joint stiffness and postural stability (Angin et al., 2018). These occur globally and locally through postural and functional joint stabilization (Bavdek et al., 2018; Colebatch et al., 2016; Dicharry et al., 2009; Feldman, 2016; Kazemi et al., 2017; Levinger et al., 2016; Svoboda et al., 2016). Thus, foot posture, through altered lower-limb motion pattern can induce injuries (Buldt et al., 2013, 2015) and it has been associated with abnormal foot motion during gait (Buldt, et al., 2018, Levinger, et al., 2018; Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). The foot, which contains numerous cutaneous mechanoreceptors, is considered a sensitive map and provides important information for body balance, posture stability, gait pattern, mobility control and, muscular response (Kim et al., 2015). Besides, afferent input from the foot sole affects postural awareness and FF increase can be triggered by neurological and muscular restrictions, ligament and joint laxity, excessive motion, and muscle activity (Hunt & Smith, 2004). It is difficult to assess the postural stability of FF subjects without assessing plantar pressure patterns that can influence negatively the results (Peterka, 2018). On the other hand, in FF subjects, the plantar foot area increases compared to the NF which can impair the plantar pressure feedback, resulting in the other receptors' compensation for maintaining postural stability (Mackinnon, 2018; Sung, 2018). Then, an imprecise plantar pressure assessment results from reduced accuracy in the sensory integration (Sung, 2018).

Biomechanically, the body can be considered as a multi-segmental structure linked globally together by main forces interactions between adjacent segments (Khamis & Yizhar, 2007). 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 repercussion on both distal and proximal joints (Ghasemi et al., 2016; Khamis et al., 2015). Any variation in lower-limbs joints can influence both positively or negatively the whole lower extremity kinematic and kinetic chain (Farokhmanesh et al., 2014). 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 (Farokhmanesh et al., 2014;

Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007; Tahmasebi et al., 2015). Therefore, a consequence of this biomechanical alteration is a femur medial rotation increase that also increases the pressure between the femoral head and acetabulum posterior portion (Ghasemi et al., 2016; Lee et al., 2017). Consequently, this will produce an anterior pelvis tilt (Ghasemi et al., 2016; Khamis et al., 2015; Khamis & Yizhar, 2007). Finally, due to the pelvis/lumbar spine relationship at the sacroiliac joint by widespread fibrous connection, the anterior pelvic tilt increases lumbar lordosis (Ghasemi et al., 2016; Khamis & Yizhar, 2007), spine instability, balance disorder, and structural abnormalities (Ghasemi et al., 2016). Exposing subjects to induced hyperpronation emphasizes an immediate effect on the intersegmental relationship and not necessarily a prolonged adaptive effect (Khamis & Yizhar, 2007). The purpose of this study was to investigate if there are kinematics and kinetics differences between subjects with and without FF condition, regarding postural stability.

Materials and Methods

Participants

This observational descriptive study was carried out at *RoboCorp Laboratory – Physiotherapy*, 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*. The sample size was calculated with the aid of the *G*power 3.1.9* software (Franz Faul, Kiel, Germany). This calculation was based on the previously published paper of *Kim et al.* (2015). A required sample size of 18 was determined by achieving an estimated, alpha level of 0.05, and a power of 0.95. Consequently, forty-three individuals were recruited. Volunteers subjects were recruited for this scientific study. Before any assessment, all subjects were informed about the study purpose and procedures and then completed a consent form. However, thirty-one participants met the eligibility criteria (13 women / 18 men – 23.26 yo ± 4.43 SD) (***Table 3.1***). The inclusion in the study was limited to subjects who presented bilateral FF or bilateral NF. Inclusion criteria in the FF group encompassed subjects that presented a >9mm NDT and >4° RCSP scores. However, the inclusion criteria in the NF group involved participants with a <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. This procedure was performed by a single physiotherapist with more than 6 years of experience in the use of these techniques. Thus, subjects who presented the following conditions were excluded: a) ankle sprain in the last 6 months; b) physiotherapy treatment program or history of injury including bilateral ankle injury; c) bone fracture associated with an ankle sprain, such as avulsion fracture or osteochondral ankle injury; d) injury or surgery to the spine, hip, knee, or ankle. Then, the FF group consisted of 15 bilateral FF participants comprising a total of 30 feet while the NF group consisted of 16 bilateral NF subjects comprising a total of 32 feet.

Table 3.1: *Sample characteristics*

Group	**n**	**NDT** *(mm)*	**RCSP** *(º)*	**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; NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position

Assessment

Both NF and FF conditions were evaluated regarding the same assessment procedure bilaterally in a weight-bearing barefoot stance position. The navicular drop was evaluated using the NDT, where three measurements mean values define the navicular drop. The practitioner placed a rigid plastic-made ruler perpendicularly to the ground and registers 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 (Sung, 2018). Then, the Rearfoot-to-leg angle was assessed using the RCSP test where three measurements mean values define 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). This angle was measured using a rigid plastic goniometer. Then, a bilateral weight-bearing stance position was measured using a *Motion Capture System Qualysis® 3D motion* (Qualisys AB, Götebor, Sweden) with a 200Hz frequency coupling with a force platform

*Bertec® FP4060 (*Bertec Corporation, USA) with a 1000Hz frequency. For the assessment, 53 kinematic marks were placed on specific anatomical locations of the participants according to the *IOR* protocol (Wilken et al., 2012). Marker clusters were placed on the thighs and shanks to improve segment tracking accuracy. Subjects stayed upon a force platform for 60 sec with eyes-open (EO) and repeated it with eyes-closed (EC). The assessment was done with subjects in a quiet, comfortable barefoot posture upon the force platform while keeping the 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 (Janusz et al., 2016). If any participants failed to maintain their position, the trial was repeated.

Data Processing and Analysis

The outcomes collected were the ankle, knee, hip, and pelvis kinematics mean values of subjects during posture analysis regarding all 6 Degrees of Freedom (flexion/extension; abduction/adduction; internal/external rotation). Also, the CoP excursion, velocity, and area were evaluated. Kinematic data assessment and processing during posture analysis were previously done using *Qualisys Track Manager v2.15* (Qualisys AB, Götebor, Sweden) software. Then, the resulting data was exported to *Visual3D* (C-Motion, 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 analyze the relative angles of ankle, knee, and hip joints and, pelvis (Winter, 2008). 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 to a 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.

Statistical Analysis

The data were statistically processed with the *IBM SPSS Statistics 27.0* software (IBM Corporation, New York, USA). The descriptive statistics, mean and standard deviation, were calculated for all variables regarding both groups. Before the inferential analysis, the normality of the distribution was explored. We identified a normal sample 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, we identified a non-normal sample distribution based on the *Shapiro-Wilk* test (*p<.001*, t>0.617). 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 *Wilcoxon* test. The level of significance was set at 5% (*p<.05*).

Results

The sample characteristics are specified in ***Table 3.1*** alongside the mean values of the different tests regarding both groups. In the procedure, 30 FF and 32 NF were identified through inclusion criteria. Both subjects were identified and allocated in the different groups using the NDT and RCSP score assessment. 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 others joint kinematics did not present statistically significant differences between groups (*p>.05*). All the results those results are presented in ***Table 3.2***.

Table 3.2: *Groups kinematics characteristics in Eyes Open assessment*

		NF	**FF**	*p-value*
Ankle *(º)*	*Dorsiflexion - Plantarflexion*	-3.77 ± *3.91*	-1.83 ± *3.54*	*.047*
	Abduction - Adduction	-8.38 ± *3.63*	-5.75 ± *4.34*	*.013*
	Internal – External rotation	-13.31 ± *6.15*	-8.29 ± *4.96*	*.001*
Knee *(º)*	*Flexion - Extension*	-2.07 ± *5.88*	-3.88 ± *4.98*	*.198*
	Abduction - Adduction	1.42 ± *4.26*	0.65 ± *5.44*	*.536*
	Internal – External rotation	18.05 ± *10.57*	16.10 ± *6.62*	*.393*
Hip *(º)*	*Flexion - Extension*	-1.48 ± *9.40*	-1.08 ± *7.67*	*.856*
	Abduction - Adduction	-0.62 ± *3.68*	-1.93 ± *5.29*	*.268*
	Internal – External rotation	3.24 ± *9.71*	-0.77 ± *7.21*	*.071*
Pelvis *(º)*	*Anterior – posterior Tilt*	-9.13 ± *7.93*	-9.47 ± *5.97*	*.894*
	Lateral Tilt	-0.66 ± *2.34*	-1.09 ± *2.64*	*.635*
	Rotation	-0.28 ± *5.69*	-0.05 ± *2.64*	*.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

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*). All the results over the CoP characteristics are presented in ***Table 3.3*** alongside stabilogram and phase graph analysis examples in ***Figures 3.1*** and 3.***2***.

Table 3.3: *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	.922	2457.15 ± 451.55	2570.49 ± 425.14	.508	.027
	Antero-Posterior	1871.44 ± 352.55	1908.29 ± 314.98	.766	1876.18 ± 334.31	1975.31 ± 337.02	.450	.016
	Medio-Lateral	1247.68 ± 239.55	1229.89 ± 212.08	.832	1218.89 ± 243.16	1256.04 ± 199.83	.667	.210
Velocity *(mm/s)*	*Total*	495.41 ± 93.65	498.61 ± 82.87	.922	491.47 ± 90.32	514.14 ± 85.03	.508	.027
	Antero-Posterior	374.32 ± 70.52	381.69 ± 63.00	.766	375.27 ± 66.87	395.09 ± 67.41	.450	.016
	Medio-Lateral	249.56 ± 47.91	245.99 ± 42.42	.832	243.80 ± 48.63	251.23 ± 39.97	.667	.210
Amplitude *(mm)*	*Antero-Posterior*	30.33 ± 12.80	27.64 ± 11.03	.637	38.85 ± 20.58	38.58 ± 26.01	.793	.011
	Medio-Lateral	17.09 ± 7.91	17.30 ± 12.27	.759	19.84 ± 12.48	17.75 ± 11.48	.867	.039
Area *(mm^2)*		284.47 ± 250.93	221.37 ± 165.93	.498	379.09 ± 453.38	376.25 ± 557.17	1.000	.486

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

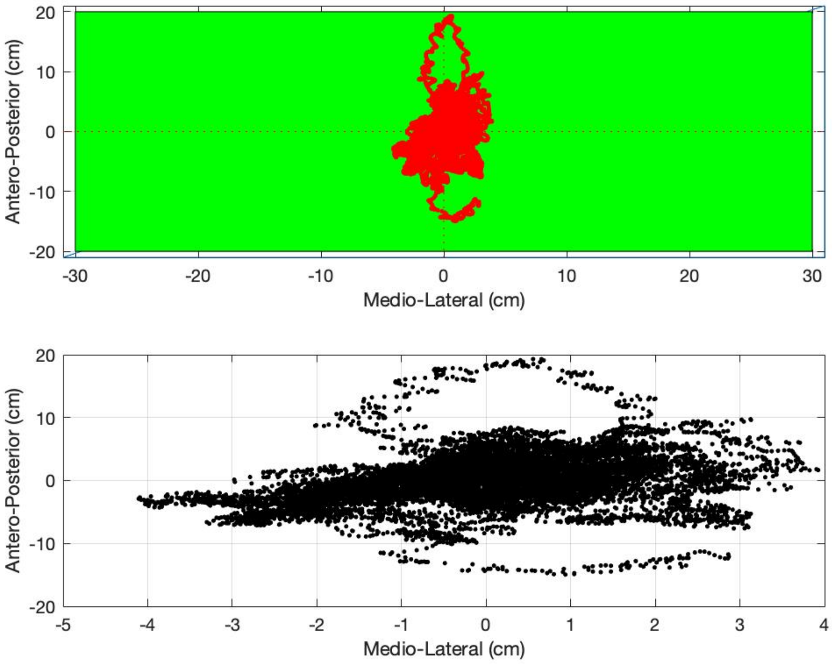

Figure 3.1: *Stabilogram*

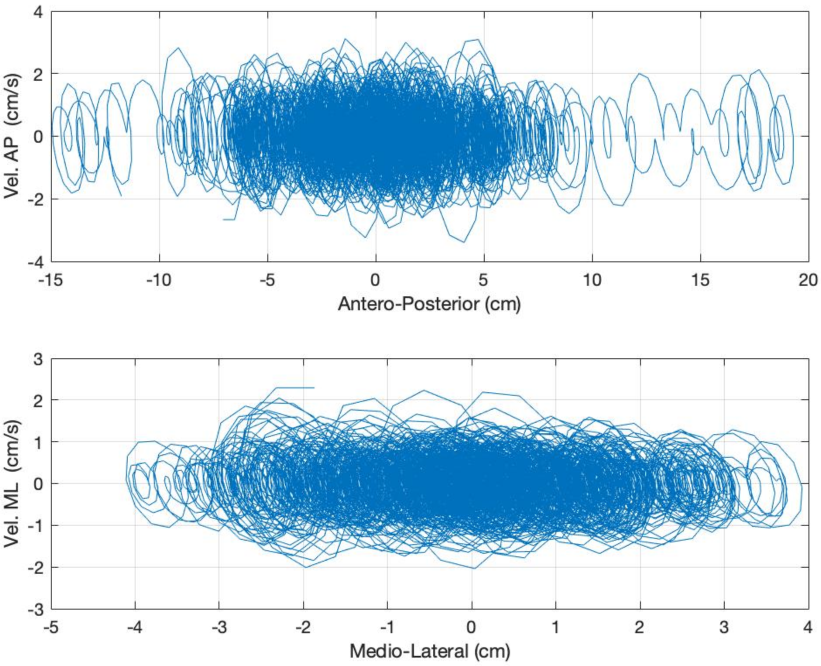

Figure 3.2: *Phase graph*

Discussion

This study is, to our knowledge, the first to look at FF and NF differences regarding overall lower-limbs kinematics, CoP characteristics, and inclusion criteria namely the NDT and RSCP evaluation. Previous works investigated kinematics and postural stability variations using different inclusion criteria and condition assessment, bilateral FF condition 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 greater dorsiflexion (*p=.047*), abduction (*p=.013*), and external rotation (*p=.001*) ROM compared to the control group. Those results can be translated into a drop of the navicular bone and the entire medial longitudinal arch collapse, i.e., alterations that are present in FF subjects. Those are also in concordance with the results of the clinical tests used to assess FF condition, namely the NDT and RCSP. Several authors analyzed kinematic outcomes in FF subjects regarding several posture assessment conditions. However, those investigated mainly the correlations between joint motion and differences between groups. Others analyzed the induced hyperpronation effect using few wedges. *Duval et al.* (2010) found differences between subjects, yet not all those were statistically significant. 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 have a statistically significant relationship 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*). Those differences can be since the authors analyzed functional alterations created by the wedges for a short time instead of a structural alteration present constantly in bilateral flatfoot subjects. However, more search needs to be developed in this area because of sample differences, used setup, and low-intermediate studies quality.

Also, *Duval et al.* (2010) found that thigh internal rotation produced an anterior pelvis tilt (*p<.001*). 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 condition (*p<.001*). No paper relating differences between groups using the combination of NDT and RCSP to assess FF condition was found. The divergence between results can be due to the chosen inclusion and exclusion criteria, namely the NDT-RCSP combination. Both tests are considered clinical tests, used to assess foot complex mobility (Queen et al., 2007; Zuil-Escobar et al., 2019). They were considered user-friendly but presented a few limitations. Instead, several authors used Footprint parameters, namely using few indexes to quantify and characterize foot posture FF, NF, and cavus foot (Zuil-Escobar et al., 2018). However, NDT and Footprint parameters present good association and reliability based on the few published papers (Queen et al., 2007; Zuil-Escobar et al., 2018, 2019). Nevertheless, those contradictions made unclear the emergence of a posture pattern often described in FF subjects. Although, regarding methodological variations, further studies need to encompass methodological variables handling to focus only on foot alteration.

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 AI 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 either 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 search, we did not find more published papers that related differences in CoP characteristics among FF subjects. In the literature, none of the selected papers investigated the EC condition assessment nor the postural system modulation. It is difficult to analyze postural stability in FF subjects without controlling or assessing the visual and oculomotor systems, which can negatively influence data results (Peterka, 2018). 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. Along with visual input assessment, one parameter that differs from previous searches is the BoS area used to assess impairments in different foot posture conditions. 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 (Sung, 2016, 2018; Sung et al., 2017) if Antero, Medio-Lateral CoP excursion, and speed increase in FF subjects with EC and EO (Kim et al., 2015). BoS variations lead to stability adaptation. In a bipedal stance, the mediolateral Center of Mass (CoM) position is usually positioned above BoS area while it is reduced in unilateral stance, and accompanied with postural corrections, using ankle, knee, or hip strategy, which increases postural instability and body sway (Forbes et al., 2018; Rogers & Mille, 2018). FF participants might develop a risk for kinetic instability when proprioception is limited since imprecise body sway estimation can be due to reduced accuracy in the sensory integration process, in unilateral stance (Forbes et al., 2018; Rogers & Mille, 2018). In our study, we used a weight-bearing bipedal stance position. In that condition, to maintain stability and a horizontal view, subjects require information from all postural receptors. As the position provides a greater 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 impair pressure feedback resulting in receptors compensation for maintaining postural stability (Mackinnon, 2018; Sung, 2018). 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 AI 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 final results and comparation.

Conclusion

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

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER IV

STUDY III · POSTURAL NON-LINEAR ANALYSIS IN FLATFOOT SUBJECTS

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Abstract

Background: Foot postural alignment has been associated with lower-limbs abnormal motion and altered postural stability. The only methodologies that ensure the use of the times series regarding Centre of Pressure outcomes are the Nonlinear measure. Those can assess the motor behavior over time through the CoP excursion analysis, and therefore quantify the regularity, adaptability, and complexity of the movement. Therefore, the purpose of this study was to investigate the postural stability differences between subjects with and without flatfoot condition, regarding a non-linear analysis. ***Methods***: The sample consisted of 31 participants (13 women / 18 men – 23.26 yo ± 4.43 SD) comprising a total of 62 feet, where 15 integrated into the experimental group with bilateral flatfoot condition and the remaining 16 in the control group with the bilateral NF condition. Subjects were screened, before posture analysis, using the *NDT* and *RCSP* test, to characterize each group. All participants were subjected to a bipedal weight-bearing stance posture stability analysis with a force platform, both in eyes-open and closed condition. Therefore, the *ApEn*, *CD*, *FD*, and *LyE* were calculated using the *Matlab-R2020b* (MathWorks Inc., USA) software. ***Results***: Considering Nonlinear methods, the only statistically significant result was the LyE value upon the Antero-posterior component regarding groups in the eyes closed condition (diff=3.09°, *p=.016*). ***Conclusion***: Flatfoot subjects present a significant difference compared to NF participants, in bipedal weight-bearing stance, in the EC condition regarding the *LyE*. This relates to increase variability and decrease stability regarding the Antero-Posterior component. However, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

Keywords: Foot Posture; postural stability; variability; center of pressure.

Introduction

Foot posture is usually classified into three categories, NF, cavus (CF), and FF with respectively normal, high, and low Medial Longitudinal Arch (MLA) height. This last one is often characterized by calcaneus plantarflexion and eversion relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008; Becerro-de-Bengoa-Vallejo, et al., 2018). Along with FF condition, tibial internal rotation, increase forefoot abduction, or ankle inversion are considered risk factors for lower limb injuries (Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). FF subjects present greater foot and ankle mobility with subjacent higher risks of developing adjacent mechanical overloading injuries (Buldt et al., 2015) like for example medial tibial stress syndrome, sacroiliac joint dysfunction, or even patella-femoral joint pain (Buldt et al., 2015; Hösl et al., 2014; Hunt & Smith, 2004; Levinger et al., 2010). Also, FF condition leads to anterior pelvic tilt, internal hip and tibia rotation, knee valgus, and extended lower back, regarding static analysis (Caravaggi et al., 2018; Douglas Gross et al., 2011; Levinger et al., 2010, 2016; Powell et al., 2011). Finally, regarding FF subjects, the MLA varies and can modify plantar pressure along the foot which can affect shock absorption, muscular activity, and gait pattern (Angin et al., 2018; Zuil-Escobar et al., 2019). Alongside those previously mentioned impairments, postural stability can therefore be compromised in FF subjects (Sung, 2018).

Postural stability is represented in most daily routines tasks and is considered a fundamental motor skill, and is associated with a correct gait pattern (Ludwig et al., 2020). This concept is described regarding the somatosensory input that is processed in the Central Nervous System (CNS) to create neuromotor necessary output commands to maintain and regulate the stability and motor control (Colebatch et al., 2016; Feldman, 2016; Kędziorek & Błażkiewicz, 2020). Because stability requires cognitive resources to process somatosensory input to therefore modulate motor output, any altered process can impair this last inducing reduced stability sustaining (Feldman, 2016; Shokouhyan et al., 2020). In healthy individuals, postural stability is the result of a complex mechanism and integration of multisensory inputs consequential from several systems (Kędziorek & Błażkiewicz, 2020; Lacour et al., 2018; Rogers & Mille, 2018). Those are represented in three references, namely the allocentric, geocentric, and egocentric (Lacour et al., 2018). The first is related to the visual system (vision and oculomotor input), the second to the vestibular system and finally the third to the somatosensory system (proprioceptive, plantar pressure, and dental-occlusal input) (Kędziorek & Błażkiewicz, 2020; Lacour et al., 2018; Mackinnon, 2018; Peterka, 2018; Young et al., 2018). 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) by requiring movement strategies coordination during both self-initiated and externally induced perturbations of stability (Kędziorek & Błażkiewicz, 2020; Ludwig et al., 2020; Nagai et al., 2011). Alterations in BoS, namely a greater area will increase sensorimotor adaptation leading to an increase in postural stability, therefore, preventing fall risks (Forbes et al., 2018; Rogers & Mille, 2018). Those can be translated into increase body sway and thereby intrinsic stiffness (Forbes et al., 2018; Rogers & Mille, 2018; Shokouhyan et al., 2020), activated systematically by the CNS (Ludwig et al., 2020). Furthermore, the balance between agonists and antagonists is necessary to support ligaments in providing joint stability and to equalize pressure distribution at the articular surface. Joint stability results from both static and dynamic mechanisms. Static stability comes from passive structures such as bony congruity, ligaments, and joint capsules. Dynamic stability is created by muscular contraction and is referred to as functional joint stabilization (Nagai et al., 2011; Sousa, 2018). Patients with musculoskeletal injury exhibit different postural patterns. Therefore, according to previous scientific search, the selected strategy to maintain efficient postural stability will be chosen according to external postural displacement characteristics, goals, and previous experiences (Kędziorek & Błażkiewicz, 2020). Regarding visual system input, the visual and oculomotor systems contribute to balance, through their unique sensorial capacity, estimating distances, and providing information about body motion and sway (Dakin & Rosenberg, 2018; Kars et al., 2009; Lacour et al., 2018; Peterka, 2018; Sung et al., 2017). Previous search encompassed the analysis of both visual and visual oculomotor systems. Several authors found an increase postural stability in tasks assessment with the eyes open compared to eyes closed (Kim et al., 2015; Lacour et al., 2018; Sung, 2018; Tahmasebi et al., 2015), regarding vergence impairments (Matheron et al., 2016) or vision of fixed target (Lacour et al., 2018).

In most published scientific papers, the assessment of the Center of Pressure (CoP) is realized according to a linear methodology, usually applied and employed by authors to analyze and quantify postural control and its variability either in bilateral and unilateral stance weight-bearing position (Kędziorek & Błażkiewicz, 2020; Kim et al., 2015; Sung, 2018). As referred by *Kedziorek et al.* (2020), even with technological advancement, the analysis of the CoP and its variability is still the most representative measurement of the whole-body activity and integration of all various neuro-musculoskeletal components (Kędziorek & Błażkiewicz, 2020). However, authors preferentially used linear outcomes in their experimental studies, i.e. they investigate and analyze two-dimensional times series, namely the anteroposterior (AP) and mediolateral (ML) excursions, area, and AP and ML velocity (Hertel et al., 2002; Kędziorek & Błażkiewicz, 2020; Kim et al., 2015). However, several authors, along with this analysis method, investigated some other outcomes, namely the *Kinetic Stability Index* which is used to assess the stabilization over a postural perturbation regarding the Ground Reaction Forces threshold (Sung, 2016, 2018). These outcomes are the output representation of the somatosensory system affecting postural stability (Kędziorek & Błażkiewicz, 2020). However, these cannot reflect with accuracy the motor behavior of the human being. As motor behavior showed high variability in human performance, the complexity of the movement system cannot, therefore, be analyzed with linear methods (Kędziorek & Błażkiewicz, 2020). The postural stability varies over time and therefore postural perturbation can influence motor behavior variability (Harbourne & Stergiou, 2009). As referred by *Stergiou* (2018), for variability understanding, the time series analysis seems to be essential, i.e, it reveals the behavior of a global system regarding movement repetitions. Also, *Harbourne et al.* (2009) refer that repetitive stress injury can be due to a reduced variability and this decrease can also lead to a considered abnormal sensory cortex mapping, leading to functionality disturbs (Harbourne & Stergiou, 2009). Therefore, according to the variability concept and linear methodologies, the assessment of the movement variability and the motor behavior cannot be assessed, showing a limitation of the static posturography in a clinical environment (Kędziorek & Błażkiewicz, 2020; Stergiou, 2018).

Consequently, non-linear methods ensure the CoP times series analysis. Those assess the motor behaviour over time through the CoP excursion analysis and quantify the regularity, adaptability, and complexity of the movement (Harbourne & Stergiou, 2009; Kędziorek & Błażkiewicz, 2020). Several nonlinear methods can assess those characteristics, like the LyE, ApEn, CD, and FD (Harbourne & Stergiou, 2009; Kędziorek & Błażkiewicz, 2020; Stergiou, 2018). However, no study analyzes the postural stability differences in flatfoot subjects regarding nonlinear methods. Therefore, regarding the lack of evidence, the study's purpose was to analyze the postural stability differences between flat and NF subjects considering the analysis of the LyE, ApEn, CD, and the FD.

Methods

Design

This observational descriptive study was carried out at *RoboCorp Laboratory – Physiotherapy*, 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*.

Participants

The sample size was calculated with the aid of the *G*power 3.1.9 software* (Franz Faul, Kiel, Germany). This calculation was based on the previously published paper of *Kim et al.* (2015). A required sample size of 18 was determined by achieving an estimated, alpha level of 0.05, and a power of 0.95. Consequently, forty-three individuals were recruited. Volunteers subjects were recruited for this scientific study. Before any assessment, all subjects were informed about the study purpose and procedures and then completed a consent form. However, thirty-one participants met eligibility the inclusion criteria (13 women / 18 men – 23.26 yo ± 4.43 SD) (***Table 4.1***). The inclusion in the study was limited to subjects who presented bilateral FF or bilateral NF. Inclusion criteria in the FF group encompassed subjects that presented a >9mm NDT and >4° RCSP scores. However, the inclusion criteria in the NF group involved participants with a <9mm NDT and <4° RCSP scores (Kim et al., 2015). All participants were submitted to the NDT and RCSP to identify whether they had a FF or a NF as this test is clinically used by practitioners worldwide. This procedure was realized by a single physiotherapist with more than 6 years of experience in the use of these techniques. Thus, subjects who presented the following conditions were excluded: a) ankle sprain in the last 6 months; b) physiotherapy treatment program or history of injury including bilateral ankle injury; c) bone fracture associated with an ankle sprain, such as avulsion fracture or osteochondral ankle injury; d) injury or surgery to the spine, hip, knee, or ankle. Then, the FF group consisted of 15 bilateral FF participants (7 women / 8 men – 24.93 yo ± 5.17 SD) comprising a total of 30 feet while the NF group consisted of 16 bilateral NF subjects (6 women / 10 men – 21.69 yo ± 2.98 SD) comprising a total of 32 feet.

Table 4.1*: Sample characteristics*

Group	**n**	**NDT** *(mm)*	**RCSP** *(º)*	**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
NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position; NF = neutral foot; FF = flatfoot

Assessment

Both NF and FF conditions were evaluated regarding the same assessment procedure bilaterally in a weight-bearing barefoot stance position. The navicular drop (ND) was evaluated using the NDT, where three measurements mean values define the ND. The practitioner placed a rigid plastic-made ruler perpendicularly to the ground and registers 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 ND severity (Sung, 2018). Then, the Rearfoot-to-leg angle was assessed using the RCSP test where three measurements mean values define 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). This angle was measured using a rigid plastic goniometer. Then, a bilateral weight-bearing stance position was measured using a 200Hz frequency coupling with a force platform *Bertec® FP4060* (Bertec Corporation, USA) with a 1000Hz frequency. Subjects stayed upon a force platform for 60 sec with eyes-open (EO) and repeated it with eyes-closed (EC). The assessment was realized with subjects in a relaxed position, and they were asked to maintain the look at a reference point for 5 sec to stabilize the position before recording the data. If any participants failed to maintain their position, the trial was repeated.

Data Processing and Analysis

The evaluated outcomes were the CoP excursion, namely through the calculation of the ApEn, CD, FD, and LyE. Therefore, the *Matlab-R2020b* (MathWorks Inc., USA) software was utilized for the CoP data processing. Initially, all CoP data were initially filtered with a *7th-order Butterworth 50-Hz low-pass* filter to reduce some high-frequency parasitic signals and then down sampled to a 200Hz frequency. Finally, a routine was created to identify all the Nonlinear outcomes and extracted them to further analysis. More specifically, all outcomes were calculated according to the following specificities:

The ApEn algorithm takes as input the time series data of length N with embedding dimension m (pattern length) and a lag. The time series of length N is divided into short vectors of length (Stergiou, 2018). The value was computed based on the following equation:

$$\Phi_m = (N - m + 1)^{-1} \sum_{i=1}^{N-m+1} \log (N_i)$$

The CD was calculated according to the following equation (Stergiou, 2018), where R corresponds to the sum, over all points on the attractor, of the count of the points within radius r, normalized by the number of points M in the attractor:

$$C(R) = \frac{2}{N(N-1)} \sum_{i=1}^{N} N_i(R)$$

The FD is a measure of the two-dimensional COP trajectory complexity and calculated with the following equation, where N is the number of data points (N=3000); d=(2a . 2b)1/2 where a and b are the major and the minor axes of the 95% confidence ellipse, respectively (Casabona et al., 2016).

$$FD = \frac{\log (\mathrm{N})}{\log (\mathrm{N}.\frac{\mathrm{d}}{\mathrm{sway}} path)}$$

The LyE algorithm can be represented by a single equation originally developed by *Wolf et al.* (1985), where L corresponds to the distance between points, t corresponds to the time lag and M is the total number of replacement steps (Stergiou, 2018).

$$\lambda_1 = \frac{1}{t_M - t_0} \sum_{k=1}^{M} \log_2 \frac{L'(t_k)}{L(t_{k-1})}$$

Statistical Analysis

The data were statistically processed with the *IBM SPSS Statistics 27.0* software (IBM Corporation, New York, USA). The descriptive statistics, mean and standard deviation, were calculated for all variables regarding both groups. Before the inferential analysis, the normality of the distribution was explored. We identified a normal sample distribution based on the *Shapiro-Wilk* test regarding CoP outcomes ($p>.05$, t>0.933). The differences between the groups were assessed according to the *T-test for independent samples* and the differences between condition assessments were assessed according to the *T-test for paired samples*. The level of significance was set at 5% ($p<.05$).

Results

The sample characteristics are specified in ***Table 4.1*** alongside the mean values of the different tests regarding both groups. In the procedure, 30 flat feet and 32 neutral feet were identified through inclusion criteria. Both subjects were identified and allocated in the different groups using the NDT and RCSP score assessment. Considering the result of the Nonlinear outcomes between both in NF and FF group in EO condition, no statistically significant results were found concerning the ApEn, CD, FD, or the LyE ($p>.05$). The same results are present in the EC condition except for the AP component of the LyE which presents a statistically significant result (diff=3.09°, $p=.016$). Finally, the results between the EO and EC did not present any statistically significant value ($p>.05$). All the results those results are presented in ***Table 4.2*** and ***Figure 4.1***.

Table 4.2: *Center of Pressure characteristics between groups*

		Eyes Open			**Eyes Closed**			**EO vs EC**
		NF	**FF**	*p-value*	**NF**	**FF**	*p-value*	*p-value*
	Antero-Posterior	1.03 ± *0.23*	1.15 ± *0.22*	*.143*	1.04 ± *0.27*	1.07 ± *0.32*	*.616*	*.694*

Aproximate Entropy *(score)*	*Medio-Lateral*	1.22 ± *0.23*	1.19 ± *0.35*	*.795*	1.21 ± *0.37*	1.19 ± *0.34*	*.887*	*.919*
Correlation Dimension *(score)*	*Antero-Posterior*	2.54 ± *0.70*	2.70 ± *0.27*	*.918*	2.51 ± *0.69*	2.76 ± *0.32*	*.616*	*.254*
	Medio-Lateral	2.05 ± *0.88*	1.77 ± *0.86*	*.525*	1.90 ± *0.82*	2.08 ± *0.60*	*.650*	*.259*
Fractal Dimension *(score)*	*Alfa 1*	1.44 ± *0.14*	1.39 ± *0.11*	*.302*	*1.37* ± *0.99*	1.36 ± *0.14*	*.836*	*.054*
	Alfa 2	1.23 ± *0.12*	1.20 ± *0.17*	*.581*	*1.18* ± *0.15*	1.26 ± *0.22*	*.313*	*.757*
Lyapunov Exponent *(score)*	*Antero-Posterior*	-0.23 ± *2.79*	-1.13 ± *6.73*	*.377*	4.19 ± *5.74*	-1.10 ± *4.84*	*.016*	*.198*
	Medio-Lateral	1.51 ± *1.97*	1.34 ± 2.06	*.814*	19.84 ± *12.48*	17.75 ± *11.48*	*.141*	*.392*

Mean + Standard Deviation
NF = neutral foot; FF = flatfoot; EO = eyes open; EC = eyes closed

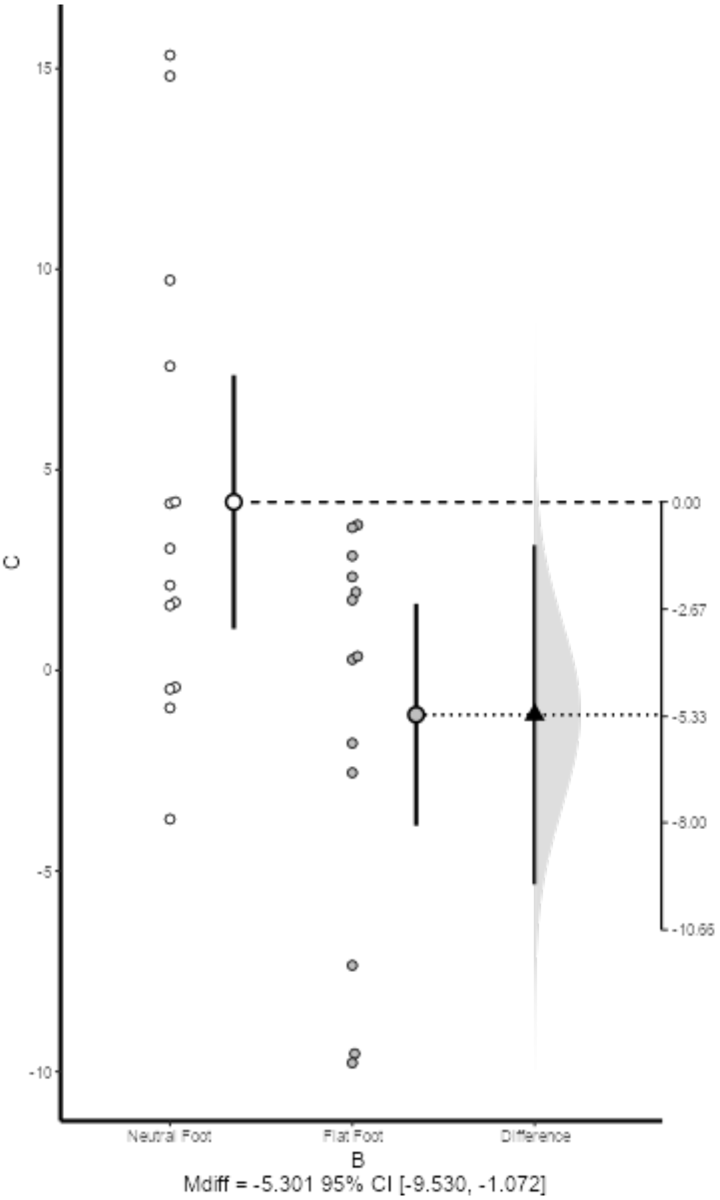

Figure 4.1: *Lyapunov Exponent descriptive analysis for the eyes-closed condition (Project, 2021)*

Discussion

This study is, to our knowledge, the first to look at FF and NF differences both in EO and EC conditions relative to Nonlinear analysis of CoP excursion and inclusion criteria. Previous works investigated kinematics and postural stability variations using different inclusion criteria and condition assessment, bilateral FF condition or induced bilateral excessive ankle eversion. Thus, a systematic review published by *Kedziorek et al.* (2020) related papers that investigated several Nonlinear measures mostly in subjects without foot characterization. The authors investigated several subjects' characteristics without different force platforms, for example, subjects considered as children, young and older adults, and athletes, and finally with disabilities. Those participants present for example, cerebral palsy, down syndrome, gymnast, multiple sclerosis, or even neck pain. Also, they investigated Nonlinear measures regarding EO, EC, and dual-task conditions.

In this observational study, CoP characteristics were investigated and analyzed through a Nonlinear methodology. We did not find any statistically significant results between groups in the EO and EC condition ($p>.05$) except for the differences between groups in the EC condition concerning the AP component of the LyE (diff=3.09°, $p=.016$). In this study, we investigated the differences between groups and assessment conditions through the FD analysis. *Qiu et al.* (2015) published a paper where they investigated the postural stability differences in young and older adults. They related a statistically significant increase of the FD value regarding the young group ($p<.001$) (Qiu & Xiong, 2015). Although, *Casabona et al.* (2016) did not find any statistically significant results between professional ballet dances and a control group ($p>.05$) (Casabona et al., 2016). The FD is used to evaluate the CoP complexity through its shape analysis and complexity of the physiological signals. more specifically, the capability of the sensorimotor system to organize the integration of the diverse afferent input and efferent response is characterized by the FD. So, a higher value indicates a greater ability to maintain postural stability (Harbourne & Stergiou, 2009; Stergiou, 2018; Treger et al., 2020). For both Alfa 1 and 2 of the FD outcomes, the NF present higher values compared to the FF group in both EO and EC conditions. However, nor present significant results ($p>.05$). Finally, we investigated also the ApEn in which we did not fin either statistically significant differences between groups and conditions. This method quantifies the postural stability by measuring the irregularity, and randomness of the CoP during upright standing. Therefore, to analyze ApEn results, it is considered that a small value will indicate a higher probability of regularly repeating sequences, a zero value will correspond to a perfectly repeatable motion and finally, a value of 2 corresponds to a random time series (Cavanaugh et al., 2007; Harbourne & Stergiou, 2009; Richman & Moorman, 2000; Stergiou, 2018). We found in our observational study higher values for the AP component either in the NF and FF group which characterize a tendency to present a reduced postural control and random motion present in FF subjects. However, no statistically significant differences were found ($p>.05$). Relatively to the CD analysis, likewise the FD and ApEn, we did not find any statistically significant differences between groups nor conditions. This novel method analyzes the degrees of freedom during upright posture through the CoP dimensionality. It investigated the dimensionality of a dynamical system and how it organizes itself within state space. A small CD value characterizes a motion with a small number of degrees of freedom (Stergiou, 2018). In our study, we did not find any statistically significant differences between conditions or groups ($p>.05$). However, the results of each group seem to be quite similar without any significant difference between them, which makes us think that in both groups, the maintenance of postural stability comes from the combination of the entire kinetic and kinematic chain, and not only through the foot or ankle. In the AP component, the FF group seems to present a greater value corresponding to a tendency of instability, i.e., a higher value characterizes completely random data (Stergiou, 2018). Finally, regarding the LyE both in the AP and ML component, in our search, we found some controversial findings for the EC and EO analysis. *Liu et al.* (2015) published a paper where they investigated the postural stability differences in young and older adults. They related a statistically significant increase of the coefficient value regarding the older adults group ($p<.05$). Also, the authors that the LyE showed a higher accuracy to identify the groups in the EC condition. Although, *Ghofrani et al.* (2017) did not find any statistically significant results investigating the EO and EC condition in normal subjects through the LyE analysis ($p>.05$) which is a similar result compared to ours ($p=.198$). As described by several authors, the LyE is considered a nonlinear parameter used to characterize a signal chaotic behavior measuring the information rate loss from time series. This exponent is used to quantify and measure the capability and resistance of subjects to several perturbations. In this study, the LyE is used to quantify the ability of a subject to maintain higher postural stability even with perturbation. So, a higher exponent value corresponds to a rapid reply to maintain stability (Harbourne & Stergiou, 2009; Liu et al., 2003; Stergiou, 2018; Treger et al., 2020). In both AP and ML components, in EO and EC conditions, the NF group presented a higher exponent value compared to the FF group, corresponding to a higher ability to maintain stability. However, no statistically significant differences were found ($p>.05$).

Since postural stability is the representation of the somatosensory, visual, and vestibular inputs integration to further produce efferent motor output, the assessment of postural assessment needs to consider the evaluation of every input. All this information is organized in the neural systems to provide appropriate motor actions via sensory integration and sensory-to-motor transformations (Miko et al., 2021; Peterka, 2018). However, as mentioned previously, every receptor presents specificities and actions where integration causes the subjects' postural stability to be maintained. This integration works from a global perspective, with one recipient prevailing or compensating for the deficit of another. Somehow, the somatosensory and visual systems are prioritized by the postural control system to maintain balance (Appiah-Kubi & Wright, 2019; Miko et al., 2021; Reche-Sainz et al., 2021). Although, if some sensory information decreases relative to a specific receptor, the postural system will rely upon the others like the vestibular system, which is less weighted than the others (Appiah-Kubi & Wright, 2019). In our study, we only analyze the pedal receptor along with the visual system where we only find a statistically significant difference regarding the AP component of the LyE. However, we did not assess the activity of the proprioceptive or either the vestibular systems. Since these methods analyze the chaotic behavior, the found differences can be due to a lack of the previously mentioned integration of the somatosensory inputs and efferent motor control. Regarding the integration of all somatosensory inputs, to maintain an upright stance, the body requires multiple neural networks, like corticospinal and vestibulospinal tracts, and CNS structures, like the cerebrum, cerebellum, basal ganglia, brainstem to realize the sensory feedback information integration

(Miyashita et al., 2020; Reilly et al., 2020). Also, as referred by *Peterka et al.* (2018) the postural stability sits on a closed-loop feedback system to maintain a stable stance through time series. The organization, through this system, requires sensory afferent inputs to coordinate the integration and processed adequate responses to perturbations. Therefore, if subjects present any impairments in those processes, they will show an increased postural sway (Lions et al., 2016; Miyashita et al., 2020). Finally, the neural maps presented between the sensory and motor integration as complex within higher movement variability (Harbourne & Stergiou, 2009).

Despite this, our study shares various Nonlinear methods to analyze postural stability, several limitations can be ensuring and compromising the results. In our study, we used a weight-bearing bipedal stance position. As this position provides a greater 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 impair pressure feedback resulting in receptors compensation for maintaining postural stability (Mackinnon, 2018; Sung, 2018).

Conclusion

Considering the overall CoP characteristics outcomes and used Nonlinear methods, we can state that FF subjects did present differences in AP excursion variability regarding the LyE analysis to NF participants, in bipedal weight-bearing stance, both in EC and EO condition. However, considering the lack of consensus regarding utilized outcomes and assessment conditions, further studies need to be performed to create more robust evidence as well as, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

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CHAPTER V

STUDY IV · GAIT PATTERN KINEMATICS ANALYSIS IN FLATFOOT SUBJECTS

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Abstract

Background: Foot postural alignment has been associated with lower-limbs abnormal motion and altered gait pattern. Consequently, this study aims to investigate kinematic differences in FF subjects' gait pattern regarding all lower limb segments. ***Methods***: The sample consisted of 31 participants comprising a total of 62 feet, where 15 subjects were integrated into the experimental group with bilateral flatfoot condition and the remaining 16 in the control group with the bilateral NF condition. Subjects were screened before posture analysis using the NDT and RCSP test to characterize each group. All participants were subjected to a gait pattern analysis using a MOCAP system. ***Results***: Considering kinematics differences between groups, statistically significant differences were found for the ankle joint ankle dorsiflexion (*p=.029*), abduction (*p=.033*), and internal and external rotation (*p<.001*). Also, differences were found for knee flexion, extension, abduction, and external rotation peak values presented significant differences between groups (*p<.001*). Finally, hip flexion (*p=.002*), extension (*p<.001*), external rotation (*p=.012*), pelvis rotation (*p=.017*) were found. Several amplitude differences were found concerning the ankle abduction/adduction (*p=.003*), knee flexion/extension (p=.000) and abduction/adduction (*p<.001*), the hip flexion/extension (*p=.002*), and rotation (*p=.007*) and finally the pelvis rotation (*p=.009*). ***Conclusion***: Subjects with flatfoot condition showed several kinematics changes when compared to NF ones during the gait task. The differences were found regarding all lower limb joints and pelvis, as well as a range of motion variations. Thus, a lack of methodological rigor was found in the literature, i.e., further studies need to encompass methodological variables handling to focus only on foot alteration and assessment.

Keywords: Foot Posture; Walking; Biomechanics, kinematics.

Introduction

Foot posture is usually classified into three categories, NF, cavus, and FF with respectively normal, high, and low medial longitudinal arch height. A FF is often characterized by calcaneus plantarflexion and eversion relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008; López-López, Becerro-de-Bengoa-Vallejo, et al., 2018). Alongside, tibial internal rotation, increased forefoot abduction, or ankle inversion are considered risk factors for lower limb injuries (Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). These were related to forces asymmetrical distribution across the subtalar joint and knee (Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). FF subjects present greater foot and ankle mobility with subjacent higher risks of developing adjacent mechanical overloading injuries (Buldt et al., 2013, 2015). Also, this condition presented an anterior pelvic tilt, internal hip and tibia rotation, knee valgus, and extended lower back, regarding static analysis (Caravaggi et al., 2018; Douglas Gross et al., 2011; Levinger et al., 2010, 2016; Powell et al., 2011). Through altered lower limb motion patterns, foot posture can induce injuries (Buldt et al., 2013, 2015) and have been associated with abnormal foot motion during gait (Levinger, et al., 2018; Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). Finally, regarding FF subjects, the medial longitudinal arch varies and can modify plantar pressure along the foot, affecting shock absorption, muscular activity, and gait pattern (Angin et al., 2018; Zuil-Escobar et al., 2019). Besides, foot sole afferent input affects postural awareness and FF triggered by neurological or muscular restrictions, ligament or joint laxity, excessive motion, and muscle activity (Hunt & Smith, 2004)

For every daily living activity, both static and dynamic postural control are required (Nagai et al., 2011). Though, foot posture can induce altered plantar pressure patterns and, therefore the motion of adjacent joints. The neuromuscular function, and so the biomechanics of the lower limbs can be affected by an altered afferent sensory input. The Central Nervous system used the muscle coactivation system through the neuromotor response, a motor control mechanism to modulate joint stiffness, postural stability, and gait pattern (Angin et al., 2018). Muscle joint coactivation varies during the gait cycle, reaching higher heel-strike and unilateral weight-bearing values during the balance transition phase and lower values in mid-stance (Varrecchia et al., 2018). Considering the kinetic analysis, several authors identified differences among FF subjects compared to neutral ones. They seemingly investigated the ground reaction forces through the aid of a force platform and analyzed the collected variables like Center of Pressure excursion and velocity maximum values using linear methods. For instance, *Buldt et al.* (2018, 2018a) found significant differences in FF subjects, i.e., smaller lateral medial range during the terminal gait stance, faster *Center of Pressure* excursion velocity in terminal stance, and specific plantar pressure characteristics (Buldt, et al., 2018; 2018a). Some authors investigated FF characteristics in pediatrics or neurological impairments. For instance, *Twomey et al.* (2012) and *Kerr et al.* (2019) examined the kinematics differences among asymptomatic pediatric FF subjects. The authors found several differences among FF subjects considering the lower limb biomechanics (Kerr et al., 2019; Twomey & McIntosh, 2012). Also, *Galli et al.* (2014) showed several gait pattern characteristics differences between FF and NF among Down Syndrome children (Galli et al., 2014). Other authors analyzed the kinematic differences in adult subjects. However, they only focus their investigation on the foot, ankle joint, or the tibia bone (Buldt et al., 2013, 2015; Saraswat et al., 2014; Shin et al., 2019; Yazdani et al., 2018). *Buldt et al.* (2013), in a systematic review, found that FF subjects showed alterations in plantar pressure characteristics, specifically higher pressure, force, and contact area values relative to the medial arch, central forefoot, and hallux, while the same parameters were minor in the lateral and medial forefoot (Buldt et al., 2013). Also, the authors investigated the kinematics variable of the foot complex. They stated that FF subjects presented significantly higher inversion and adduction motion of the rearfoot during the last 20% of the stance phase. They also found a positive correlation regarding condition subjects and the rearfoot peak eversion, in the first half of the stance phase (Buldt et al., 2013). However, no study analyzes the kinematic gait pattern differences in FF subjects regarding the lower limbs. Therefore, the study's purpose was to analyze the kinematic gait pattern differences in FF subjects considering all segments of the lower limb regarding the lack of evidence.

Methods

Participants

This descriptive observational study was conducted at *RoboCorp Laboratory*, at the *Polytechnic Institute of Coimbra* after approval of the *Ethics Committee of Polytechnic Institute of Coimbra* approval based on the revised version of the 2013 *Declaration of Helsinki* (Holt, 2014; Vandenbroucke et al., 2014), where it was recorded with the number *13_CEPC2/2019*. The sample size was calculated using the *G*power 3.1.9* software (G*power 3.1.9, Kiel, Germany) based on previously recorded data. A required sample size of 28 was determined by achieving an estimated, alpha level of 0.05, and a power of 0.80. Consequently, forty-three volunteers were recruited for this study. Therefore, thirty-one subjects aged between 18 and 35 years old met the eligibility criteria. All subjects read and signed the informed consent, agreeing to participate in the study. The inclusion in the study was limited to subjects who presented bilateral FF or NF participants. All participants were submitted to the NDT and the RCSP test to identify whether they had a FF or a NF. Fifteen subjects were included in the FF group where they presented a >9mm NDT score and >4° RCSP scores. Sixteen subjects were incorporated in the NF group, with a 5-9mm NDT and <4° RCSP scores. Exclusion criteria were based on medical history and the subjects who presented the following conditions were excluded: a) any disturbance that might affect gait pattern like orthopedic, neurological or visual impairment or other, including current injury, pain, active ulceration, or previous amputation; b) physiotherapy treatment program; c) bone fracture; d) injury or surgery to the spine, hip, knee, or ankle; e) aged less than 18 and higher than 40 years old; f) Medication intake that can affect gait and muscle activity.

Assessment

Foot posture was diagnosed based on clinical procedures including the NDT and RSCP test as those are clinically used by practitioners worldwide (Kim et al., 2015; Sung, 2018; Tsai et al., 2006). 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. Before data collection, subjects were asked to maintain a weight-bearing barefoot stance position to perform both tests. Firstly, the navicular drop was evaluated using the NDT, where three measurements mean values define the drop severity. A rigid plastic-made ruler was placed by the practitioner perpendicularly to the ground and registers the distance between the ground and the navicular bone (millimetres). Then, the talus was inverted into a neutral position by the practitioner and the procedure was repeated. The assessment positions difference quantifies the navicular drop severity (Sung, 2018). Afterward, the angle between the rearfoot and the leg was assessed by the same practitioner using the RCSP test where three measurements mean values define the angle. This was 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. A rigid goniometer was used to measure this angle (Enraf-Nonius B.V, Rotterdam, The Netherlands) (Tsai et al., 2006).

Three-dimensional computerized gait analysis was performed on all FF and NF groups to assess the movement characteristics such as joint angular kinematics and spatiotemporal gait parameters. Data was captured with a 10-camera *Qualisys® 3D Motion Capture System* (Qualisys AB, Götebor, Sweden). A full-body marker setup based on the *IOR* model (Wilken et al., 2012), comprising fifty-three reflective kinematic markers, was used, on participants' specific anatomical locations, namely on the thorax, head upper, and lower limbs. Tracking markers, i.e. four marker clusters, were placed over the thighs and shanks to improve the segment tracking accuracy. Therefore, kinematic data were collected in a previously calibrated volume, with a calibration error bellow 0.7 mm, recorded at a 200 Hz sampling frequency. Before gait acquisition, subjects were asked to perform a bilateral stance posture assessment regarding processing model creation. Therefore, all subjects were instructed to walk barefoot at a self-selected and comfortable pace across an 8-meter walkway, which allowed them to reproduce their daily gait. To standardize the gait initiation, a starting point was established so that participants perform four gait cycles before reaching the force platforms to stabilize gait velocity. No other restrictions were placed on participants. At least, fifteen passages were collected at a comfortable speed to generate sufficient data to obtain a mean value for each parameter being measured. Ten seconds of rest was set between trials. If any participants failed to produce a daily gait behaviour and was perceived by the researchers, the trial was discarded and a new was performed without warning the subject. Trials in which all the markers were clearly and possible to identify were defined as valid and finally, ten valid passages were selected for further processing.

Data Processing and Analysis

Initially, the recorded data was pre-processed using the *Qualisys Track Manager v2.15* (Qualisys AB, Götebor, Sweden) software. Then the resulting data was exported to *Visual3D* (C-Motion, USA) for further analysis. The marker's trajectories were then filtered with a *6-Hz low-pass Butterworth* filter and gait events (heel strike and toe-off) were automatically identified with the software's routine. A 3D model was created to analyze the relative angles of ankle, knee, and hip joints. Finally, *Visual 3D* (C-Motion, USA) software commands were computed and identically replicated for each subject to identified outcomes measures, namely joint angular kinematics (ankle, knee, hip, and pelvis angle), gait spatiotemporal parameters, and vertical center of mass displacement.

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 in the descriptive analysis of the sample. Before any further statistical procedure, the normality of the distribution was explored. The sample presented a non-normal distribution using the *Kolmogorov-Smirnov* (*p<.001*, t>0.041) regarding all variables. Continuous variables were described using the median and variance based on the non-normal distribution of the variables. The *U-Mann Whitney* test was used to test hypotheses in two independent samples. The level of significance was set at 5% (*p<.05*) for all hypothesis tests.

Results

Sample and groups characteristics

The following data is presented for both groups, the FF and NF groups. In ***Table 5.1*** is presented the distribution of age, height, the weight of all participants alongside NDT and RCSP scores. As expected, regarding both groups separately, both groups presented the mean score of the NDT and RCSP scores in concordance with the cut-off value previously established and selected in the method section. Those can be described with a value higher than 9mm and 4º cut-off value for the FF group and lower than 9mm and 4º in the NF group.

Table 5.1: *Sample characteristics*

Group	**n**	**k**	**NDT** (mm)*	**RCSP** (º)*	**Age** (years)*	**Height** (m)*	**Weight** (kg)*
NF	*16*	32	5.06 ± *2.42*	1.44 ± *1.19*	21.69 ± *2.98*	1.72 ± *0.09*	75.92 ± *17.03*
FF	*15*	30	11.35 ± *1.43*	5.52 ± *2.22*	24.93 ± *5.17*	1.68 ± *0.10*	74.32 ± *12.90*
Total	*31*	62	-		23.26 ± *4.43*	1.70 ± *0.98*	75.14 ± *14.94*

**Mean + Standard Deviation*

NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position; NF = neutral foot; FF = flatfoot; n = sample; k = lower limb number

Kinematics analysis

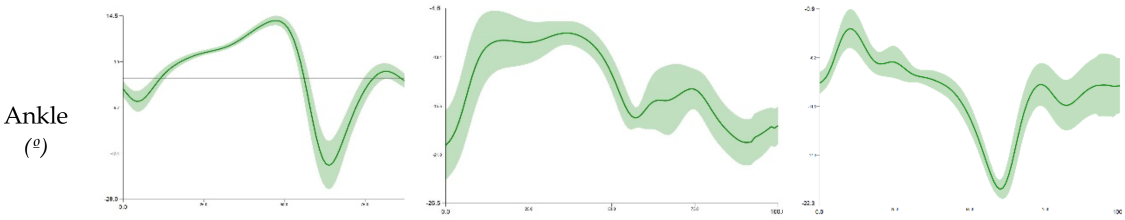
Kinematics data collected, included 16 participants in the NF group (32 lower limbs) and 15 participants in the FF group (30 feet). The ankle, knee, hip, and pelvis angles of each lower limb (right / left) were analyzed and are presented in ***Table 5.2***. For each segment, the movement is described in the sagittal (x), frontal (y), and transverse (z) planes. Significant differences between groups are observed in the ankle, knee, hip, and pelvis during the gait. The FF group is characterized by less ankle peak dorsiflexion (*p=.029*), abduction (*p=.033*), and internal and external rotation (*p<.001*). FF group tends to exhibit less knee and hip peak extension (*p<.001*), and external (*p<.001, p=.012*) rotation, and also knee abduction (*p<.001*). A higher peak value in the FF group was found for the knee (*p<.001*) and hip flexion (*p=.002*), hip internal rotation, and pelvis right rotation (*p=.017*). Additionally, the FF group is characterized also by less range of motion (ROM) concerning ankle abduction/adduction (*p=.003*), knee abduction/adduction (*p<.001*), hip rotation (*p=.007*). Also, the FF group exhibits a higher ROM value concerning knee (*p=.000*) and hip flexion/extension (*p=.002*), and pelvis rotation (*p=.009*). Concerning the center of mass displacement, significant differences among groups are found for the maximum value as well as for the amplitude (*p<.001*).

Table 5.2: *Groups kinematics*

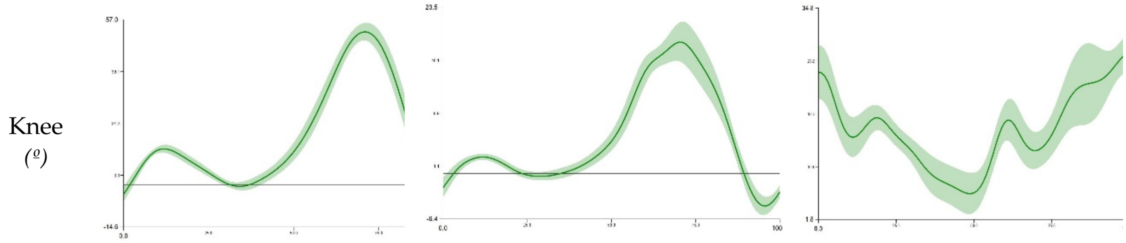
		Peak value			**Amplitude (ROM)**		
		FF	**NF**	**p-value**	**FF**	**NF**	**p-value**
Ankle *(º)*	*Dorsiflexion*	12.49 ± 3.52	13.58 ± 6.94	0.029	27.87 ± 6.28	29.29 ± 8.47	0.163
	Plantarflexion	-15.67 ± 6.61	-16.09 ± 8.36	0.541			
	Abduction	0.38 ± 4.09	1.59 ± 9.95	0.033	16.81 ± 4.06	17.79 ± 10.51	0.003
	Adduction	-16.61 ± 5.20	-16.43 ± 6.43	0.398			
	External rotation	-3.35 ± 5.48	-7.05 ± 8.08	<0.001	15.85 ± 5.00	17.16 ± 7.89	0.105
	Internal	-19.36 ± 5.42	-19.63 ± 23.56	<0.001			
Knee *(º)*	*Flexion*	60.60 ± 4.68	56.87 ± 12.41	<0.001	65.64 ± 5.05	61.28 ± 8.93	0.000
	Extension	-5.04 ± 4.53	-5.16 ± 10.71	<0.001			
	Abduction	18.04 ± 5.71	21.21 ± 9.60	<0.001	18.84 ± 6.57	24.24 ± 11.20	<0.001
	Adduction	-0.81 ± 5.61	-1.92 ± 8.34	0.236			
	External rotation	29.19 ± 7.94	33.71 ± 15.30	<0.001	23.77 ± 8.40	26.83 ± 5.69	0.079
	Internal	5.42 ± 10.37	0.15 ± 32.89	0.342			
Hip *(º)*	*Flexion*	30.67 ± 8.82	27.36 ± 10.90	0.002	40.88 ± 7.81	39.79 ± 7.54	0.002
	Extension	-10.21 ± 8.34	-12.42 ± 10.36	0.006			
	Abduction	18.18 ± 14.48	17.79 ± 13.60	0.552	14.80 ± 5.70	15.91 ± 7.05	0.156
	Adduction	-9.27 ± 5.99	-9.34 ± 6.31	0.883			
	External rotation	7.48 ± 7.21	11.91 ± 12.71	0.012	15.80 ± 5.34	16.64 ± 10.26	0.007
	Internal	-7.79 ± 7.08	-2.61 ± 13.63	<0.001			
Pelvis *(º)*	*Anterior Tilt*	-4.13 ± 12.49	-4.23 ± 10.90	0.905	7.83 ± 6.80	8.25 ± 6.72	0.744
	Posterior Tilt	3.70 ± 10.93	4.02 ± 11.91	0.900			
	Lateral Tilt	5.09 ± 3.63	4.71 ± 2.83	0.489	10.28 ± 4.44	9.81 ± 3.22	0.720
		-5.18 ± 3.14	-5.10 ± 3.15	0.909			
	Rotation	10.66 ± 4.70	8.79 ± 6.33	0.017	20.98 ± 11.53	18.01 ± 7.81	0.009
		-10.67 ± 8.20	-9.22 ± 5.94	0.125			
Center of Mass *(height %)*	*Vertical Maximum*	55.07 ± 1.23	55.67 ± 0.85	<0.001	2.38 ± 0.41	2.62 ± 0.39	<0.001
	Vertical Minimum	52.68 ± 1.40	53.04 ± 0.91	0.243			

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

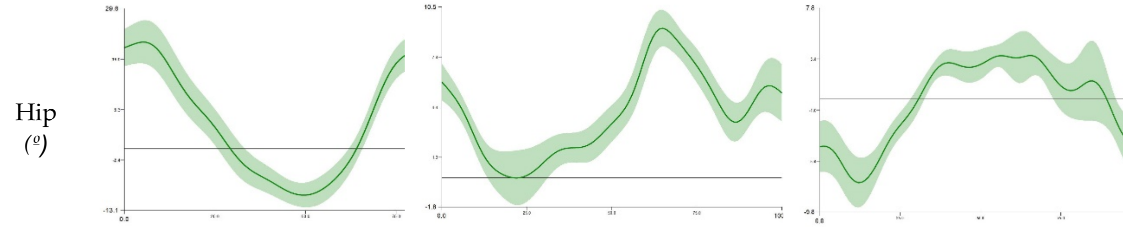
Figures 5.1 and ***5.2*** illustrate the joint angles of the ankle, knee, and hip during the gait (NF and FF subjects respectively).



Dorsiflexion / Plantarflexion   Abduction / Adduction   External / Internal rotation

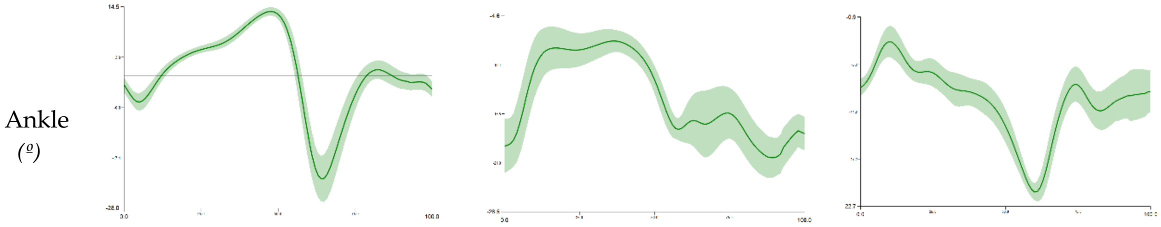


Flexion / Extension   Abduction / Adduction   External / Internal rotation

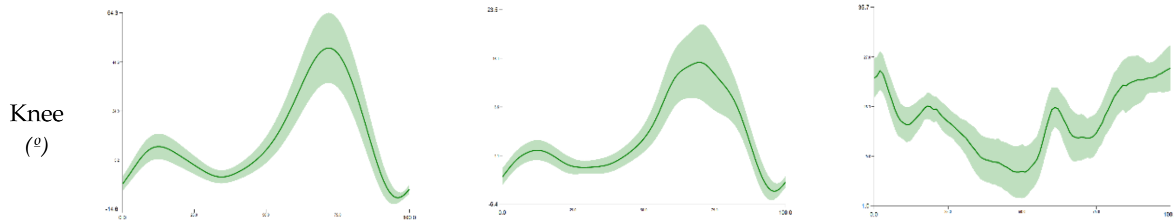


Flexion / Extension   Abduction / Adduction   External / Internal rotation

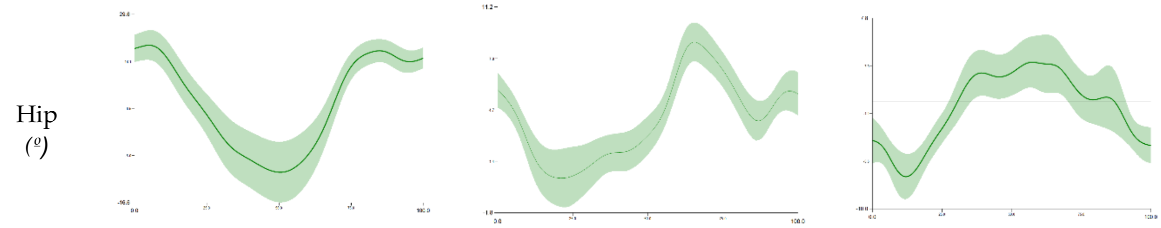
***Figure 5.1:** Kinematics various of NF lower limbs joints during gait*



Dorsiflexion / Plantarflexion   Abduction / Adduction   External / Internal rotation



Flexion / Extension   Abduction / Adduction   External / Internal rotation



Flexion / Extension   Abduction / Adduction   External / Internal rotation

***Figure 5.2:** Kinematics various of FF lower limbs joints during gait*

The Center of Mass variation over gait is illustrated in ***Figures 5.3*** and 5.***4*** (NF and FF subjects respectively).

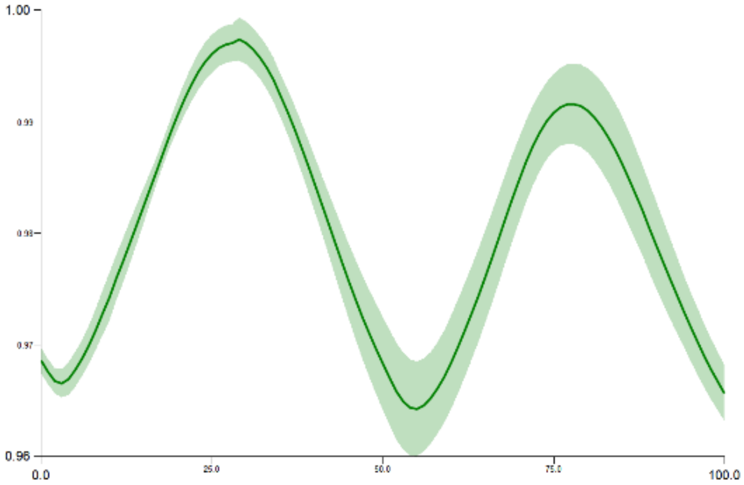


Figure 5.3: *Center of Mass variation of NF subjects alongside gait pattern*

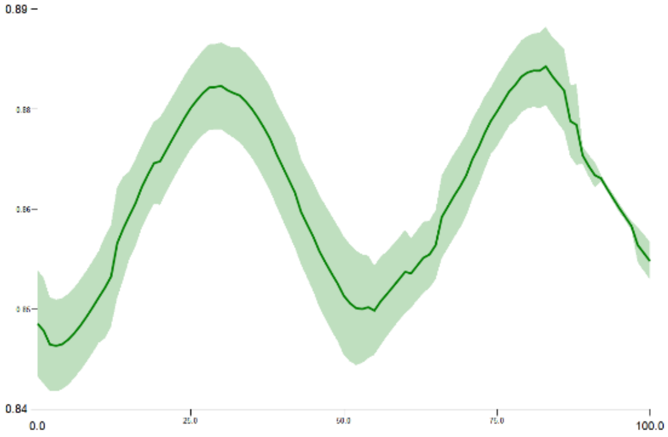


Figure 5.4: *Center of Mass variation of FF subjects alongside gait pattern*

Discussion

FF is a condition that can be triggered by several reasons, namely, neurological or muscular restrictions, ligament laxity, joint laxity, excessive motion, and muscle activity (Farokhmanesh et al., 2014; Hunt & Smith, 2004; Tahmasebi et al., 2015). It is present in children, targets 10-25% of adults, and can be disastrous for patients. This leads to several injuries (Angin et al., 2014; Caravaggi et al., 2018; Kosashvili et al., 2008; Sung, 2016; Sung et al., 2017), often accompanied by pain, affecting gait pattern and speed, balance, and decreasing function, consequently increasing fall risk (Farokhmanesh et al., 2014; Sung, 2016; Sung et al., 2017). Due to these several complications associated with FF, the insight into the impact of this condition on the biomechanical aspects of human locomotion is clinically essential. Therefore, the use of 3D gait biomechanical analysis could be advantageous and crucial in the early detection of health impairments related to foot posture. According to our knowledge, this is the first study that investigates overall lower-limb kinematic characteristics during gait in FF subjects. The purpose of the present study was to characterize the gait kinematics during the entire gait cycle of subjects with FF conditions. Comparative observations of lower extremity kinematics during a walking task were performed between individuals with FF compared to NF ones. Gait was characterized in all three dimensions employing a Motion Capture system.

In this study, the group's comparison showed statistically significant differences between most of the studies' kinematics variables, more specifically to the ankle, knee, and hip joints. However, the *Motion Capture* analysis of gait kinematics and complete lower limb analysis for FF subjects are not easily found in the literature. The current study provided a full assessment of the pelvis and lower limbs to better characterize the movement in all three planes during gait. ROM differences have been found in the kinematics of both groups concerning the pelvis and all lower-limbs joints.

During gait, in this study FF participants presented lower ankle dorsiflexion (*p=.029*), abduction (*p=.033*), external and internal rotation (*p<.001*). Also, only the ankle abduction/adduction ROM presented a statistically significant increase in the NF group (*p=.003*). Those results are following those found by *Twomey et al.* (2012), who stated no significant differences (*p>.05*) between the same group in the ankle kinematics during gait (Twomey & McIntosh, 2012). However, we need to highlight the fact that those results were found in children. In another study realized by *Twomey et al.* (2010) in children, they found significant differences relative to the forefoot supination angle (*p<.003*). On the other hand, *Levinger et al.* (2010), investigate kinematics changes of the foot and the ankle along with gait task in FF subjects compared to neutral ones, in adults. They found a greater forefoot abduction (*p=.002*) and internal rotation (*p=.018*) in FF subjects. The authors found a significantly greater peak forefoot plantarflexion (*p=.004*) and adduction (*p=0.004*). However, we found no adduction differences between groups during the gait cycle (*p=.398*). This can be due to ankle stabilization during gait, namely during the propulsion phase in the late stance phase of the gait cycle. As pointed by *Levinger et al.* (2010), the electromyography activity of the tibialis posterior is greater in FF subjects, which may explain the joint stabilization, not inducing a change both in foot pronation and ankle adduction. Also, *Buldt et al.* (2015) investigated the kinematics of ankle and foot differences between FF and NF groups during gait. Their findings support a significantly smaller inversion/eversion ROM (*p<.05*) in the FF group as well as a significantly smaller peak plantarflexion value (*p<.05*). The authors performed a systematic review concerning the foot and ankle kinematics analysis during gait comparing FF and NF subjects. Few papers were included in their review and the authors stated that there was some evidence for increased motion in the FF subjects, but limited by small effect sizes. They also stated some evidence of increasing FF posture was positively correlated with an increased frontal plane motion of the rearfoot and therefore translated into the navicular bone drop present in FF subjects. As pointed previously, we did not find greater ankle adduction or abduction in the FF subjects. Our results don't always match several studies that analyzed static posture of FF subjects and found those correlations between joints kinematics (Farokhmanesh et al., 2014; Ghasemi et al., 2016; Khamis et al., 2015; Lee et al., 2017; Tahmasebi et al., 2015; Twomey & McIntosh, 2012). They stated that during the medial longitudinal arch drop, the foot is forced to maintain exaggerated pronation, and through the coupling kinematics between the foot, tibia, and femur, subjects presented an increased internal rotation of the hip.

FF subjects only showed a greater knee peak flexion peak (*p<.001*) during gait. Even so, those subjects showed a lesser knee peak extension (*p<.001*), abduction (*p<.001*), and external rotation (*p<.001*) with significant differences compared to NF participants. However, knee flexion/extension ROM (*p=.000*) is higher concerning FF subjects while the NF group present a higher abduction/adduction ROM (*p<.001*). *Twomey et al.* (2012) found in children aged 11-12 years a significant difference between the two groups regarding the adduction/abduction peak value (*p=.01*) with a greater value for the FF group concerning the valgus condition. Also, the authors did not find any significant results in the sagittal or transverse plane of the knee.

Also, FF subjects presented a higher hip peak flexion (*p=.002*) alongside a higher internal rotation peak value (*p<.001*). However, the NF participants presented higher peak values of hip extension (*p=.006*) and hip external rotation (*p=.012*) with significance. Thus, the FF subjects showed a significantly lesser ROM concerning hip flexion/extension (*p=.002*) and internal/external rotation (*p=.007*). Our results are controversial to those stated by *Twomey et al.* (2012) who related greater hip external rotation peak (*p<.05*) in the FF group. A gait pattern is considered a cyclic movement, where the coordination of several joints movements concerning the same plane is necessary to optimize the gait efficiency (Dietz, 2003). The increase in knee and hip flexion along gait for the FF subjects can result from a greater need to absorb impacts that, in FF, are not absorbed at foot level. This occurs as FF subjects showed lesser ankle dorsiflexion and knee extension peak, corresponding to a lack of mobility.

Finally, regarding the pelvic kinematics, the only significant difference concerning peak value was found relative to the pelvic rotation with an increased value in the FF over the NF group (*p=.017*). Lastly, the FF group showed a significantly higher pelvic rotation ROM (*p=.009*). As stated by *Levinger et al.* (2010), our findings, regrouped with the comparison of the other studies related to an altered ankle and foot motion associated with foot posture, namely the FF condition can induce altered motion over gait pattern (Levinger et al., 2010). The FF subjects exhibit a greater abduction and pronation both in static posture but also during gait which can increase injury risk. However, FF subjects did not present greater frontal plane motion ROM, i.e., abduction/adduction ROM. Therefore, without an increased amplitude, we can hypothesize that FF subjects did not present greater ankle mobility during gait, which is contradictory to several authors' key findings. In the systematic review done by *Buldt et al.* (2013) concerning the kinematics differences between FF and NF subjects during gait, the authors provide some evidence of the FF condition and lower limb motion relationship during the gait. However, they only focus their analysis on the foot and ankle kinematics without an entire lower limb analysis. However, they stated that their study was not conclusive as the included papers presented several limitations.

Finally, we found in our study a statistically significant increase in vertical maximum center of mass value in the NF compared to the FF (*p<.001*). FF subjects present a lower mean value corresponding to the minimum vertical score during the double stance support phase of the gait cycle and the medial longitudinal arch drop. As stated, we did not find any significant increase concerning ankle abduction, but this can also result in less impact absorption by the foot and therefore this absorption is carried out by joints above such as the knee and hip and with this, the maximum displacement of the centre of mass be smaller. However, more study needs to be conducted on FF subjects as no papers were found in the literature about this content.

After all, one should consider that other parameters than foot posture variation can induce motion alterations in subjects during the gait pattern. Although this study shares various foot postures on gait patterns, namely in FF conditions, several limitations can be pointed out. Only subjects who presented bilateral FF conditions using the NDT and the RCSP participated in this study. However, like the foot complex lays on several joints and present few inter-associations, it will be interesting to evaluate the same results using the FootPrint parameters as an inclusion criterion.

Conclusion

Regarding the overall kinematics of lower limbs assessment through gait pattern, the sample studied showed that FF subjects did present few alterations compared to NF participants, during the entire gait cycle. The differences were present in the ankle, knee, hip, and pelvis joints and ROM variations. Considering the lack of consensus and low evidence present, studies need to be realized to produce a piece of more robust evidence and can encompass the assessment of kinematics changes between groups regarding the foot posture assessment through Footprint parameters.

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER VI

STUDY V . TIBIALIS POSTERIOR MUSCLE STIFFNESS ASSESSMENT IN FLATFOOT SUBJECTS BY ULTRASOUND-BASED SHEAR-WAVE ELASTOGRAPHY

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Abstract

Background: Few methodologies are used to assess Tibialis Posterior muscle stiffness. Those present limitations leading to a lack of evidence. Muscle stiffness assessment can help in the injuries risk factors identification while coupling with Ultrasound based Shear-Wave Elastography for its management. However, a precise and reliable methodology needs to be utilized to increase stiffness accuracy among the entire Tibialis Posterior muscle. Therefore, this study aims to investigate the stiffness association between Tibialis posterior deep and superficial layer and between flat and NFed subjects. ***Methods:*** The sample consisted of 18 participants, where 9 subjects represent the flatfoot group and 9 the NF group. Only the subjects who presented a NDT value of >9mm were included in the flatfooted group. All participants were submitted to the Tibialis posterior stiffness assessment with the help of Ultrasound base Shear-Wave Elastography in a lying supine position. Association between Tibialis Posterior deep and superficial layers were determined by Pearson's correlation analysis and group differences were assessed using the U-Mann Whitney test in the comparison between flat foot and NF group ($p<.05$). ***Results:*** No significant correlations between Tibialis Posterior layers stiffness were found ($p=.194$), nor in the comparison between both neutral and flat foot groups ($p=.424$ / $p=.258$). ***Conclusion:*** Among participants, no associations between tibialis posterior layers stiffness were found. Also, we did not find any differences in the stiffness between flat and NF groups. In this study, the stiffness did not differentiate flat-footed subjects from neutral subjects.

Keywords: Intramuscular tendon; Ultrasound; muscular characteristics; foot posture.

Introduction

Foot problems are related to impaired mobility and postural stability, which have a detrimental impact on the quality of life and have been reported as a common concern in the community (Sung et al., 2017). FF is a foot's deformity, characterized by calcaneus plantarflexion and eversion relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Buldt et al., 2013; Caravaggi et al., 2018; Horwood & Chockalingam, 2017; Kohls-Gatzoulis et al., 2004). This condition can be triggered by several causes, namely, neurological or muscular restrictions, ligament, and joint laxity, excessive motion, and muscle activity (Hösl et al., 2014; Hunt & Smith, 2004). Alongside, foot sole afferent input can affect postural awareness. FF subjects present greater foot and ankle mobility with subjacent higher risks of developing adjacent mechanical overloading injuries (Buldt et al., 2013, 2015) like for example tibial stress syndrome, sacroiliac joint dysfunction, or even patella-femoral joint pain (Buldt et al., 2015; Hösl et al., 2014; Hunt & Smith, 2004; Levinger et al., 2010). One of the most affected muscles concerning this condition is the Tibialis Posterior (TP) that can further lead to developing medial tibial stress syndrome (Bowring & Chockalingam, 2010; Kohls-Gatzoulis et al., 2004; Ohya et al., 2017). However, previous works show that medial tibial stress syndrome mechanisms and risk factors weren't perfectly understood, symptoms can de due to medial tibia border fascia and periosteum stress response (Ohya et al., 2017).

The active tension formed by the muscle contraction and the passive tension formed by the connective tissue produces normal skeletal muscle stiffness (Eby et al., 2013; Kelly et al., 2018). Thus, muscle stiffness is reliant on different factors, like applied forces, and the intrinsic material properties of muscle (Kelly et al., 2018). Although, the mechanical properties of passive muscle influence importantly the movements' functional behavior (Eby et al., 2013; Le Sant et al., 2017) and, can impact the appearance of several pathologies (Creze et al., 2017; Eby et al., 2013). Thus, stiffness assessment can help in the identification of those injuries' risk factors (Kelly et al., 2018; Koppenhaver et al., 2018). Several authors reported important physiological baseline measurements in the muscle at rest where contracted or stretched muscles stiffness differs from normal muscles compared to altered ones (Creze et al., 2017; Dubois et al., 2015). Also, stiffness is related to elasticity, as an intrinsic biomechanical property that is quantified through *Young's modulus* based on the shear wave velocity of ultrasound propagation (Creze et al., 2017; Kelly et al., 2018). An emerging technique recently employed to assess skeletal muscle stiffness is Ultrasound based Shear-Wave Elastography (SWE). It was developed to assess in real-time, in vivo muscle stiffness to quantify elasticity and stiffness (Bercoff et al., 2004; Koppenhaver et al., 2018; Le Sant et al., 2017; Mendes et al., 2018). Thus, like ultrasound shear wave elastography is strongly associated with *Young's modulus*, thereby, SWE can provide a localized estimation of muscle stiffness (Eby et al., 2013; Le Sant et al., 2017; Mendes et al., 2018). Researchers found that active component deficits have been constantly investigated, instead of passive components, as the first one is important to functional activities (Eby et al., 2013).

Relatively to previously published papers, several authors investigated muscles with the use of SWE and found reliability in wide muscle group variety (Kelly et al., 2018; Le Sant et al., 2017; Ohya et al., 2017; Saeki et al., 2018; Saeki et al., 2017). However, few analyzed the TP in different assessment conditions while several muscles were identified in the same measurement position. The TP presents two layers that can be evaluated, the deep (DL) and superficial (SL) layers. Three authors investigated the stiffness variation between and within several muscle groups including the TP_ DL (Saeki et al., 2017). Although, one author investigated the same muscles and reliability along with several lower limb muscles but assessing the TP_ SL (Le Sant et al., 2017; Ohya et al., 2017; Saeki et al., 2018; Saeki et al., 2017). Authors reported a lack of consensus in their search based on several technical assessment parameters resulting in an unknown variability regarding subject and measurement position, or rest and contraction evaluation (Creze et al., 2017; Dubois et al., 2015). Regarding measurement position, the stiffness value depends on probe position and parameters making it examiner dependent (Creze et al., 2017). Firstly, as stated by *Dubois et al.* (2015), a lack of consensus is present among the literature concerning technical aspects of the SWE measurements. Among the most SWE characteristics, the angle formed between the probe and the muscle fibers orientation can influence the stiffness measurements as this is correlated with Young’s modulus in a parallel position of the probe relative to the muscle fibers

(Creze et al., 2017; Dubois et al., 2015; Taljanovic et al., 2017). This last is closely correlated with the anatomy knowledge and experience of the examiner, which needs to distinguish the several types of muscles, i.e., multipennate, bipennate, fusiform, or convergent (Creze et al., 2017). Also, the examiner needs to have precaution relative to the probe pressure along the skin as the skeletal muscle is considered a deformable tissue as muscle is anisotropic, nonlinearly viscoelastic compressive, and deformable and active tissue (Creze et al., 2019; Kot et al., 2012). Alongside, a plentiful gel amount needs to be collocated on the skin surface to prevent exaggerated probe pressure from the examiner and therefore create localized stiffness increase (Creze et al., 2017, 2019). Finally, according to *Creze et al.* (2019), the ultrasound signal is decreasing when analyzing deep tissue making it difficult to assess. Therefore, regarding the lack of consensus in measurement probe position and foot posture variability, the present study's purpose was to analyze association within the Deep and Superficial TP layers and to compare the stiffness differences between subjects with FF and NF using ultrasound SWE.

Materials and Methods

Design

This observational descriptive study was carried out at the *RoboCorp Laboratory – Physiotherapy*, at the *Coimbra Health School – Polytechnic Institute of Coimbra* after the *Ethics Committee of Polytechnic Institute of Coimbra* (*13_CEPC2/2019*) approval. The procedures were conducted according to the principles expressed in the *Declaration of Helsinki*.

Participants

The sample size was calculated using the *G*power 3.1.5* software (Franz Faul, Kiel, Germany) based on the study previously published by *LeSant et al.* (2017). A required sample size of 18 was determined by achieving an estimated, alpha level of 0.05, and a power of 0.80. Consequently, eighteen volunteers were assessed for eligibility and recruited for this study (***Table 6.1***) from the *Polytechnic Institute of Coimbra*. Before any assessment, study purpose and procedures, benefits, and risks involved were explained to each participant. Subjects were guaranteed that they could withdraw at any time without justification and asked to provide informed consent. The study inclusion was limited to subjects aged between 18 and 40 years. All participants were submitted to the NDT to identify whether they had a FF or a NF as this test is clinically used by practitioners worldwide (Sung, 2018). Inclusion criteria in the FF group encompassed subjects that presented a bilateral >9mm NDT score and in the NF group involved participants with a bilateral <9mm NDT score (***Table 6.2***). Subjects could participate in recreational sports, but not in any strength or flexibility training and were excluded following these conditions: a) Ankle sprain in the last 6 months; b) Physiotherapy treatment program or history of injury including bilateral ankle injury; c) Bone fracture associated with an ankle sprain, such as avulsion fracture or osteochondral ankle injury; d) Injury or surgery to the spine, hip, knee, or ankle e) Medication intake that can affect gait, muscle activity or stiffness. Indeed, the FF and the NF groups consisted of 9 participants each comprising a total of 18 flatfeet and 18 neutral feet.

Table 6.1: *Sample characteristics*

	n	**Minimum**	**Maximum**	**Mean**	**Standard Deviation** *(SD)*
Age *(years)*	*18*	18	35	22.7	4.5
Height *(cm)*		155	182	172.2	8.4
Weight *(kg)*		53	95	72.6	11.4

Table 6.2: *Groups characteristics*

Group	**n**	**Age** *(years ± SD)*	**Height** *(cm ± SD)*	**Weight** *(kg ± SD)*	**NDT** *(score ± SD)*	**TP_DL** *(kPa ± SD)*	**TP_SL** *(kPa ± SD)*
NF	*9*	22.7 ± *4.3*	172.8 ± *8.7*	71.1 ± *10.1*	4.9 ± *2.4*	25.8 ± *3.7*	10.2 ± *4.9*
FF	*9*	22.8 ± *4.9*	171.9 ± *8.5*	74.2 ± *13.1*	11.5 ± *1.4*	24.6 ± *8.1*	8.1 ± *2.3*

TP = Tibialis Posterior; DL = Deep Layer; SL= Superficial Layer; NF = neutral foot; FF = flatfoot; NDT = Navicular Drop Test; n = sample
Mean + Standard deviation

Assessment

Both NF and FF conditions were evaluated regarding the same assessment procedure bilaterally in a weight-bearing barefoot stance position. The navicular drop was evaluated using the NDT, where three measurements mean values define the navicular drop severity. The investigator placed a rigid ruler perpendicularly to the ground and registers the ground-navicular bone distance. Then, inverts the talus into a neutral position and repeats the procedure (Sung, 2018). For the SWE, the muscle shear modulus was assessed using the *Acuson Sequoia Ultrasound System 2018* (Siemens Healthcare GmbH, Erlangen, Germany) coupled with a linear transducer array (SL10-4, 4-10 MHz, Siemens Healthcare GmbH, Erlangen, Germany) in the SWE mode, namely the *musculoskeletal preset* and *B-mode*. The SWE system was developed based on some technical specificities to ensure stiffness evaluation. A shear wave is created within the assessed muscle in a propagation way, to further be evaluated by measuring the shear wave velocity (Vs) using a specific algorithm. As reported by *Bercoff et al.* (2004), assuming a linear elastic behavior, a *shear modulus* (μ) is calculated using *Vs* as follows $\mu = \rho \times Vs2$, where ρ corresponds to the muscle mass density (1000 kg/m3). The push frequency (that generated the elastogram window) was set automatically by the ultrasound equipment to approximately 1 Hz (range 0.8 – 1.4 Hz). All the assessments were realized only by a single ultrasound radiologist which had a wide experience (>10 years) using the ultrasound and SWE to avoid interobserver variation. Alongside, the same ultrasound device, transducer, setup parameters, and assessment locations were identical for all assessments. For all subjects regarding both the superficial and deep layers of the TP, the transducer locations were realized and marked by another experienced examiner (>7 years), directly on the skin with the aid of a waterproof ink pen. Regarding the transducer location, all muscles location were determines based on previous methodologies used for SWE as follows: both layers were evaluated at the mid-cross sectional area, at *~60%* of the proximal-to-distal anterior shank length for the deep layer of the TP (Saeki et al., 2017), and *~40%* between the proximal fibula head and medial malleolus for the superficial layer of the TP (Le Sant et al., 2017; Ohya et al., 2017). All assessments were realized with the subjects lying supine (Saeki et al., 2018). The subjects were asked to stay relaxed during all the assessments. Before probe colocation, the radiologist sprayed a large amount of coupling gel. The pressure between the transducer and the skin was minimized by the radiologist to avoid an increase in stiffness created by exaggerated external pressure. Therefore, stable distribution of the elastographic color was set for a few seconds before acquiring the images and three measurements were realized for each muscle layer, bilaterally. Before data recording, both longitudinal and transverse scans were performed to find the *regions of interest* (ROI) along with the ultrasound software, and the transducer was aligned along the muscle fascicle direction to assess the shear modulus (Le Sant et al., 2017). For the ROI evaluation, a circular area was set where the *shear modulus* (kPa) was calculated.

Data Processing and Analysis

The shear modulus was automatically calculated by the *ACUSON Sequoia* software (Healthcare GmbH, Erlangen, Germany) using the previously mentioned algorithm. The images recorded were automatically processed converting each color map pixel into a shear modulus value. The largest ROI was set previously by the experienced radiologist and maintained equally for all assessments reaching a 5mm diameter. The ROI was determined in the elastogram window by avoiding aponeurosis and tissue artifacts. The SWE assessment is shown in ***Figure 6.1***.

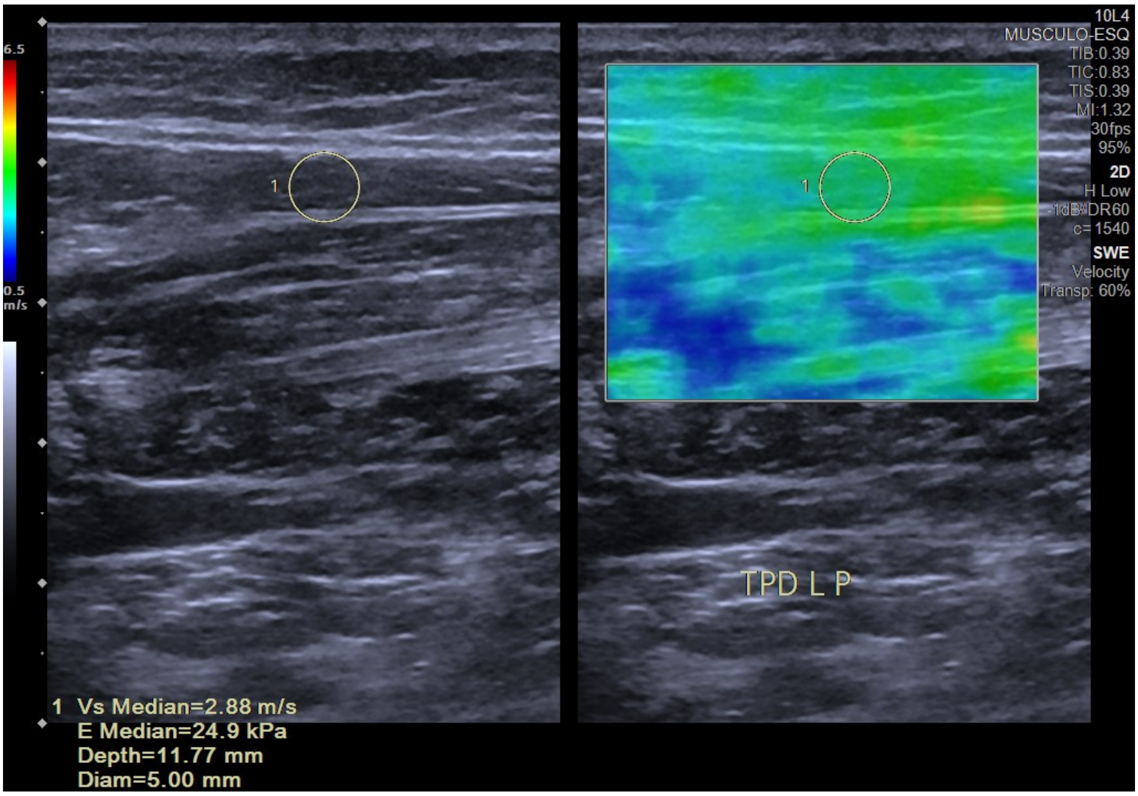

Figure 6.1: *SWE TP_SL assessment*

Statistical Analysis

The data were statistically processed with the *IBM SPSS Statistics 25.0* software (IBM Corporation, New York, USA). The descriptive statistics, mean and standard deviation, were calculated for all variables regarding both groups. Before the inferential analysis, the normality of the distribution was explored. We identified an abnormal sample distribution based on the *Shapiro-Wilk* test (d=0.826/0.869, *p<.001*). Differences between groups were assessed using the U-Mann Whitney test in the comparison between the experimental and control groups. Finally, associations between the SWE scores regarding probe position were therefore established by *Pearson's* correlation analysis. The level of significance was set at 5% (*p<.05*).

Results

The sample characteristics are specified in ***Table 6.1***. In the procedure, 18 FF and 18 NF were identified. Both subjects were identified and allocated in the different groups through the NDT score assessment. The mean values of the different tests regarding both groups are presented in ***Table 6.2***. Considering the differences between the NF and FF groups, none of the two layers of the TP muscle presented statistically significant results (*p>.05*). More specifically, according to the *U-Mann Whitney* test, the TP_DL didn't present significant results between groups (*p=.424*) neither the TP_SL (*p=.258*) (***Table 6.3***). Concerning the overall sample, based on Pearson's correlation analysis, the correlation between the DL and SL of the TP muscle presents a negative coefficient value of 0.225 corresponding to a low score. However, this correlation didn't present a statistically significant result (*p=.194*) (***Table 6.4***). This correlation is shown in ***Figure 6.2***.

Table 6.3: *Flat and neutral foot comparison*

	Mean ± SD		***p-value*** **(FF vs NF)**
	NF	**FF**	
TP_DL *(kPa ± SD)*	25.8 ± *3.7*	24.6 ± *8.1*	*.424*
TP_SL *(kPa ± SD)*	10.2 ± *4.9*	8.1 ± *2.3*	*.258*

TP = Tibialis Posterior; DL = Deep Layer; SL= Superficial Layer; NF = neutral foot; FF = flatfoot
Mean + Standard deviation

Table 6.4: *Pearson's correlation values of Tibialis Posterior layers*

		TP_SL
TP_DL	*Correlation value*	-0.225
	p-value	*.194*

TP = Tibialis Posterior; DL = Deep Layer; SL= Superficial Layer

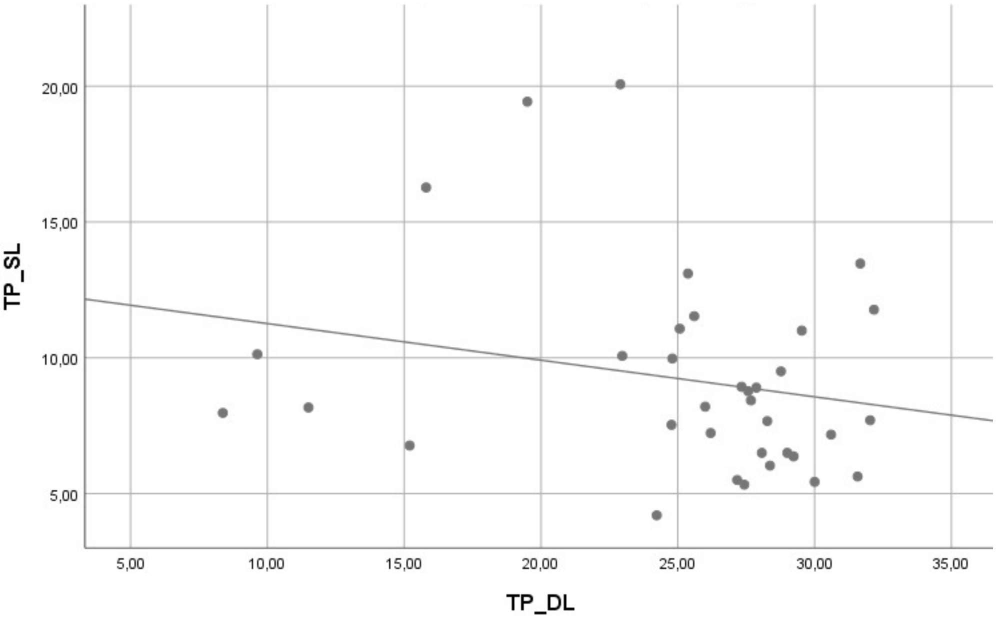

Figure 6.2: *Correlation coefficient of Tibialis Posterior layers*

Discussion

This study is, to our knowledge, the first to look at correlations and group differences regarding DL and SL of the TP muscle stiffness. Previous works related muscle stiffness alterations in the lower limb and different measurement positions for the TP muscle.

Our results showed no statistically significant differences between the NF and the FF groups for the TP_DL (*p=.424*) or the TP_SL (*p=.258*). In our literature search, we found a study, published by *Le Sant et al.* (2017) that investigated the stiffness variations in lower leg muscles during passive dorsiflexion, using SWE. Contrary to our study, they included every subject without assessing foot posture. Indeed, they found a similar mean result (μ=11.0±4.2 kPa) for the TP_SL but highlighting the non-reliability of this assessment. In another study published by *Ohya et al.* (2017), the authors evaluated the running effect on lower leg muscle stiffness. They found a value concerning muscle stiffness lower than ours (μ=3.5±1.6 kPa) at rest and a higher value after 30 minutes running (μ=4.5±2.5 kPa*, p=.035*). Likewise, *Saeki et al.* (2017) found similar results in subjects without any condition (μ=9.2±3.1 kPa) and a statistically different result (*p=.036*) compared with MTSS subjects (μ=12.7±4.3 kPa). Finally, the same author analyzes the same muscle characteristics and found similar results in subjects without any condition (μ=7.3±2.0 kPa). According to those findings, we found a similar result in GC (μ=10.2±4.9 kPa). Moreover, one author, *Saeki et al.* (2018)

also investigated the TP_DL during passive ankle dorsiflexion in subjects without any condition (μ=7.7±1.8 kPa). Their results between 0°, 10°, and 20° of dorsiflexion regarding the TP_DL and TP_SL were very similar between each. In the literature, only one study analyzes the deep layer of the TP muscle instead of the superficial layer of the TP muscle which is analyzed by several authors (Le Sant et al., 2017; Ohya et al., 2017). In other words, there is unavailability in the literature of this methodology showing a lack of evidence. However, without a correlational analysis between the two layers, we cannot emphasize which one should be used at the expense of the other or have a sense of the existing or no relationship between those layers. The wide use of a methodology and assessment of the superficial layer of the TP is relatively sprayed among the literature since it is easier to find with the transducer regarding the ultrasound assessment. Furthermore, the positioning of both the subject and the examiner becomes more comfortable and appropriate, facilitating the acquisition of data for the superficial layer instead of the deep one, which requires more accuracy and dexterity of the examiner. In addition, the deep layer of the TP muscle is considered more difficult to find, identify and evaluate, and vast knowledge of anatomy from the radiologist is necessary. In this case, the deep layer of the TP can easily be confused with other muscles in the same compartment of the leg, namely *the flexor digitorum longus* and the *flexor hallucis longus* (Saeki et al., 2017). The fact that several authors use exclusively the superficial layer of the TP muscle can lead to different conclusions without having a global notion of the entire TP muscle stiffness.

However, we didn't similar results, with our finding been high (μ=25,8±3,7 kPa). However, as we stated before, we didn't find statistically significant differences between NF and FF groups (*p=.424 / p=.258*). Despite our results being partially like those found by several authors regarding the GC, we can hypothesize that those differences can be due to postural compensations. Several authors showed that postural FF subjects have higher risks of developing mechanical overloading injuries triggered on either ankle, knee, or hip joints (Hösl et al., 2014; Hunt & Smith, 2004; Kim et al., 2015; Tahmasebi et al., 2015). Those are due to skeletal system interactions, muscular system, and Central Nervous System (CNS), joint or muscle dysfunction, that are reflected in others functionalities, not locally but globally (Feldman, 2016; Ghasemi et al., 2016).

Likewise, the TP act as a plantar flexor and inverter of the foot. As a plantar flexor, this muscle realizes this movement in coordination with several muscles like the *flexor digitorum longus*, the *flexor hallucis longus* tendons, the soleus, and the gastrocnemius muscle group. Then, like an inverter, the TP muscle realizes the foot adduction and supination working in coordination with for example de tibialis anterior (Barn et al., 2013; Flores et al., 2019; Le Sant et al., 2017; Saeki et al., 2017). Regarding synergist chains and muscle co-activation, several muscles can perform the same osteokinematic motion, working globally (Um et al., 2015). Therefore, muscle stiffness and especially TP stiffness can be scattered by all synergist muscles.

We didn’t find a statistically significant result (*p=.194*) between both layers of the TP muscle, according to *Pearson’s* correlation analysis. In our literature search, we only found one author that assessed both layers of the TP muscle (Saeki et al., 2017). As stated in the literature, the TP muscle-tendon units enhance subtalar-joint mediolateral, rearfoot, and medial longitudinal arch stability (Barn et al., 2013; Maharaj et al., 2016; Semple et al., 2009). Therefore, ankle joint motion alteration can increase TP muscle and tendon stress and, is related to muscle activity (Barn et al., 2013). Anatomically, the TP tendinous tissue can store and return elastic energy while performing gait, running, or in any functional activity. As the TP is a short, pennate muscle, it can act as a synergist or compliant agonist (Maharaj et al., 2016; Semple et al., 2009). Authors also refer that an increase in TP muscle activity may enhance tendon disease (Barn et al., 2013). In our study, we can state that FF participants cannot be considered as pathological subjects who presented different stiffness values compared to the control group who can be dissipated by the previously mentioned various postural compensation and also by the TP muscle navicular insertion, described by *Barn et al.* (2013) as a site of stress dissipation.

Despite this, our study presents various limitations, but it can be seen as an opening view regarding stiffness assessment. Stiffness is dependent on pathological conditions and movement patterns with higher obtained values. In our study, we analyze the TP muscle stiffness in a laying supine position. However, in a stance position, active muscle stiffness can differ compared to rest muscle stiffness that presents lower values (Brandenburg et al., 2014) and cannot ensure a realistic representation of stiffness differences or correlation. Also, as stated by *Creze et al.* (2017), stiffness is not uniform throughout the entire muscle and can display variability regarding muscle areas with variation along the longitudinal and transversal axis. In an upright stance position, whether in gait pattern, standing posture, or different movement patterns, the muscle stiffness can vary and are strictly different regarding resting muscle stiffness. Finally, in our study, we use to determine the inclusion criteria for each group the NDT as it is a clinical, user-dependent test, used worldwide. However, to diagnose flat foot conditions, several used the FootPrint parameters which can impair the allocation results.

Conclusion

This study shows the stiffness differences between neutral and flat-footed subjects and correlations regarding the tibialis posterior muscle using Shear-Wave Elastography. However, no statistically significant results were found regarding both group differences and Pearson's correlation. Stiffness analysis cannot be considered as an important indicator to analyze flat-footed subjects.

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER VII

STUDY VI · CORRELATIONS OF MUSCLE STIFFNESS BY ULTRASOUND-BASED SHEAR-WAVE ELASTOGRAPHY.

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Abstract

Background: Myofascial chains present an interesting and significant role regarding musculoskeletal disorders, influencing neuromuscular activity. Muscle and connective tissue characteristics, like muscle fiber percentage, fiber angle, or stiffness can vary regarding several details, like age, pathological condition, or sports activity. Muscle stiffness assessment can help in the injuries risk factors identification while coupling with Ultrasound based Shear-Wave Elastography for its management. This study aims to investigate the stiffness association between various muscle groups regarding myofascial chains. ***Methods***: The observational descriptive study was carried out at RoboCorp Laboratory – Physiotherapy, at the Coimbra Health School, at the Polytechnic Institute of Coimbra. The sample consisted of 18 participants (22.7±4.5 years). All participants were submitted to *Gastrocnemius lateralis* and *medialis*, *Biceps femoris*, and *lumbar Erector spinae* with the help of Ultrasound base Shear-Wave Elastography. Data were statistically processed with the IBM SPSS Statistics 25.0 software (IBM Corporation, New York, USA). Association between stiffness muscles was determined by *Pearson's* correlation analysis (*p<.05*). ***Results:*** Regarding the myofascial chains of the lower-limbs, only the correlation between the rights *Gastrocnemius lateralis* and *lumbar Erector Spinae* (r=- .500 / *p=.034*), the lefts *Gastrocnemius lateralis* and *medialis* (r=0.476 / *p=.046*) present statistically results. Concerning the overall sample, the only statistically significant result was the correlation between the *Gastrocnemius lateralis* and *lumbar Erector Spinae* (r=-0.376 / *p=.024*). ***Conclusions:*** We did not find a global significant correlation regarding specific muscle stiffness. Therefore, stiffness analysis cannot be considered as an important indicator to identified myofascial stiffness.

Keywords: Ultrasound; muscular characteristics; young's modulus; myofascial chains.

Introduction

The fascia has been vividly investigated among several researchers (Ajimsha et al., 2020; Wilke et al., 2016). Some find its role interesting and significant regarding musculoskeletal disorders, thereby influencing neuromuscular activity (Ajimsha et al., 2020). The treatment of fascial tissue is due to the proprioceptive and mechanically active role in the disorder, as the cerebellum is involved in all perceptual information and processing (Bordoni & Myers, 2020; Wilke et al., 2016). This is due to proprioceptors, nociceptors, interceptors, exteroceptors present in fascial tissue (Bordoni & Myers, 2020). The approach of myofascial chains outstands the fact that skeletal muscles, in the entire body, didn't work in an independent process but instead in a global way (Ajimsha et al., 2020; Wilke et al., 2016). According to various authors, several myofascial chains are identified regarding one important condition, which is the direct linear connection between two adjacent muscles or between muscle groups (Ajimsha et al., 2020; Wilke et al., 2016; Wilke & Krause, 2019). The most known and studied myofascial chain is the *Superficial Back Line* (Wilke et al., 2016). The lower part of this “line” is formed by the linear fascial junction among the *gastrocnemius*, *hamstring*, and the *lumbar erector spinae* muscles via the *sacrotuberous* ligament and *lumbar fascia* (Wilke et al., 2016; Wilke & Krause, 2019). Also, knowing that myofascial continuity is associated with connective tissue regarding several adjacent muscles, a published systematic review, performed by *Wilke et al.* (2016) related the existence of the *Superficial Back Line* over research including 62 cadavers studies, forming a continuous line from toes to the occiput. This approach of globality is also investigated in the *Synergy Concept* of muscle activity, where muscles work together intentionally, clearly representing kinematic motion (Bordoni & Myers, 2020; Dischiavi et al., 2018). Also, myofascial tissue can transmit the tension to adjacent muscles, i.e., the intermuscular myofascial force transmission, or to other soft-tissue, i.e., the extra muscular myofascial force transmission (Bordoni & Myers, 2020; Schleip et al., 2019). Thus, the tension of muscles and connective tissue, along with several characteristics, namely the muscle fiber percentage and penation angle, can vary regarding several details, like age, pathological condition, or sports activity (Bordoni & Myers, 2020).

Normal muscle stiffness is ensured by the contraction of muscles that produce an active tension, and the connective tissue which is related to passive tension (Brandenburg et al., 2014; Eby et al., 2013; Hug et al., 2015; Kelly et al., 2018). A muscle that is passively stretched may show an increase and measurable resistance, known as passive muscle stiffness or passive muscle tone. The authors refer to a higher stiffness in tonic muscles and along with intramuscular connective tissue can adapt and adjust muscle stiffness regarding sensory afferent input and efferent output (Schleip et al., 2006). As movement's functional behavior is constantly produced by everyone, the mechanical properties of passive muscle can influence importantly those motion patterns (Eby et al., 2013; Le Sant et al., 2017) and thereby influence the development of several pathologies (Creze et al., 2017; Eby et al., 2013). Regarding those properties, stiffness assessment and its understanding can thereby help in the identification of injury risk factors (Kelly et al., 2018; Koppenhaver et al., 2018). Scientific searches demonstrated a reliant effect of muscle stiffness on different extrinsic and intrinsic factors such as muscle properties and variability among muscles (Kelly et al., 2018). One important intrinsic biomechanical factor is muscle elasticity. This is quantified through *Young's modulus* based on the shear wave velocity of ultrasound propagation (Creze et al., 2017; Kelly et al., 2018). This shear wave assessment can be realized with the use of an ultrasound-based *Shear-Wave Elastography*. This was initially developed to assess, in real-time, in vivo pathological conditions but can be used also for muscle stiffness to quantify elasticity and stiffness (Bercoff et al., 2004; Koppenhaver et al., 2018; Le Sant et al., 2017; Mendes et al., 2018). Also, as this new assessment method is associated with *Young's modulus, Shear-Wave Elastography* can provide a localized stiffness estimation (Eby et al., 2013; Le Sant et al., 2017; Mendes et al., 2018). Firstly, *Eby et al.* (2013), realized a paper that stated the validity of this method in skeletal muscle.

Considering works developed by several authors, they reported stiffness alteration compared to normal or pathological muscles within rest, contracted, or stretched conditions (Creze et al., 2017; Dubois et al., 2015). For instance, the authors investigated the muscle stiffness of the *lumbar erector spinae* and *hamstring* (*semitendinous*, *semimembranosus*, *biceps femoris long* and *short* heads) muscles with the aid of ultrasound-based *Shear-Wave Elastography*.

They found an increased muscle stiffness considering a passive stretch of the hip for the *hamstring* muscles and in a seated position compared to resting lying prone position for the *lumbar erector spinae* muscle (Blain et al., 2019; Le Sant et al., 2015). Also, *Creze et al.* (2019) state an increased muscle stiffness in bending and upright stance position compared to lying rest position analyzed with ultrasound-based *Shear-Wave Elastography*. Therefore, muscles, namely tonic ones presented a stiffness increase regarding postural and biomechanical necessities (Schleip et al., 2006). Alongside, relatively to previously published papers, several authors investigated different muscles with the use of *Shear-Wave Elastography* and found good reliability in wide muscle groups variety (Creze et al., 2017; Kelly et al., 2018; Le Sant et al., 2017; Ohya et al., 2017; Saeki et al., 2018; Saeki et al., 2017). However, no study analyzes the correlation between the muscle stiffness integrated into a myofascial chain. Therefore, regarding the lack of consensus in stiffness measurement, the study's purpose was to analyze the relationship between the *gastrocnemius*, *biceps femoris*, and the *lumbar erector spinae* muscle based on *Shear-Wave Elastography*.

Materials and Methods

Design

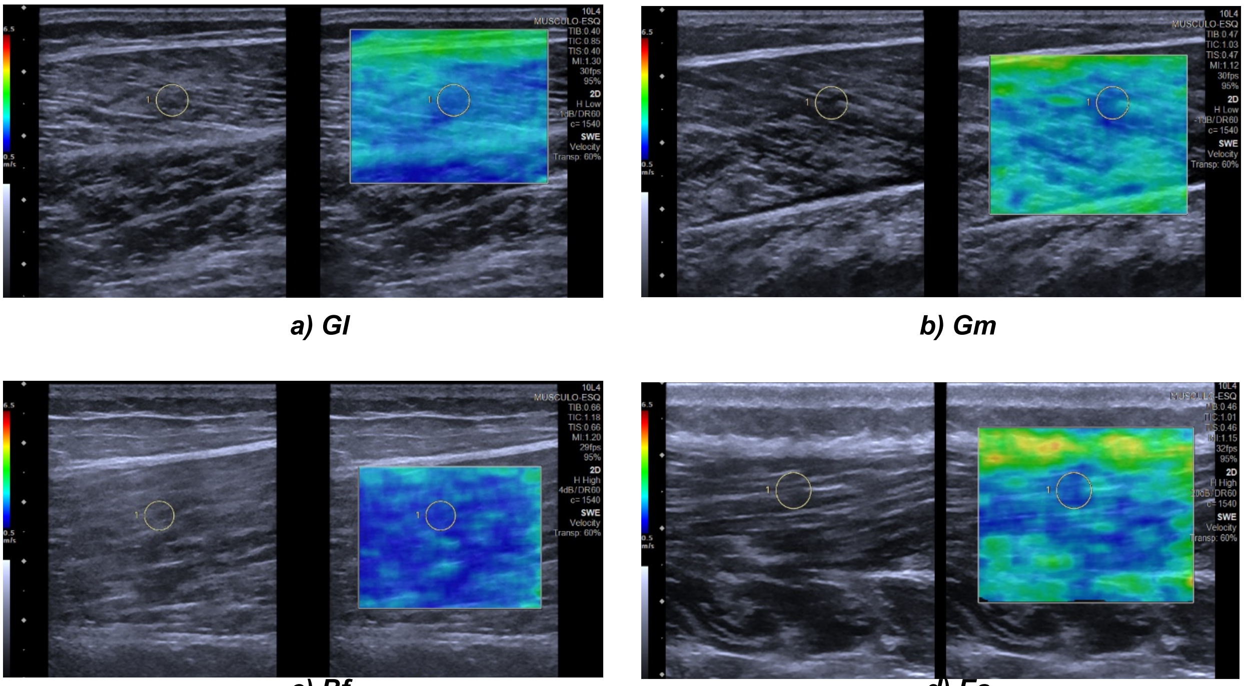
This observational descriptive study was carried out at the *RoboCorp Laboratory – Physiotherapy*, at the *Coimbra Health School – Polytechnic Institute of Coimbra* after the *Ethics Committee of Polytechnic Institute of Coimbra* (*13_CEPC2/2019*) approval, based on the revised version of the *2013 Declaration of Helsinki.*

Participants

The sample size was calculated using the *G*power 3.1.5* software (Franz Faul, Kiel, Germany). A required sample size of 13 was determined by achieving an estimated alpha level of 0.05, and a power of 0.95 based on previous data assessment. Consequently, 18 volunteer students were recruited from the *Polytechnic Institute of Coimbra*. Before any assessment, study purpose and procedures, benefits, and risks involved were explained to each participant. Subjects were guaranteed that they could withdraw at any time without justification and asked to provide informed consent. The study inclusion was limited to subjects aged between 18 and 40 years. Also, subjects could participate in recreational sports, but not in any strength or flexibility training and they were asked to not perform any type of physical activity 48h before the *Shear-Wave Elastography* assessments. Subjects who presented the following conditions were excluded: a) ankle sprain in the last 6 months; b) physiotherapy treatment program or history of injury including bilateral ankle injury; c) Bone fracture or ankle surgery; d) Medication intake that can affect gait and muscle activity; e) sports athletes.

Assessment

For the *Shear-Wave Elastography*, the muscle *shear modulus* was assessed using the *Acuson Sequoia Ultrasound System 2018* (Siemens Healthcare GmbH, Erlangen, Germany) coupled with a linear transducer array (SL10-4, 4-10 MHz, Siemens Healthcare GmbH, Erlangen, Germany) in the *Shear-Wave Elastography* mode, namely the *musculoskeletal preset* and *B-mode*. The *Shear-Wave Elastography* system was developed based on some technical specificities to ensure stiffness evaluation. A shear wave is created within the assessed muscle in a propagation way, to further be evaluated by measuring the shear wave velocity (*Vs*) using a specific algorithm. As reported by *Bercoff et al.* (2004), assuming a linear elastic behavior, a *shear modulus* (μ) is calculated using *Vs* as follows *μ = ρ×Vs2*, where ρ corresponds to the muscle mass density (1000 kg/m3). The push frequency (that generated the elastogram window) was set automatically by the ultrasound equipment to approximately 1 Hz (range 0.8 – 1.4 Hz). All the assessments were realized only by a single ultrasound radiologist which had a wide experience (>10 years) using the ultrasound and *Shear-Wave Elastography* to avoid interobserver variation. Alongside, the same ultrasound device, transducer, setup parameters, and assessment locations were identical for all assessments. For all subjects, and regarding muscles, the transducer locations were realized and marked by another experienced examiner (>7 years), directly on the skin with the aid of a waterproof ink pen. Regarding the transducer location, all muscles location were determines based on previous methodologies used for *Shear-Wave Elastography*. Both *gastrocnemius lateralis* (Gl) and *medialis* (Gm) were evaluated at the mid-cross sectional area, at *~30%* of the proximal-to-distal *shank* length, between the proximal *fibula* head and medial *malleolus* for the lateral portion and medial *femoral condyle* and the *lateral malleolus* relatively to the medial portion (Le Sant et al., 2017; Saeki et al., 2017). The *biceps femoris long head* (Bf) was assessed at the mid-cross sectional area, at *~55%* of the greater *trochanter*-to-lateral *femoral condyle* (Miyamoto et al., 2018). For the *lumbar erector spinae* (Es), firstly, the examiner localized the *iliac crest* by manual palpation to therefore identified the L3 and L4 *spinous processes*. Then, the muscle was evaluated at 2cm lateral to the L3-L4 spinous processes (Blain et al., 2019). All assessments were realized with the subjects in a lying prone position. The pressure between the transducer and the skin was minimized by the radiologist to avoid an increase in stiffness created by exaggerated external pressure. Therefore, stable distribution of the elastographic color was set for a few seconds before acquiring the images and three measurements were realized for each muscle, bilaterally (***Figure 7.1***). Before data recording, both longitudinal and transverse scans were performed to find the regions of interest (ROI) along with the ultrasound software, and the transducer was aligned along the muscle fascicle direction to assess the shear modulus (Le Sant et al., 2017). For the ROI evaluation, a circular area was set where the *shear modulus* (kPa) was calculated.



a) Gl ***b) Gm***

c) Bf ***d) Es***

Figure 7.1: *Shear-Wave Elastography assessment examples*

Data Processing and Analysis

The shear modulus was automatically calculated by the *ACUSON Sequoia* software (Siemens Healthcare GmbH, Erlangen, Germany) using the previously mentioned algorithm. The images recorded were automatically processed converting each color map pixel into a shear modulus value. The largest ROI was set previously by the experienced radiologist and maintained equally for all muscles assessment reaching a 10mm diameter. The ROI was determined in the elastogram window by avoiding aponeurosis and tissue artifacts. Three shear modulus data were recorded for each muscle where the average mean was used as the relative value.

Statistical Analysis

The data were statistically processed with the *IBM SPSS Statistics 25.0* software (IBM Corporation, New York, USA). The descriptive statistics, mean and standard deviation, were calculated for all variables. Associations between the *Shear-Wave Elastography* scores regarding muscles were therefore established by *Pearson's* correlation analysis. The level of significance was set at 5% (*p<.05*).

Results

The sample characteristics are specified in ***Table 7.1***. In the procedure, 18 subjects were included representing 36 lower limbs. All subjects were submitted to *Shear-Wave Elastography* assessment of the Es, Bf, Gl, and Gm muscles of both lower limbs. The mean values of muscle stiffness are presented in ***Table 7.2***.

Table 7.1: *Sample characteristics*

	n	**Minimum**	**Maximum**	**Mean**	**Standard Deviation** *(SD)*
Age *(years)*	*18*	18	35	22,72	4,52
Height *(cm)*		155,00	182,00	172,23	8,38
Weight *(kg)*		53,00	95,00	72,65	11,45

Table 7.2: *Muscles Shear-Wave Elastography assessment characteristics*

	n	**Gl** *(kPa ± SD)*	**Gm** *(kPa ± SD)*	**Bf** *(kPa ± SD)*	**Es** *(kPa ± SD)*
Right	*18*	9.52 ± *2.10*	10.37 ± *2.76*	5.94 ± *1.46*	8.03 ± *2.57*
Left	*18*	9.61 ± *2.03*	10.64 ± *2.25*	5.65 ± *1.14*	8.02 ± *1.95*
Overall	*36*	9.56 ± *2.03*	10.51 ± *2.49*	5.80 ± *1.30*	8.03 ± *2.25*

Mean + standard deviation
n = sample; Gl = Gastrocnemius lateralis; Gm = Gastrocnemius medialis; Bf = Biceps femoris; Es = Erector spinae

Regarding the right and left lower limb, both presented only one statistically significant result each, based on *Pearson's* correlation analysis. For the right leg, the correlation between the Gl and Es muscles presents a negative coefficient value of 0.500 corresponding to a moderate score (*p=.034*). Thus, for the left leg, a statistically significant result was found between the Gl and Gm muscles, with a positive coefficient value of 0.476 corresponding to a moderate score (*p=.046*). However, the remaining *Pearson's* correlation of both lower limbs didn't present statistically significant results (*p>.05*)(***Table 7.3*** and ***7.4***).

Table 7.3: *Pearson's correlation values of the right lower limb between all muscles*

		Gm	Bf	Es
Gl	*Correlation value*	0,169	-0,057	-0,500
	p-value	*,503*	*,823*	*,034*
Gm	*Correlation value*		0,283	-0,043
	p-value		*,255*	*,864*
Bf	*Correlation value*			0,193
	p-value			*,443*

Gl = Gastrocnemius lateralis; Gm = Gastrocnemius medialis;
Bf = Biceps femoris; Es = Erector spinae

Table *Erro! Não existe nenhum texto com o estilo especificado no documento.**7.**Erro! Não existe nenhum texto com o estilo especificado no documento.**4:** Pearson's correlation values of the left lower limb between all muscles*

		Gm	Bf	Es
Gl	Correlation value	0,476	0,029	-0,213
	p-value	*,046*	*,908*	*,397*
Gm	Correlation value		0,311	-0,039
	p-value		*,209*	*,878*
Bf	Correlation value			0,148
	p-value			*,557*

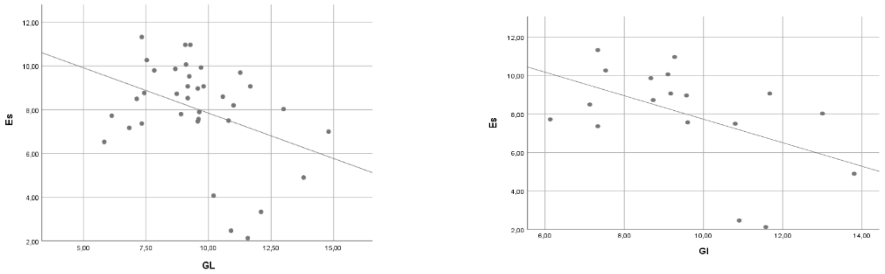
Gl = Gastrocnemius lateralis; Gm = Gastrocnemius medialis;
Bf = Biceps femoris; Es = Erector spinae

Concerning the overall sample, all correlations didn't present statistically significant results (*p>.05*) except for the Gl-Es correlation. This presents a value of -0.376 corresponding to a negative moderate coefficient score (*p=.024*)(***Table 7.5).*** All graphs concerning significant correlation are presented in ***Figure 7.2***.

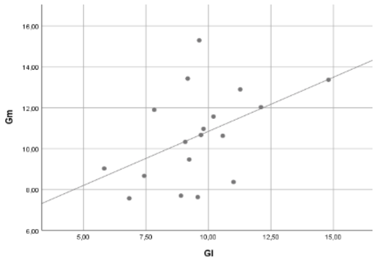
Table 7.5: *Overall Pearson's correlation values between all muscles*

		Gm	Bf	Es
Gl	*Correlation value*	0,304	-0,022	-0,376
	p-value	*,071*	*,899*	*,024*
Gm	*Correlation value*		0,285	-0,042
	p-value		*,092*	*,809*
Bf	*Correlation value*			0,175
	p-value			*,306*

Gl = Gastrocnemius lateralis; Gm = Gastrocnemius medialis;
Bf = Biceps femoris; Es = Erector spinae



a) Gl-Es *(Overall sample)* **b) Gl-Es *(Right side)***



c) Gl-Gm *(Left side)*

Figure 7.2: *Correlation coefficient of Shear-Wave Elastography muscle assessment*

Discussion

To the best of our knowledge, this is the first study to look at partial myofascial chain stiffness correlations, regarding the lower part of the Superficial Back Line. Previous works related muscle stiffness alterations in the lower limb and different measurement positions in several individualized lower limbs muscles.

In biomechanics analysis, clinicians analyzed several movement patterns, throughout an isolated form, based on a linear framework dividing the whole body into sections regarding singular muscles anatomy characteristics and biomechanics (Dischiavi et al., 2018). Myofascial and fascial tissue present several characteristics like active fascial contractility (Schleip et al., 2019), intermuscular myofascial force transmission and, extra muscular myofascial force transmission (Bordoni & Myers, 2020; Schleip et al., 2019). Those can thereby influence musculoskeletal dynamics and further induce the development of several pathologies (Schleip et al., 2019). Regarding the right and left lower-limb, our results did not show a statistically significant correlation except for the right Gl-Es and the left Gl-Gm correlation. The first correlation presents a negative coefficient value of 0.500 corresponding to a moderate score (*p=.034*) and the second presents a positive coefficient value of 0.476 corresponding to a moderate score (*p=.046*). Also, concerning the overall sample, only the Gl-Es correlation presents a value of -0.376 corresponding to a negative moderate coefficient score with a statistically significant result (*p=.024*).

We did not find any stiffness inter-association or relation between the studied muscles regarding myofascial chains as we did not find any related paper that previously investigated the stiffness of the myofascial chains. We earlier stated that the body and muscles work in a controlled and global environment. In movement patterns, muscles work together according to the *Synergy Concept* (Dischiavi et al., 2018). According to *Dischiavi et al.* (2018), human movement relates to the muscle synergy concept. They stated that muscles are contracted voluntarily or involuntarily together to perform coordinated movement patterns. Those are controlled by the motor system and can be negatively altered by several internal or external factors, based on afferent information acquired by visual, vestibular, and proprioceptive systems to therefore be used by the central pattern generator (Dietz, 2003; Minassian et al., 2017). An appropriate movement pattern lies in the perfect combination and coordination of the central programming and afferent inputs and therefore organize muscle synergies (Dietz, 2003; Garofolini & Svanera, 2019). Therefore, alteration of muscle isolated activity or synergies can produce an adjustment of intermuscular myofascial and extra muscular myofascial force transmission inducing several pathological conditions regarding different external factors like age, or sports activity (Bordoni & Myers, 2020; Schleip et al., 2019).

Based on the results of our study, *Shear-Wave Elastography* can be utilized in an isolated way to assess muscle stiffness, but further work must be developed until it will be possible to identify if this method can be useful to assess globally myofascial chains, to further help practitioners in musculoskeletal disorders diagnosis. Comparing our mean stiffness results obtained for each muscle, our results are different from those found by other authors for the Es, Bf, Gl, and Gm muscles (***Table 7.2***). For instance, in our literature search, we found a study, published by *Koppenhaver et al.* (2018), which investigated low back musculature stiffness in asymptomatic individuals based on *Shear-Wave Elastography* assessment in resting prone position. Similar to our study, they included asymptomatic subjects, where authors found different results compared to ours regarding the Es muscle (μ=4.1 ±1.6 kPa) using a different ultrasound recorder and linear transducer (SL10-2). Relatively to the *Shear-Wave*

Elastography assessment of the Bf muscle, a paper realized by *LeSant et al.* (2015) investigated the muscle stiffness differences of the different hamstring muscles in several hip passive stretch positions. However, the knee flexion was maintained at 90º for all measurements. The authors stated a higher muscle stiffness in greater hip flexion for all muscles including the Bf muscle (μ=37.5 ±8.8 kPa). This seems to be higher than our results, which was a consequence of the stretching component. Concerning the Gm and Gl muscles stiffness assessment, in a study published by *Lacourpaille et al.* (2012), the authors evaluated several muscles' shear elastic modulus values in asymptomatic subjects in resting prone position with the knee at 90° of flexion. They found Gm muscle stiffness values contradictory compared to ours (μ=3.0 ±0.6 kPa). Those results were found using a different recorder and probe linear transducer (SL15-4), and the same probe position and shear elastic modulus formula. Also, *Saeki et al.* (2017) analyzed muscle stiffness based on Shear-Wave Elastography assessment, regarding specifically the GL and Gm muscles in a resting position with a 20° of dorsiflexion. They found similar results concerning the Gl muscle (μ=8.5 ±1.7 kPa) but slightly higher values for the Gm (μ=12.1 ±2.7 kPa) using a different recorder and probe linear transducer (SL10-2). However, those results were found using the same probe position and shear elastic modulus formula.

The majority of the papers found in our literature search were performed in stretching or muscle contraction conditions. However, lower muscle stiffness values are found in resting conditions due to load and torque absence, and neuromuscular inactivity (Creze et al., 2017). Otherwise, contraction can produce stiffness value variability in association with neuromuscular activity, force intensity, a vector quantity, or fascicle length. Thus, some limitations are detected when higher neuromuscular activity was reached, ensuring *Shear-Wave Elastography* assessment bias (Creze et al., 2017; Motomura et al., 2019). Finally, the authors found a linear increase in muscle stiffness regarding stretching conditions (Creze et al., 2017; Le Sant et al., 2015). Also, we investigated all muscles in a lying position. Some papers refer to stiffness dissimilarity regarding hip, knee, and ankle joint angle variation as muscle stiffness can be different regarding stretched or shortened muscle (Hug et al., 2013; Le Sant et al., 2015, 2017; Saeki et al., 2017). Our different results can be due to position assessment as we investigated muscle stiffness in a resting prone lying position to analyze the myofascial chains. Most of the authors analyze individualized muscle stiffness within assessment condition differences, contraction, and stretching, where they identified local stiffness alterations.

Despite this study's limitations, it can be seen as an opening view regarding stiffness assessment in posture and gait pattern analysis. However, stiffness is dependent on pathological conditions and movement patterns with higher obtained values. In our study, we analyzed all muscle stiffness in a laying prone position. However, in a stance position, active muscle stiffness can differ compared to rest muscle stiffness that presents lower values (Brandenburg et al., 2014) and cannot ensure a realistic representation of stiffness differences or correlation. Also, the authors stated that stiffness is not uniform throughout the entire muscle and can display variability regarding muscle areas with variation along the longitudinal and transversal axis (Creze et al., 2017). In an upright stance position, whether in gait pattern, standing posture, or different movement patterns, the muscle stiffness can vary and are strictly different regarding resting muscle stiffness. To maintain postural stability, the body requires sensitive inputs of lower-limb proprioceptive receptors relative to several environmental alterations (Rogers & Mille, 2018). Postural stability rests on sensorimotor receptors feedback, namely plantar pressure, visual system, dental-occlusal, and vestibular adjustments (Mackinnon, 2018; Peterka, 2018; Young et al., 2018). When the body’s center of gravity deviates from its ideal alignment, postural compensation strategies are employed to achieve a stable posture (Angin et al., 2018). Neuromotor responses to the altered sensory afferents signals affect muscle function (Angin et al., 2018) and therefore increase muscle stiffness temporarily regarding the motion task required (Creze et al., 2017).

Conclusion

This study relates the stiffness analysis along with several muscles, namely in the specific part of the *Superficial Back Line* within the lower limbs. The stiffness muscle assessment was based on *Shear-Wave Elastography*. However, few statistically significant *Pearson’s* correlations were found regarding both lower-limbs and overall sample with no repercussion along myofascial chains. Therefore, several scientific search needs to be realized regarding posture and gait pattern stiffness assessment.

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER VIII

STUDY VII . CORRELATION BETWEEN DIFFERENT METHODS TO DIAGNOSE FOOT POSTURE CONDITION

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Abstract

Background: Authors refer to different methods to assess subjects' foot posture. All methods present several limitations depending on the examiner or the chosen test. This study aims to investigate the relationship between different tests and Footprints parameters to diagnose subjects with a flat and NF. ***Methods***: The sample consisted of 37 participants, where 16 were included in the flatfoot group and 21 in the NF group. Only subjects who presented a NDT value of >9 mm were included in the flatfooted group. All participants were submitted to RCSP and plantar pressure platform assessment for Footprints analysis. Associations between all tests and Footprints parameters were determined by Pearson's correlation analysis. ***Results***: Regarding both groups, significant correlations between tests were moderate to nearly perfect to identified both conditions of foot posture. All correlations were statistically significant (*p<.05*). ***Conclusions***: The diagnosis accuracy of foot posture condition can be compromised depending on the used test. The NDT and the RCSP were shown to mislead foot posture condition assessment, unlike Footprints parameters that can be important evaluation tools in a clinical environment.

Keywords: FootPrint; navicular drop; pes planus

Introduction

The body requires sensitive inputs of lower limbs proprioceptive receptors relative to several environmental alterations (Rogers & Mille, 2018; Sung, 2018; Sung et al., 2017) as several sensorimotor receptors' feedback, namely plantar pressure, visual system, and vestibular alterations to maintain postural stability (Mackinnon, 2018; Peterka, 2018; Sung, 2018; Young et al., 2018). The foot skeleton alignment, known as foot posture, varies for each individual (Angin et al., 2018). The foot complications are related to impaired mobility and postural stability, having a detrimental impact on the quality of life (Sung, 2016; Sung et al., 2017), and are also related to inadequate footwear use (Alonso-Montero et al., 2020). Those alterations are reported as a common concern in the community (Sung, 2016; Sung et al., 2017) as static and dynamic postural controls are required during daily living activities and can be impaired (López-López et al., 2018; Nagai et al., 2011). Thus, foot posture, through altered lower limb motion patterns, can induce injuries (Buldt et al., 2013, 2015) and has been associated with abnormal foot motion during gait and posture (Alonso-Montero et al., 2020; Buldt, et al., 2018; Douglas Gross et al., 2011; Eslami et al., 2014; Hunt & Smith, 2004; Levinger et al., 2016; Twomey et al., 2010). In addition, foot posture variations can induce plantar pressure pattern alterations, which consequently alter the proximal lower limb joints' range of motion (Alonso-Montero et al., 2020; Angin et al., 2018). Foot posture is usually classified into three categories, NF, cavus (CF), and FF, with respectively normal high and low medial longitudinal arch height. This last one is often characterized by calcaneus plantarflexion and eversion relative to the tibia, talus plantarflexion, navicular dorsiflexion, and forefoot supination (Caravaggi et al., 2018; Kosashvili et al., 2008; López-López, et al., 2018). In FF subjects, the medial longitudinal arch varies and can modify plantar pressure along the foot, which can affect shock absorption, muscular activity, stability, and, therefore, gait pattern (Zuil-Escobar et al., 2018, 2019).

Several methods are commonly used by practitioners to identify alterations to diagnose those conditions but present several limitations (Cho et al., 2019; Zuil-Escobar et al., 2018, 2019). According to several authors, practitioners can use visual observation, radiographs, FootPrints, or clinical measurements (Khanna & Premavathy, 2019). The most and easily used test remains the NDT, which is used to quantify subjects' hyperpronation. This test value describes the height differences between navicular tuberosity in a neutral position compared to the relaxed posture (Zuil-Escobar et al., 2018), where values higher than 9 mm are associated with FF condition (Sung, 2018), while others refer to values higher than 10 mm. Furthermore, values between 5 to 9 mm identify subjects with NF (Kim et al., 2015; Sung, 2018). This test is considered a cheap, easy, and rapid method (Zuil-Escobar et al., 2019). Other tests can be used to assess foot posture conditions, including the Arch Angle, RCSP, AI, FPI, CSI, or even the SI (Cho et al., 2019; Zuil-Escobar et al., 2018; 2019). All the assessment methods have several limitations depending on the examiner or the chosen test (Cho et al., 2019; Khanna & Premavathy, 2019; Zuil-Escobar et al., 2018; 2019). FootPrints methods, according to *Zuil-Escobar et al.* (2019), are all non-invasive. The ink methods present several biases, such as inaccuracy, and are practitioner dependent, while digital systems are expensive although user-friendly and very useful in both clinical and investigation practice (Chen et al., 2011; Khanna & Premavathy, 2019; Zuil-Escobar et al., 2018; 2019). Finally, RCSP is a simple method and can be used quickly in a clinical environment using few resources (Cho et al., 2019). No previously mentioned methods have any side effects on testes subjects (Zuil-Escobar et al., 2018; 2019).

Concerning all methods, the Arch Angle corresponds to the angle created between the medial line and the most medial aspect of the metatarsus, where values >42° represent the FF condition (Queen et al., 2007; Tahmasebi et al., 2015; Zuil-Escobar et al., 2018). The RCSP is the angle formed by the calcaneus, a perpendicular line to the ground, where values >4° represent the FF condition (Cho et al., 2019). The AI corresponds to the ratio between the middle third area and the entire toeless FootPrint area. A higher value represents FF conditions (Queen et al., 2007; Tahmasebi et al., 2015). The FPI is described in the literature by *Cavanagh et al.* (1987) as the ratio of the non-contact to the contact area, excluding the toes (Cavanagh & Rodgers, 1987; Queen et al., 2007). The authors identified values >0.26 as hyperpronation conditions (Tahmasebi et al., 2015). The CSI represents the ratio between the midfoot area minimal distance and the forefoot area maximal distance (Khanna & Premavathy, 2019; Queen et al., 2007; Zuil-Escobar et al., 2019), and finally, the SI refers to the minimal midfoot distance ratio to the maximal rearfoot distance (Queen et al., 2007).

In our search, only a few papers related both the sensibility and specificity of those tests. The CSI presented an 87.6% sensitivity and an 88.4% specificity, and the AI presented an 89.2% sensitivity and an 80.6% specificity (Chen et al., 2011). Although modifications of the NDT, namely the Normalized Truncated Navicular Height, presented a sensitivity of 88.1% and a specificity of 99.5% (Aboelnasr et al., 2019), and the Navicular Index presented a 86% sensitivity and 75% specificity (Roth et al., 2013), few studies have investigated the associations between those tests. The AI is the only method that depends on the toeless foot contact area while the others evaluate different fore- mid- or hindfoot parameters (Wong et al., 2012; Zuil-Escobar et al., 2018). The papers that related correlations between few various tests present moderate to low values between tests but strong values for the inter- and intra-reliability, making them useful and easy to apply in the clinical environment (Cho et al., 2019; Queen et al., 2007; Zuil-Escobar et al., 2018). However, they did not investigate several test correlations, such as the RCSP (Queen et al., 2007; Zuil-Escobar et al., 2018; 2019), AI, or FPI (Zuil-Escobar et al., 2018; 2019).

Given the diversity of methods, this study aims to investigate the correlations between the NDT, RCSP, Arch Angle, FPI, AI, CSI, and SI among subjects with FF and NF conditions.

Materials and Methods

Participants

This observational, correlational descriptive study was carried out at the *RoboCorp Laboratory — Physiotherapy*, at the *Polytechnic Institute of Coimbra* after the *Ethics Committee of Polytechnic Institute of Coimbra* (*13_CEPC2/2019*) approval based on the revised version of the 2013 Declaration of Helsinki (Holt, 2014; Vandenbroucke et al., 2014). The sample size was calculated using the *G*power 3.1.5* software (G* power 3.1.5, Kiel, Germany) based on the study previously published by *Zuil-Escobar et al.* (2018). A required sample size of 13 was determined by achieving an estimated alpha level of 0.05 and a power of 0.95. Consequently, 37 volunteer individuals aged between 18 and 35 years old were recruited for this scientific search. Before any assessment, all subjects were informed about the study's purpose and procedures benefits, and risks involved were explained to each participant. Subjects were guaranteed that they could withdraw at any time without justification and asked to provide informed consent. Thirty-seven volunteers met eligibility (***Table 8.1***). The inclusion in the study was limited to subjects who presented bilateral FF and bilateral NF participants, aged between 18 to 40 years old. The FF group encompassed subjects that presented a > 9 mm NDT score while the NF group involved participants with a 5–9 mm NDT score. All participants were submitted to the NDT to identify whether they had a FF or a NF as this test is clinically used by practitioners worldwide. This procedure was realized by a single physiotherapist with more than 6 years' experience in the use of these techniques. Thus, subjects who presented the following exclusion criteria were not included in this study: (a) ankle sprain in the last 6 months; (b) physiotherapy treatment program or history of an ankle injury; (c) bone fracture associated with an ankle sprain, such as avulsion fracture or osteochondral; (d) ankle surgery; (e) subjects with unilateral FF and NF condition; (f) subjects aged less than 18 and higher than 40 years old; Then, the FF group consisted of 16 bilateral FF participants comprising a total of 32 feet while the NF group consisted of 21 bilateral NF subjects comprising a total of 42 feet.

Table 8.1*: Sample characteristics.*

	N	Minimum	Maximum	Mean	Standard Deviation (SD)
Age (years)	37	18	35	23.10	4.30
Height (m)		1.47	1.85	1.70	9.55
Weight (kg)		46.90	116.00	74.51	15.44

Procedures

Assessment

Both NF and FF conditions were evaluated regarding the same assessment procedure bilaterally in a weight-bearing barefoot stance position. The navicular drop was evaluated using the NDT, where three measurements' mean value defined the navicular drop. The practitioner placed a rigid plastic-made ruler perpendicularly to the ground and registered the ground-navicular bone distance (in millimeters). Then, the practitioner inverted the talus into a neutral position and repeated the procedure. The difference between both assessment positions quantified the navicular drop severity (Sung, 2018). Then, the Rearfoot-to-leg angle was assessed using the RCSP test, where three measurements' mean values defined 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). This angle was measured using a rigid plastic goniometer (Enraf-Nonius B.V, Rotterdam, The Netherlands). Finally, a bilateral digital FootPrint was recorded using a plantar pressure platform with a 100Hz frequency (PhysioSensing-Sensing Future Technologies, Coimbra, Portugal) for further analysis of specific FootPrint parameters, namely the Arch Angle, FPI, AI, CSI, and SI. The FootPrints assessment was realized with subjects in a relaxed upright position, and they were asked to maintain focus on a reference point for 5sec to stabilize the position before recording the data. If any participants failed to maintain their position, the trial was repeated.

Data Processing and Analysis

The primary outcomes collected were the NDT and the RCSP scores, which correspond to mobility foot tests of all subjects during a weight-bearing stance. As secondary outcomes were calculated through the FootPrint parameters, the Arch Angle, FPI, AI, CSI, and SI. The NDT and the RCSP scores were obtained using the mean results of the three collected scores, calculated using the *IBM SPSS Statistics 27.0* software (IBM Corporation, Armonk, NY, USA). With the exception of those, all the FootPrints parameters resulting from the plantar pressure platform assessment were obtained through specific processing steps. All data were initially converted to an image format to be processed using the *Image J* software (National Institute for Health, Rockville, MD, USA). In addition, all Footprint parameters scores were calculated individually by the investigator regarding previously mentioned angles, entire foot contact area and, fore-mid and rearfoot toeless contact area.

Statistical Analysis

The data were statistically processed with the *IBM SPSS Statistics 27.0* software (IBM Corporation, Armonk, NY, USA). The descriptive statistics, mean and standard deviation, were calculated for all variables regarding both groups, the NF, and FF groups. Associations between all tests and indexes were therefore established by *Pearson's* correlation analysis. The level of significance was set at 5% ($p<.05$).

Results

Sample and Groups Characteristics

In the procedure, 32 FF and 42 NF were identified (***Table 8.1***). Subjects were identified and allocated into different groups through the NDT score assessment (***Table 8.2***).

Table 8.2: *Groups characteristics.*

Group	**n**	**NDT** *(mm)*	**RCSP** *(º)*	**AA** *(º)*	**FPI** *(Score)*	**AI** *(Score)*	**CSI** *(Score)*	**SI** *(Score)*
NF	21	5.36 ± *2.31*	2.15 ± *1.74*	43.86 ± *5.34*	0.28 ± *0.05*	0.22 ± *0.06*	0.36 ± *0.14*	0.48 ± *0.20*
FF	16	11.23 ± *1.45*	4.72 ± *1.56*	61.13 ± *12.21*	0.23 ± *0.06*	0.25 ± *0.05*	0.43 ± *0.14*	0.53 ± *0.17*

Mean ± Standard Deviation
NF = neutral foot group; FF = flatfoot group; NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position; AA = Arch Angle; FPI = FootPrint Arch Index; AI = Arch Index; SI: Staheli Index; CSI = Chippaux-Smirak Index.

Neutral Foot Subjects

Considering the result values for the NF group, none of the correlations presented statistically significant results between NDT and the others (*p>.05*) as well as the RCSP correlations (*p>.05*). FootPrint parameters presented absolute values ranging from 0.341 to 0.965, corresponding to a moderate to nearly perfect correlation. All those correlations were statistically significant (p<.05) except for the Arch Angle/SI correlation (***Table 8.3*** and ***Figure 8.1***).

Table 8.3: *Pearson's correlation values of the neutral foot group between all tests.*

		RCSP	**AA**	**FPI**	**AI**	**CSI**	**SI**
NDT	Correlation value	0.267	−0.193	−0.018	−0.011	−0.005	−0.029
	p-value	*.087*	*.259*	*.917*	*.949*	*.978*	*.868*
RCSP	Correlation value		−0.269	0.084	−0.076	−0.052	−0.036
	p-value		*.112*	*.627*	*.658*	*.764*	*.834*
AA	Correlation value			0.443	−0.434	−0.341	−0.303
	p-value			*.007*	*.008*	*.042*	*.072*
FPI	Correlation value				−0.901	−0.850	−0.813
	p-value				*.000*	*.000*	*.000*
AI	Correlation value					0.928	0.918
	p-value					*.000*	.000
CSI	Correlation value						0.965
	p-value						*.000*

NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position; AA = Arch Angle; FPI = FootPrint Index; AI = Arch Index; SI = Staheli Index; CSI = Chippaux-Smirak Index.

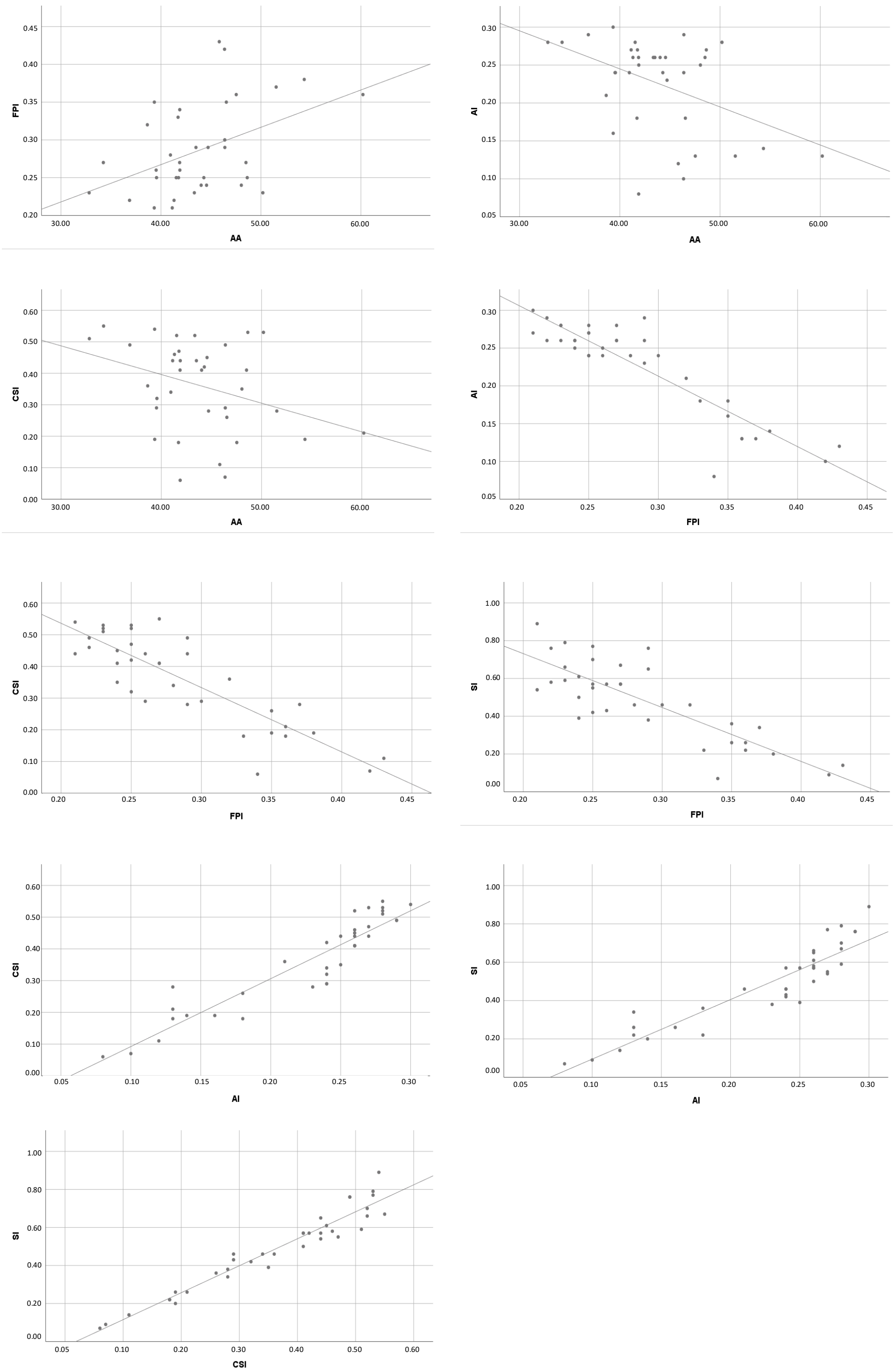


Figure 8.1: *Significant correlations result in neutral foot subjects.*

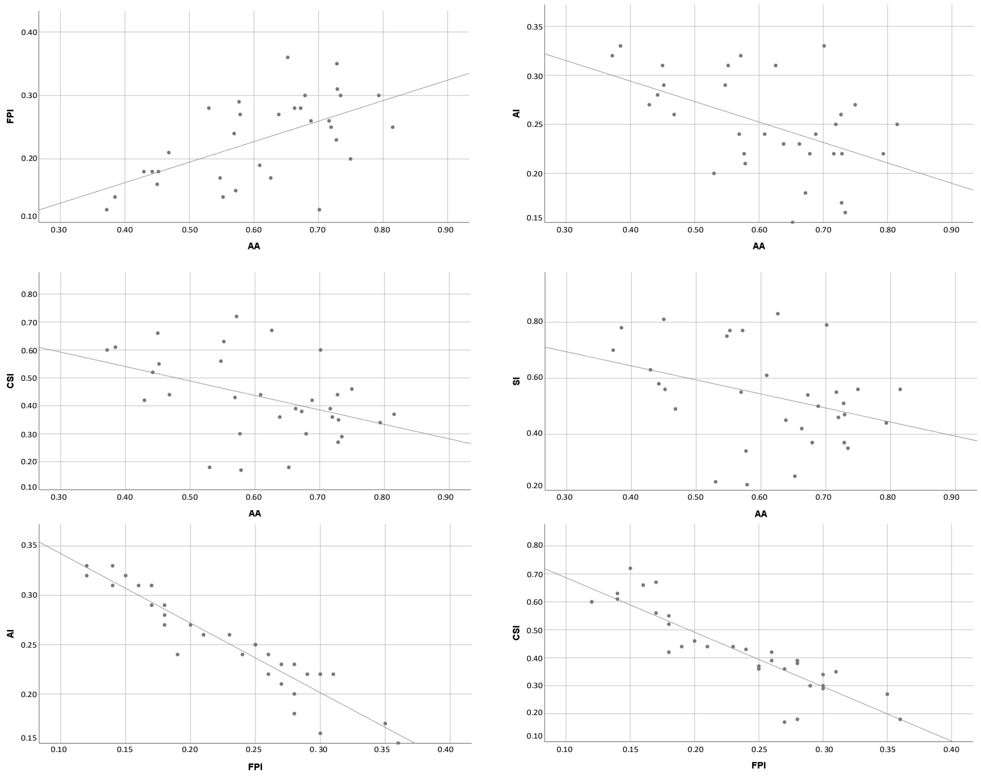
Flat Foot Subjects

Regarding the FF group, none of all correlations presented statistically significant results between NDT and the others (*p>.05*). Alongside these, the RCSP correlations did not present significant results (*p>.05*) either. Otherwise, the other tests, relative to the FootPrint assessment, showed absolute values ranging from 0.353 to 0.955, corresponding to moderate to nearly perfect correlation(Hopkins, 2002). All those correlations were statistically significant (*p<.05*) (***Table 8.4*** and ***Figure 8.2***).

Table 8.4: *Pearson's correlation values of the flatfoot group between all tests.*

		RCSP	**AA**	**FPI**	**AI**	**CSI**	**SI**
NDT	Correlation value	0.279	0.190	0.181	−0.123	−0.224	−0.228
	p-value	*.122*	*.297*	*.321*	*.502*	*.218*	*.208*
RCSP	Correlation value		−0.161	0.079	−0.157	−0.113	−0.100
	p-value		*.378*	*.668*	*.390*	*.539*	*.584*
AA	Correlation value			0.590	−0.509	−0.430	−0.353
	p-value			*.000*	*.003*	*.014*	*.048*
FPI	Correlation value				−0.943	−0.885	−0.868
	p-value				*.000*	*.000*	*.000*
AI	Correlation value					0.906	0.867
	p-value					*.000*	*.000*
CSI	Correlation value						0.955
	p-value						*.000*

NDT = Navicular Drop Test; RCSP = Resting Calcaneal Stance Position; AA = Arch Angle; FPI = FootPrint Index; AI = Arch Index; SI = Staheli Index; CSI = Chippaux-Smirak Index.



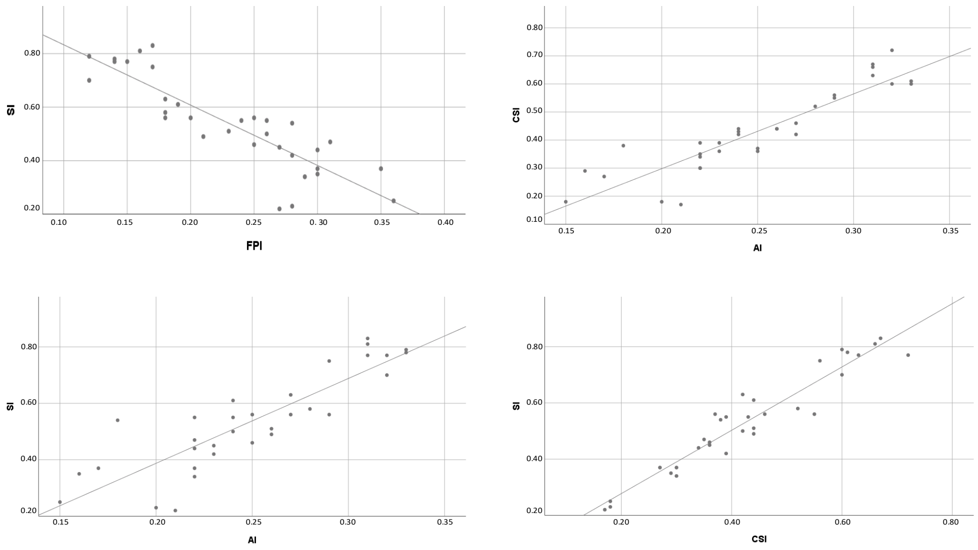


Figure 8.2: *Significant correlations result in flatfoot subjects.*

Discussion

Many studies use these methods to assess foot posture, but few have made a correlation between them. Contrary to our study, previous works regarded just a few tests to assess accuracy, reliability, and correlations, or just with the inclusion of FF subjects or even without foot posture assessment inclusion criteria.

In FF subjects classified by the NDT, we did not find any statistically significant correlations between the RCSP and the NDT (*p>.122* / r=0.279). In our search, no papers relating the association between those two previous tests were found. In addition, no statistically significant correlation was found between the RCSP and any FootPrint parameters (*p>.05*). Our results regarding the NDT correlations with the FootPrint parameters are controversial compared to the two previous papers. We did not find any statistically significant results in the FF (*p>.05*). Though, *Zuil-Escobar et al.* (2019) found in FF subjects, statistically significant results (*p<.01*) between the NDT and the Arch Angle (r=−0.732), SI (r = 0.788), and CSI (r=0.722) where absolute values corresponded to very high correlation values. Alongside this, in another study, *Zuil-Escobar et al.* (2018) found in subjects without any foot posture inclusion criteria, the same statistically significant results (*p<.05*) for several correlations namely the Arch Angle (r=−0.643), SI (r=0.633), and finally CSI (r=0.614). These results and this controversial finding can be due to functional alterations present in FF individuals.

Literature shows that greater and complex mobility of the foot is present in FF compared to NF as well as a larger range of motion variability (Sung, 2018). This greater foot mobility can also lead to further impairments, such as lower limb mechanical imbalance, decreased postural stability, or several pathological complications (Kim et al., 2015; Sung, 2018). Furthermore, *Alonso-Montero et al.* (2020) stated the existence of great variability among foot posture based on the Footprint evaluation realized through the analysis of the angle between the fore- and rearfoot. They referred to a more precise need for footwear adequation to prevent further associated complications. Moreover, the NDT and the RCSP are two tests that do not assess the foot area contact to the ground, instead of FootPrint parameters. *Baumfeld et al.* (2017) found that several tendons and muscle contracture can lead to increased load transfer from the hindfoot to the forefoot. Similarly, *Fernandez-Seguin et al.* (2014) referred to controversial results regarding plantar pressure distribution in NF subjects between fore- and hindfoot distributed pressure load. The NDT refers to midfoot mobility to assess foot posture while the RCSP, to the hindfoot. However, FootPrint parameters suggest the whole assessment of foot posture by sole load distribution. This can lead to an incorrect foot posture assessment, increasing the controversial assessment methods (Sung, 2016). Concerning the FootPrint parameters, few indexes were investigated regarding the entire toeless foot contact with the ground in the FF group. Correlations between the Arch Angle and the remaining FootPrint parameters, which correspond to absolute moderate to high values (r=0.353−0.590), presented statistically significant results (*p<.05*), respectively. Those results follow *Zuil-Escobar et al.* (2019), who found significant results among the Arch Angle/SI and Arch Angle/CSI correlations. However, there was a discordance about the correlation coefficient since the authors found a higher coefficient respectively nearly perfect absolute scores (r=0.901−0.930). Finally, all the correlations between the other FootPrint parameters, the FPI, AI, CSI, and SI, presented statistically significant results (*p=.01*) with absolute very high and nearly perfect coefficient scores (r=0.875−0.964). The CSI/SI correlation followed the results found by *Zuil-Escobar et al.* (2019), which was statistically significant (*p=.01* / r=0.931). Therefore, since the SI is related to the mid-hindfoot and the CSI to the fore-mid foot, this accordance among the CSI/SI correlation can state an entire foot complex analysis and inner relationship.

Likewise, in the NF group, concerning the correlation between the NDT and the RCSP, we did not find a statistically significant correlation (*p>.087* / r=0.267). In this group, the result seemed to be quite identical for the correlations of FPI, AI, CSI, and SI compared to the FF group. Yet only the Arch Angle/SI correlation did not show statistically significant results (*p=.072* / r=−0.303), while the other Arch Angle correlations showed statistically significant results (*p<.05*). These results are in discordance with those found by *Zuil-Escobar et al.* (2018). In their study, the authors related statistically significant results for the Arch Angle, SI, and CSI correlations (*p<.05*), displaying absolute values ranging from 0.838 to 0.881, corresponding to a very high coefficient. Likewise, the SI/CSI correlation statistically significant result (p<.01 / r=0.965) follows those reported by *Zuil-Escobar et al.* (2018) who found a statistically significant positive very high correlation coefficient (*p<.05* / r = 0.881). Though, since the Arch Angle is characterized by the angle between the medial line and the most medial aspect of the midfoot area, the load distribution negatively influences this variable leading to a misunderstanding of the score and thereby, to foot posture assessment (Queen et al., 2007; Tahmasebi et al., 2015; Zuil-Escobar et al., 2018). In addition, in NF subjects, using plantar pressure platforms, authors refer to a slightly higher load on the hindfoot relative to the mid-and forefoot (Fernández-Seguín et al., 2014). Comparing the Arch Angle, SI, and CSI tests, most authors analyze the foot contact area in various ways. The approaches of the different tests are different as the FPI and the AI assess regarding all feet, the CSI considers the fore-mid foot, and the SI the mid-hindfoot relationships. Since the foot is a multiple joints complex with different degrees of freedom, the discordance between tests can happen depending on the sample distribution and, therefore, mislead the Arch Angle accuracy.

Finally, analyzing the means value and standard deviation for each test (***Table 8.2***), some incoherence was found regarding the cut-off values of each foot posture assessment test. Some scores did not reach the cut-off values to diagnose foot posture conditions. For example, regarding the Arch Angle, values greater than 42° correspond to FF conditions (Queen et al., 2007; Tahmasebi et al., 2015; Zuil-Escobar et al., 2018). However, in both groups of our study, the Arch Angle reached values greater than 42°, misleading the NF condition assessment. Interesting results were the FPI score on both groups. The NF present value was superior to 0.28 when the FF showed an opposite score which was 0.23, which is in contradiction to the cut-off value related previously (Tahmasebi et al., 2015). Analyzing the AI score, both mean scores represented the NF condition (0.21<NF< 0.26), which was contradictory with the reference values that related 0.25 score as the FF condition (Tahmasebi et al., 2015; Queen et al., 2007; Menz et al., 2012). Finally, both CSI score means related to a NF condition in either group where the score was inferior to 0.45 and SI score related to CF in the NF group (CF<0.5) and related to NF in the FF group (NF<0.7) (Khanna & Premavathy, 2019; Queen et al., 2007; Zuil-Escobar et al., 2019). Those alterations of the mentioned test showed a false score which can mislead the evaluation and indeed can classify the foot posture antagonistically.

Although this study shares various foot posture test assessments and associations with each other, several limitations can compromise the results. Only subjects who presented bilateral FF conditions using the NDT participated in this study. However, as the foot complex lays on several joints and inter-associations, it will be interesting to evaluate the same correlation regarding the FootPrint parameters' inclusion criterion instead of the NDT or the RCSP, whose assessment of foot posture is based on mobility. Furthermore, as stated previously, only subjects with a bilateral condition, whether FF or NF, were included in this study to include excluded temporary or functional alterations presented in unilateral conditions. Therefore unilateral FF or NF was excluded as stated previously in the exclusion criteria. Another study limitation is the non-characterization of subjects' weight since several authors relate increased weight as a factor to develop higher foot arch values, i.e., FF condition. However, as the main purpose of this study was to investigate the correlation between the different diagnosis methods, the participants' weight was not considered relevant as the study did not investigate condition assessment accuracy. Finally, the participants' recruitment was realized according to convenience sampling methods. Thus, further studies with the inclusion of a random sampling process can ensure a more robust methodology.

Conclusion

Regarding both NF and flatfoot groups, the correlations between those tests presented moderate to nearly perfect coefficient scores to identify NF and flatfoot subjects while using FootPrint parameters. However, the combined use of several FootPrint parameters can be an important evaluation tool in the clinical environment with the understanding of several limitations and costs.

Conflicts of interest statement: The authors declare no conflict of interest.

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CHAPTER IX

CONCLUSION

Following the findings in the studies presented in this thesis, it seems reasonable to stress the following conclusions:

i. There is little evidence for the use of different methods to analyze kinetics and kinematics effects on static and dynamic posture, with a wide diversity of outcomes and intervention protocols, times of assessment, samples included, and outcome measurements used within the available studies. (**Chapter II**)

ii. Posture stability through the Center of Pressure analysis and kinematics alterations were found between FF and NF subjects. However, our results seem to be contradictory to those found in the literature as we did not find any static kinematics pattern, as we only found kinematics alteration relatively to the ankle joint. Other authors specified several alterations present in FF subjects, such as knee hyperextension and internal rotation, coupling with a hip internal rotation, and pelvis anteversion. Also, FF subjects present Center of Pressure characteristics differences when compared to NF subjects, with an increased anteroposterior sway, as well as velocity, amplitude, and mediolateral amplitude. (**Chapter III**)

iii. In the same way, we studied postural stability through linear methods, we intended to analyze postural stability variability applying several methods, namely the ApEn, CD, FD, and LyE, to analyze respectively the regularity, the organization (dimensionality), the complexity of the task as well as the capacity to reply to several perturbations. Only the anteroposterior aspect of the LyE was statistically significantly greater in the NF groups compared to the FF, in the eyes-closed condition. The higher exponent value presented in the NF group corresponds to greater ability and a rapid reply to maintain stability. This showed decrease stability present in FF subjects. (**Chapter IV**)

iv. Consequently, several gait pattern kinematics alterations were presented in FF compared to NF subjects. Differences were found regarding all lower-limb joints and pelvis. We noticed that the alterations comparing static posture and gait pattern were different between groups. Also, differences were found for knee flexion, extension, abduction, and external rotation peak values presented significant differences between groups. And finally, hip flexion, extension, external rotation, pelvis rotation were found. Several amplitude differences were also found concerning the ankle abduction/adduction, knee flexion/extension and abduction/adduction, hip flexion/extension, and rotation, and finally the pelvis rotation. (**Chapter V**)

v. Ultrasound-based Shear Wave Elastography is showed as a novel method to assess diverse pathological and musculoskeletal changes concerning stiffness. In FF subjects, we intend to explore muscle stiffness of the Tibialis Posterior muscle, both for the Superficial and Deep layers. However, no associations between tibialis posterior layers stiffness were found nor any differences between FF and NF subjects (**Chapter VI**). Alongside, we investigated also with the aid of the Shear Wave Elastography the stiffness correlation along with different lower limbs muscles. Thus, no global significant correlation regarding specific muscle stiffness where found, i.e., stiffness analysis cannot be considered as an important indicator to identified myofascial stiffness. (**Chapter VII**)

vi. The assessment of foot posture showed to be controversial as we found results contradictory to the literature. We found that the NDT and the RCSP showed to mislead foot posture condition assessment, unlike Footprints parameters that can be important evaluation tools in a clinical environment. (**Chapter VIII**)

CHAPTER X

SUGGESTION FOR FURTHER STUDIES

FF condition has a huge impact on health politics, and according to the previously found results, it is crucial to conduct a more cost-effective approach to ensure more precise evidence of this condition. Further searches with adults with this condition should be planned based on all achieved knowledge through the studies of this thesis. With those several studies, we intended to answer to gaps and limitations present when investigating the FF condition.

i. Therefore, starting with using the first data collection, we suggest analyzing kinematics changes of FF subjects gait pattern regarding the spatiotemporal characteristics, namely specifying kinematics and kinetics along with stance and oscillation phase. The primary aim of this study is to investigate whether or not the kinematics differences are present during each phase of the gait pattern.

ii. In conjunction with this gait pattern analysis, the muscle activity characteristics through surface Electromyography should be analyzed. The muscular onset of different lower limbs muscles and synergistic activity throughout the gait pattern should be explored.

iii. Also, regarding gait pattern, our analysis was made by the use of linear methods. However, the study of those parameters with novel methodology, i.e., Non-Linear methods, by the use of several indexes and exponent, namely, the *LyE*, *ApEn*, *FD,* and the *CD* should be performed.

iv. Along with novel methods to analyze gait pattern, a different analysis of the gait task, by using absolute joint angles relatively to segment position to the laboratory to calculate *Continuous Relative Phase* should be done. With this approach, the gait phase (*In* or *Out of Phase*) and the movement coordination would be analyzed.

v. Finally, as we later found controversial results concerning foot posture assessment, the Specificity and Sensitivity of the NDT and RCSP must be performed to determine if those tests can be used along with the high predictability of the foot posture condition.

APPENDIXES AND ANNEXES

Appendix A - Correlation between different tests to diagnose flatfoot condition.

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Abstract

The NDT, AA, and the RCSP are different ways to assess foot posture alteration in subjects, a condition that leads to both kinematic and kinetics adaptation along the whole body. This study aims to analyze the relationship between three different tests to assess a FF. Sixteen participants were included in this study and the tests NDT, AA, and RCSP were performed to identify a FF condition. Data didn't show a significant correlation between the tests which can impair the FF condition assessment.

Keywords: Foot posture, foot assessment, footprint, navicular drop, calcaneal angle

Introduction

Foot problems are related to impaired mobility and postural stability, having a detrimental impact on life quality, and are reported as a common concern in the community (Sung, 2016). Foot alignment, as the most distal part of the lower extremity kinematic chain as well as providing support to maintain the body's balance, has an important role in standing and walking (Tahmasebi et al., 2015) and foot alignment alterations affect the spine biomechanics that can lead to spine instability, muscle imbalance and structural adjustments (Farokhmanesh et al., 2014). Besides, changes in foot posture induce altered plantar pressure patterns, which consequently alter the proximal lower limb joints (Angin et al., 2018). Thus, foot posture, through a transformed lower limb motion pattern can induce injuries (Buldt et al., 2013). In FF subjects, the Medial Longitudinal Arch (MLA) varies and can modify plantar pressure patterns along the foot than can affect shock absorption, muscular activity, stability, and therefore gait pattern (Zuil-Escobar et al., 2019). In the literature, authors refer to different methods to assess subjects' foot posture (Cho et al., 2019) including different MLA and Footprint Arch angles (AA), NDT, RCSP, or even AI. Although, all the assessment methods present several limitations depending on the examiner or the chosen test (Cho et al., 2019; Khanna & Premavathy, 2019; Zuil-Escobar et al., 2019). On the other hand, those three tests are simple and can be used quickly in a clinical environment (Cho et al., 2019). Although, those have no side effects on tested subjects (Zuil-Escobar et al., 2018). Though, correlations between the NDT, AA, and RCSP were not previously estimated.

Purpose

The purpose of this study was to investigate the relationship between the NDT, AA, and the RCSP tests in subjects with FF.

Material and Methods

The observational descriptive study was carried out at RoboCorp Laboratory – Physiotherapy, at the Coimbra Health School, at the Polytechnic Institute of Coimbra. The sample consisted of 16 bilateral FF participants (24,75 years ± 5.05 SD) comprising a total of 32 feet. Only the subjects who presented an NDT value of >9mm were included in this study which characterized those as FF. Subjects were assessed using a rigid ruler to measure NDT, a plantar pressure platform (PhysioSensing – Sensing Future Technologies, Coimbra, Portugal) for the AA, and a rigid plastic goniometer for the RCSP. FF condition is considered respectively when the AA value is >42º (Tahmasebi et al., 2015) and RCSP value is >4º (Kim et al., 2015). Data were statistically processed with the IBM SPSS Statistics 25.0 software (IBM Corporation, New York, USA). Before the inferential analysis, the sample presented, associations between NDT, AA, and RCSP were determined by Pearson's correlation analysis (95% CI).

Results

Regarding the values of the correlation, NDT and RCSP presented a 0.397 score which corresponds to a positive moderate coefficient (Figure.1). NDT and AA presented a 0.184 score corresponding to a positive low coefficient and RSCP and AA presented a -0.118 corresponding to a negative low coefficient. However, none presented statistically significant values (*p*>*.05*).

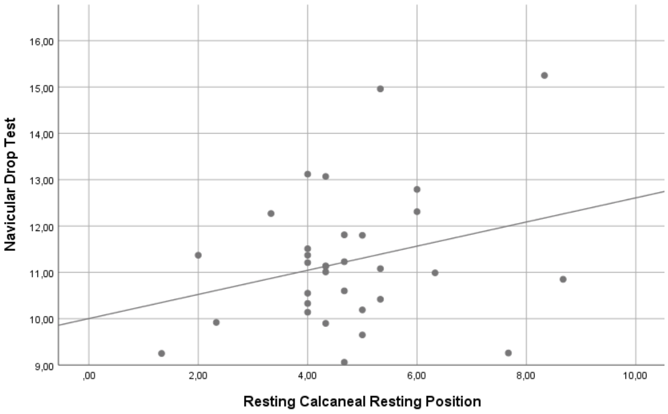

Figure 1. Graphic example for NDT and RCSP correlation

Discussion and Conclusion

This study related the correlations score acquired between the AA, RCSP, and NDT. Regarding FF subjects, the correlations between those tests weren't statistically significant to identified FF. According to these results, the diagnosis accuracy of the FF condition can be compromised depending on the NDT combined with the AA or the RCSP.

Acknowledgments

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Body Keeper Carlos Morgado Santos - Physiotherapy, Osteopathy and Posturology Clinic, Nutrition and Psychology (Coimbra, Portugal).

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Appendix B - Relationship between various tests to diagnose bilateral neutral foot subjects.

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Abstract

To assess foot posture alteration, various tests and indexes can be used to assess the Medial Longitudinal Arch heigh, to further prevent lower limbs injuries. This study aims to assess the relationship between three 3 different tests to categorize neutral-foot subjects. Twenty participants (14 males and 6 females) were included in this study and exposed to the NDT, AA, and the RCSP. Data showed a moderately significant correlation between tests that can decrease the accuracy to identify neutral-foot subjects.

Keywords: Foot posture, medial longitudinal height, footprint, navicular drop, calcaneal angle

Introduction

Since lower limbs postural alterations lead to postural variations in the pelvic girdle and increase low back pain risk, foot alignment should be pondered as an important and effective factor (Farokhmanesh et al., 2014). Foot posture is generally characterized by the alignment of the foot skeleton and varies considerably between individuals (Angin et al., 2018). Foot posture induces plantar pressure patterns alterations, proximal joints motion and neuromotor responses to the altered sensory afferents signals affect muscle function, foot and lower-limb biomechanics (Angin et al., 2018). Those patterns show higher pressure, force, and contact area values in the medial arch, central forefoot, and hallux, while these variables are lower in the lateral and medial forefoot (Buldt, et al., 2018). Thus, foot posture, through altered lower limb motion pattern can induce injuries (Buldt et al., 2013) and have been associated with abnormal foot motion during gait (Buldt et al., 2015). Regarding the existing scientific literature, several tests and indexes can be used to ensure the foot posture type of each individual (Cho et al., 2019; Zuil-Escobar et al., 2019) like the Medial Longitudinal (MLA) and AA, NDT, RCSP. According to *Zuil-Escobar et al.* (2019), the NDT can be useful for clinical settings assessment (Zuil-Escobar et al., 2019). Thought, associations between the NDT, AA, and RCSP were not previously estimated in NF subjects.

Purpose

The aim of this study was to investigate the association between the NDT, AA, and the RCSP tests in subjects with bilateral NF subjects.

Material and Methods

This observational descriptive study was carried out at the RoboCorp Laboratory – Physiotherapy, at the Coimbra Health School - Polytechnic Institute of Coimbra. Twenty bilateral NF participants (21.90 years ± 3.31 SD) were included in the sample, comprising a total of 40 feet. Subjects who presented an NDT value of >9mm were excluded to restrain the inclusion of only NF individuals. The procedure includes an analysis of the NDT using a plastic-made ruler, the AA with the aid of a plantar pressure platform (PhysioSensing – Sensing Future Technologies, Coimbra, Portugal), and finally the RCSP with a rigid plastic goniometer. NF condition is considered respectively when RCSP value is <4º (Kim et al., 2015) and thereby the AA value is <42º (Tahmasebi et al., 2015). The *IBM SPSS Statistics 25.0* software (IBM Corporation, New York, USA) was used to statistically process all the extracted data. Associations between NDT, AA, and RCSP were therefore established by Pearson's correlation analysis (95% CI).

Results

According to the results of the correlation, NDT and RCSP presented a 0.326 score which corresponds to a positive moderate coefficient (Figure.1) with statistical significance (*p=.05*). NDT and AA presented a -0.179 score corresponding to a negative low coefficient and RSCP and AA presented a -0.328 corresponding to a negative moderate coefficient. Although, those last ones didn't present statistically significant results (*p>.05*).

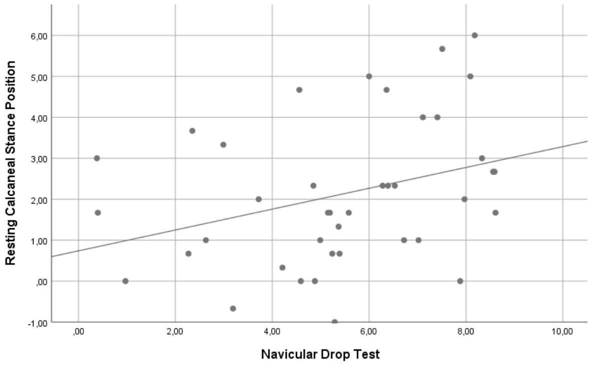

Figure 1 – Graphic example for NDT and RCSP correlation

Discussion and Conclusion

The associations between three different foot posture assessment procedure were related in this study Regarding NF subjects, correlations presented a moderate score value to identified NF. Thereby, the accuracy of the NF subjects can be examiner-depending, regarding the combination of the selected procedures. However, the combined use of both NDT and AA or even RCSP and AA can impair the NF condition evaluation regarding the lack of significance revealed by the present study.

Acknowledgments

RoboCorp laboratory co-funded by QREN under the Programa Mais Centro, of the Coordination Commission of the Central Region and the European Union through the European Regional Development Fund.

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Cho, Y., Park, J.-W., & Nam, K. (2019). The relationship between foot posture index and resting calcaneal stance position in elementary school students. Gait & Posture, 74(August), 142–147.

Farokhmanesh, K., Shirzadian, T., Mahboubi, M., & Shahri, M. N. (2014). Effect of Foot Hyperpronation on Lumbar Lordosis and Thoracic Kyphosis in Standing Position Using 3-Dimensional Ultrasound-Based Motion Analysis System. Global Journal of Health Science, 6(5), 254–260.

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Appendix C - Flat foot condition diagnosis regarding different methods.

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Background:

Flat-footed subjects present a medial longitudinal arch collapse that modifies plantar pressure pattern, therefore influencing negatively shock absorption, muscular function, postural stability, and gait pattern (Buldt et al., 2013; Kim et al., 2015; Sung, 2016). Several authors reported different methodologies to analyze foot posture, for instance, the NDT, FPI, AI, CSI, and SI (Zuil-Escobar et al., 2018). The first is considered a clinical, examiner-reliable test and the others need a plantar pressure assessment. All methods present several limitations which depend on the chosen one (Cho et al., 2019).

Objectives: This study's purpose was to analyze the relationship between the NDT, FPI, AI, CSI, and SI in flat-footed subjects.

Methods: An observational descriptive study was realized at the *RoboCorp Laboratory-Physiotherapy* (Polytechnic Institute of Coimbra, Portugal). Sixteen bilateral flatfooted subjects were included in the study. Only subjects who presented a NDT value of <9mm were included using a ruler. Therefore, all participants were submitted to a plantar pressure platform assessment in a weight-bearing barefoot stance position using a plantar pressure platform (PhysioSensing, Coimbra, Portugal). Data were processed using the *Image J* software (National Institute for Health, Bethesda, USA) and, statistically analyzed using the *IBM SPSS Statistics 25.0* software (IBM Corporation, New York, USA) where associations between all methods were determined using the Pearson's correlation analysis (*95% ICC*).

Results: Correlations values between NDT and FootPrint parameters didn't present statistically significant values (*p>0.05*). However, correlations among FootPrint methods present statistically significant results (p<0.001) with a score ranging from very high to nearly perfect (r=0.867-0.955).

Conclusions: Regarding both assessment methods and parameters, the combined use of several FootPrint parameters can be an important evaluation tool in a clinical environment while the use of NDT can mislead the accuracy of the flat-footed condition.

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Keywords: Foot posture, footprint parameters, baropodometry

References:

Buldt, A. K., Murley, G. S., Butterworth, P., Levinger, P., Menz, H. B., & Landorf, K. B. (2013). The relationship between foot posture and lower limb kinematics during walking: A systematic review. Gait and Posture, 38(3), 363–372.

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Appendix D - Postural stability assessment in flatfoot subjects through Lyapunov Exponent analysis.

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Background:

FF subjects present an increased plantar foot area which is related to a plantar pressure feedback impairment. The LyE is considered a nonlinear parameter used to characterize a signal chaotic behavior measuring the information rate loss from time series, i.e., for the Center of Pressure data. This exponent is used to quantify and measure the capability and resistance of subjects to several perturbations. The study's purpose was to investigate the postural stability differences among foot posture conditions through the LyE analysis.

Methods:

The sample of the observation descriptive study consisted of 31 participants (*23.26 yo ± 4.43 SD*) comprising a total of 62 feet, where 15 integrated into the experimental group with bilateral FF condition and the remaining 16 in the control group with the bilateral NF condition. Subjects were screened, before posture analysis, using the NDT and RCSP test, to characterize each group. All participants were subjected to a bipedal weight-bearing stance posture stability analysis of a force platform, both in eyes-open and closed condition. Therefore, the LyE was calculated using the *Matlab-R2020b* (*MathWorks Inc., USA*) software. Data were statistically processed with the *IBM SPSS Statistics 27.0* software (*IBM Corporation, New York, USA)*. The differences between the groups were assessed according to the *T-test for independent samples* and the differences between condition assessments were assessed according to the *T-test for paired samples*. The level of significance was set at 5% ($p<.05$).

Results:

Regarding the CoP outcomes, only the LyE value upon the Antero-posterior component regarding groups in the eyes closed condition (*diff=3.09°*, $p=.016$) presented a significant result.

Conclusion:

FF subjects present a significant difference compared to NF participants, in bipedal weight-bearing stance, in the EC condition regarding the LyE. This relates to increase variability and decrease stability regarding the Antero-

Posterior component.

Keywords: Foot Posture; Center of Pressure, pés planus, non-linear analysis.

Appendix E - Association among different methods for neutral foot condition diagnosis

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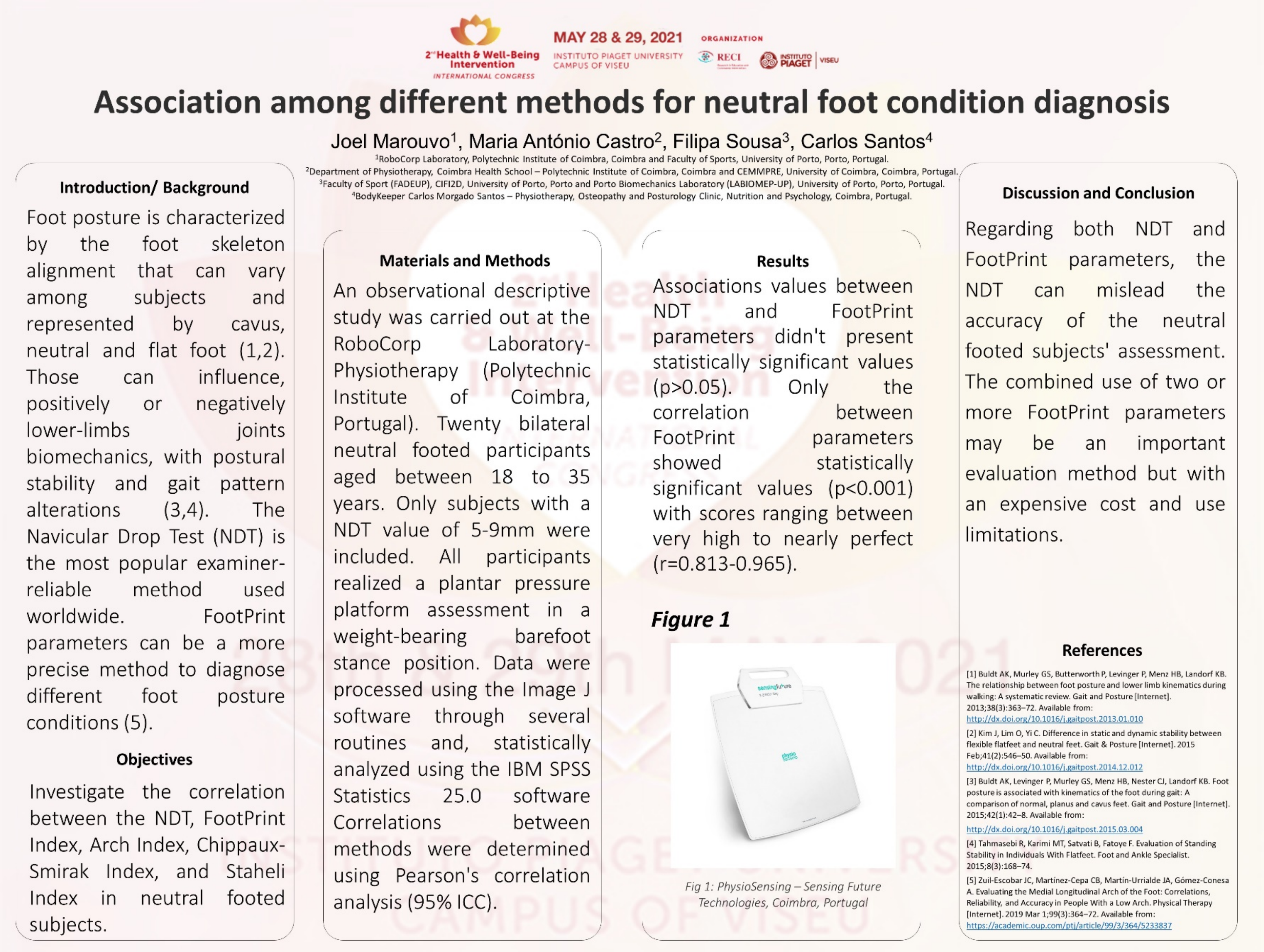

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Association among different methods for neutral foot condition diagnosis

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Introduction/ Background

Foot posture is characterized by the foot skeleton alignment that can vary among subjects and represented by cavus, neutral and flat foot (1,2). Those can influence, positively or negatively lower-limbs joints biomechanics, with postural stability and gait pattern alterations (3,4). The Navicular Drop Test (NDT) is the most popular examiner-reliable method used worldwide. FootPrint parameters can be a more precise method to diagnose different foot posture conditions (5).

Objectives

Investigate the correlation between the NDT, FootPrint Index, Arch Index, Chippaux-Smirak Index, and Staheli Index in neutral footed subjects.

Materials and Methods

An observational descriptive study was carried out at the RoboCorp Laboratory-Physiotherapy (Polytechnic Institute of Coimbra, Portugal). Twenty bilateral neutral footed participants aged between 18 to 35 years. Only subjects with a NDT value of 5-9mm were included. All participants realized a plantar pressure platform assessment in a weight-bearing barefoot stance position. Data were processed using the Image J software through several routines and, statistically analyzed using the IBM SPSS Statistics 25.0 software Correlations between methods were determined using Pearson's correlation analysis (95% ICC).

Results

Associations values between NDT and FootPrint parameters didn't present statistically significant values (p>0.05). Only the correlation between FootPrint parameters showed statistically significant values (p<0.001) with scores ranging between very high to nearly perfect (r=0.813-0.965).

Figure 1

Fig 1: PhysioSensing – Sensing Future Technologies, Coimbra, Portugal

Discussion and Conclusion

Regarding both NDT and FootPrint parameters, the NDT can mislead the accuracy of the neutral footed subjects' assessment. The combined use of two or more FootPrint parameters may be an important evaluation method but with an expensive cost and use limitations.

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Appendix F- Bipedal weight-bearing stance postural kinematic analysis in flatfoot subjects.

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Bipedal weight-bearing stance postural kinematic analysis in flatfoot subjects

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INTRODUCTION

Foot posture alignment has been associated with lower-limbs abnormal motion and altered postural stability. In flatfoot subject, the risk of developing mechanical overloading injuries is higher compared to control subjects. This alteration can induce knee pain, cartilage damage, medial tibial stress syndrome, or sacroiliac joint dysfunction.

OBJECTIVES

The study aim was to investigate the overall kinematics differences among foot posture condition.

METHODOLOGY

An observational descriptive study was carried out at the *RoboCorp Laboratory – Physiotherapy*, at the *Polytechnic Institute of Coimbra*. The sample consisted in 31 participants (*23.26±4.43 years*), where 15 participants joined the bilateral flatfoot group and the remaining 16 bilateral neutral-foot group. Subjects were screened, prior to kinematic posture analysis, using the ***Navicular Drop Test*** and ***Resting Calcaneal Stance Position*** test, to characterize each group. All participants realized a bipedal weight-bearing stance assessment, using ***3D-Motion Capture system*** and a ***force platform***. Data were statistically processed with the *IBM SPSS Statistics 27.0* software (*IBM Corporation, New York, USA*). The differences between the groups were assessed according to the T-test for independent samples and *U-Mann Whitney (ICC 95%).*

RESULTS

Considering the kinematics outcomes, the only statistically significant results found were concerning the ankle joint namely in the sagittal *(d=1.93°, p=.047)*, coronal *(d=2.62°, p=.013)* and transverse *(d=5.02°, p=.001)* planes.

Conclusion

Flatfoot subjects presents few alterations compared to neutral-foot participants, in bipedal weight-bearing stance. Those results can be translated in a drop of the Navicular bone and the entire Medial Longitudinal Arch collapse, i.e., alterations that are present in flatfoot subjects.

Table 1. Groups kinematics characteristics in Eyes Open assessment

		NF	FF	p-value
Ankle (º)	*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 (º)	*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 (º)	*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 (º)	*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.

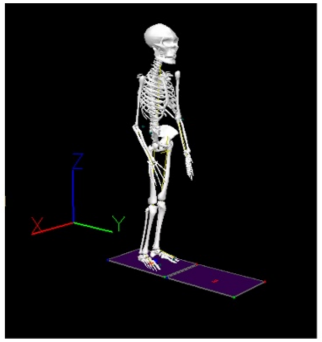

Figure 1. Posture assessment

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Appendix G - Postural stability analysis in flatfoot subjects.

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Postural stability analysis in flatfoot subjects

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INTRODUCTION

Stability requires cognitive resources to process somatosensory input, any additional process can reduce stability maintenance, increasing fall risk. Flatfoot subjects presents plantar foot area increase compared to neutral-foot subjects which can impair the plantar pressure feedback, resulting in the other receptors system compensation for maintaining postural stability.

OBJECTIVES

The study purpose was to investigate the postural stability differences among foot posture condition.

METHODOLOGY

An observational descriptive study was carried out at the *RoboCorp Laboratory – Physiotherapy*, at the *Polytechnic Institute of Coimbra*. The sample consisted in 31 participants (*23.26±4.43* years), where 15 participants joined the bilateral flatfoot group and the remaining 16 bilateral neutral-foot group. Subjects were screened, prior to kinematic posture analysis, using the ***Navicular Drop Test*** and ***Resting Calcaneal Stance Position test***, to characterize each group. All participants realized a bipedal weight-bearing stance assessment, using ***3D-Motion Capture system*** and a ***force platform***. Data were statistically processed with the *IBM SPSS Statistics 27.0* software (*IBM Corporation, New York, USA*). The differences between the groups were assessed according to the *T-test for independent samples* and *U-Mann Whitney* (*ICC 95%*).

RESULTS

Regarding the ***Center of Pressure*** outcomes, no statistically significant results were found (*p>.05*) between groups.

Conclusion

Considering the Center of Pressure characteristics, flatfoot subjects did not presented alterations compared to neutral-foot participants, in bipedal weight-bearing stance. Considering the lack of consensus among evidence further studies need to encompass methodological variables handling to focus only on foot alteration.

Table 1. *Center of Pressure* characteristics

		NF	**FF**	**p-value**
Excursion (mm)	*Total*	-3.77 ± 3.91	-1.83 ± 3.54	0.047
	Antero-Posterior	-8.38 ± 3.63	-5.75 ± 4.34	0.013
	Medio-Lateral	-13.31 ± 6.15	-8.29 ± 4.96	0.001
Velocity *(mm/s)*	*Total*	-2.07 ± 5.88	-3.88 ± 4.98	0.198
	Antero-Posterior	1.42 ± 4.26	0.65 ± 5.44	0.536
	Medio-Lateral	18.05 ± 10.57	16.10 ± 6.62	0.393
Amplitude *(mm)*	*Antero-Posterior*	-1.48 ± 9.40	-1.08 ± 7.67	0.856
	Medio-Lateral	-0.62 ± 3.68	-1.93 ± 5.29	0.268
Area *(mm^2)*		-9.13 ± 7.93	-9.47 ± 5.97	0.894

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

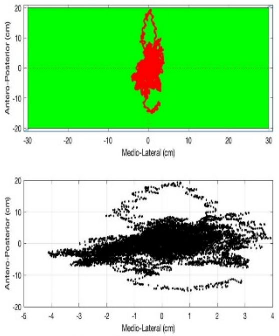

***Figure 1**. Stabilogram*

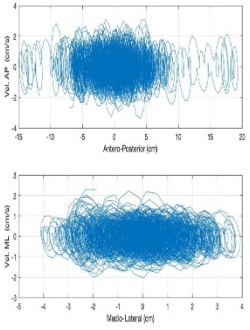

***Figure 2:** Phase graph*

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Acknowledgements: ROBOCORP laboratory co-funded by QREN under the Programa Mais Centro, of the Coordination Commission of the Central Region and the European Union through the European Regional Development Fund.

Appendix H - Postural stability assessment in flatfoot subjects through - Approximate Entropy analysis.

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Postural stability assessment in flatfoot subjects trough Approximate Entropy analysis

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INTRODUCTION

Stability requires cognitive resources to process somatosensory input, any additional process can reduce stability maintenance, increasing fall risk. The Approximate Entropy is a method that quantifies the postural stability by measuring the irregularity, and randomness of the Center of Pressure during upright standing. Therefore, to analyze the ***Approximate Entropy*** results, it is considered that a small value will indicate a higher probability of regularly repeating sequences, a zero value will correspond to a perfectly repeatable motion and finally, a value of 2 corresponds to a random time series.

OBJECTIVES

This study aims to investigate the postural stability differences in flat foot subjects through the ***Approximate Entropy*** analysis.

METHODOLOGY

This observation study was realized at the *RoboCorp Laboratory – Physiotherapy*, at the *Polytechnic Institute of Coimbra*. The sample of 31 participants (*23.26 yo ± 4.43* SD) comprising a total of 62 feet, where 15 integrated into the experimental group with bilateral flatfoot condition and the remaining 16 in the control group with the bilateral neutral foot condition. Subjects were screened, before posture analysis, using the Navicular Drop Test and ***Resting Calcaneal Stance Position test***, to characterize each group. All participants were subjected to a bipedal weight-bearing stance posture stability analysis a force platform, both in eyes-open and closed condition. Therefore, the ***Approximate Entropy*** was calculated using the Matlab-R2020b (*MathWorks Inc., USA*) software. Data were statistically processed with the *IBM SPSS Statistics 27.0* software (*IBM Corporation, New York, USA*). The differences between the groups were assessed according to the T-test for independent samples and the differences between condition assessments were assessed according to the T-test for paired samples. The level of significance was set at 5% (p<.05).

RESULTS

Among groups and condition, no statistically significant results were found (*p>.05*) in the postural stability analysis.

Table 1. *Center of Pressure* characteristics

Excursion *(score)*	**Eyes-Open**			**Eyes-Closed**			**EO vs EC**
	NF	**FF**	*p-value*	**NF**	**FF**	*p-value*	*p-value*
Antero-Posterior	1.03 ± *0.23*	1.15 ± *0.22*	*0.143*	1.04 ± *0.27*	1.07 ± *0.32*	*0.616*	*0.694*
Medio-Lateral	1.22 ± *0.23*	1.19 ± *0.35*	*0.795*	1.21 ± *0.37*	1.19 ± *0.34*	*0.887*	*0.919*

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

Conclusion

Regarding the ***Center of Pressure*** data, for the Approximate Entropy analysis, no differences were found between groups or condition, which corresponds to an identical postural stability between groups. However, regarding methodological deficiency regarding influencing aspects, further studies need to encompass methodological variables handling to focus only on foot alteration.

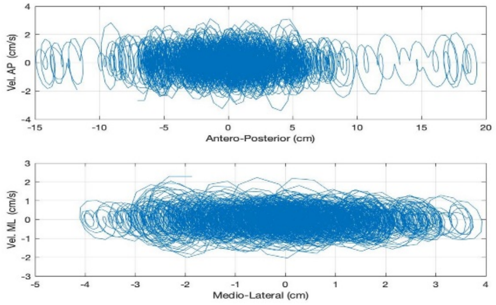

Figure 1: *Phase graph*

References: ***1.*** Colebatch JG, Govender S, Dennis DL. Postural responses to anterior and posterior perturbations applied to the upper trunk of standing human subjects. Experimental Brain Research. 2016;234(2):367-376. ***2.*** Feldman AG. The Relationship Between Postural and Movement Stability. In: Laczko J, Latash ML, eds. Vol 957. Advances in Experimental Medicine and Biology. Cham: Springer International Publishing; 2016:105-120. ***3.*** Kędziorek J, Błażkiewicz M. Nonlinear measures to evaluate upright postural stability: A systematic review. Entropy. 2020;22(12):1-24. ***4.*** Shokouhyan SM, Davoudi M, Hoviattalab M, et al. Linear and Non-linear Dynamic Methods Toward Investigating Proprioception Impairment in Non-specific Low Back Pain Patients. Frontiers in Bioengineering and Biotechnology. 2020;8(November):1-12. ***5.*** Rogers MW, Mille M. Balance Perturbations. Vol 159. 1st ed. Elsevier B.V.; 2018. ***6.*** Peterka RJ. Sensory integration for human balance control. In: Handbook of Clinical Neurology. Vol 159. 1st ed. Elsevier B.V.; 2018:27-42. ***7.*** Mackinnon CD. Sensorimotor Anatomy of Gait , Balance , and Falls. Vol 159. 1st ed. Elsevier B.V.; 2018. ***8.*** 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. Archives of Gerontology and Geriatrics. 2011;53(3):338-343. ***9.*** Rogers MW, Mille M. Balance Perturbations. Vol 159. 1st ed. Elsevier B.V.; 2018. ***10.*** Dakin CJ, Rosenberg A. Gravity Estimation and Verticality Perception. Vol 159. 1st ed. Elsevier B.V.; 2018. ***11.*** Sung PS. The ground reaction force thresholds for detecting postural stability in participants with and without flat foot. Journal of Biomechanics. 2016;49(1):60-65. ***12.*** Harbourne RT, Stergiou N. Movement Variability and the Use of Nonlinear Tools: Principles to Guide Physical Therapist Practice. Physical Therapy. 2009;89(3):267-282. ***13.*** Stergiou N. Nonlinear Analysis for Human Movement Variability. 4th ed. (Stergiou N, ed.). CRC Press - Taylor & Francis; 2018. ***14.*** Treger I, Mizrachi N, Melzer I. Open-loop and closed-loop control of posture: Stabilogram-diffusion analysis of center-of-pressure trajectories among people with stroke. Journal of Clinical Neuroscience. 2020;78(xxxx):313-316. ***15.*** Cavanaugh JT, Mercer VS, Stergiou N. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: A methodological report. Journal of NeuroEngineering and Rehabilitation. 2007;4:1-7. ***16.*** Ghofrani M, Olyaei G, Talebian S, Bagheri H, Malmir K. Test-retest reliability of linear and nonlinear measures of postural stability during visual deprivation in healthy subjects. Journal of Physical Therapy Science. 2017;29(10):1766-1771.

Acknowledgements: ROBOCORP laboratory co-funded by QREN under the Programa Mais Centro, of the Coordination Commission of the Central Region and the European Union through the European Regional Development Fund.

Appendix I - Tibialis posterior muscle stiffness assessment regarding foot posture, by ultrasound-based Shear-Wave Elastography.

Joel Marouvo[1,2,*], Filipa Sousa[3,4], Maria Alexandra André[5], Maria António Castro[6,7]

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ESTeSC Coimbra Health School

ANNUAL MEETING 2021 | 17-19 junho

ID27684

Tibialis posterior muscle stiffness assessment regarding foot posture, by ultrasound-based Shear-Wave Elastography

Marouvo J[1,2], Sousa F[3,4], André MA[5], Castro MA[6,7]

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INTRODUCTION

Flatfoot subjects present greater foot complex mobility with a predisposition for developing adjacent overloading injuries. Foot and ankle joint biomechanics impairment can lead to muscle and tendon pathologies regarding ***Tibialis posterior*** muscle. Ultrasound assessment of muscle stiffness can be useful to injuries risk factors identification-based Shear-Wave Elastography. The study purpose was to investigate the ***Tibialis posterior deep*** and ***superficial layers*** stiffness differences between flat- and neutral-foot subjects.

OBJECTIVES

The study purpose was to investigate the ***Tibialis posterior deep*** and ***superficial layers*** stiffness differences between flat- and neutral-foot subjects.

METHODOLOGY

This observational descriptive study was realized at the *RoboCorp Laboratory – Physiotherapy*, at the Polytechnic Institute of Coimbra. Eighteen subjects were recruited for this study (*22.7±4.5 years*). Nine subjects were included in the flatfoot group and the others in the neutral-foot group. Inclusion criteria in the flatfoot group encompassed subjects that presented a *>9mm* ***Navicular Drop Test*** score. All participants realized a *Tibialis posterior* stiffness assessment with the help of **Ultrasound base Shear-Wave Elastography** (*Acuson Sequoia Ultrasound System 2018, Siemens Healthcare GmbH, Erlangen, Germany*). Data were statistically processed with the *IBM SPSS Statistics 25.0* software (*IBM Corporation, New York, USA*) where group differences were assessed using the *U-Mann Whitney* test (*95% ICC*).

RESULTS

Regarding both groups and layers, no statistically significant differences between groups were found (*p=0.424/0.258*).

Conclusion

This study related the stiffness differences among foot posture. However, stiffness analysis in this study cannot be considered as an important indicator to analyze flatfoot nor neutral-foot subjects.

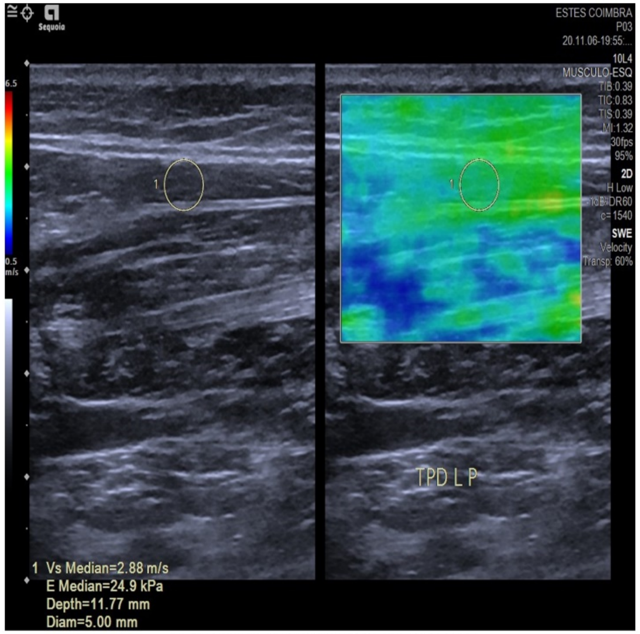

Figure 1: Tibialis Posterior Superficial Layer assessment

References: ***1.*** 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. ***2.*** Caravaggi P, Sforza C, Leardini A, Portinaro N, Panou A. Effect of plano-valgus foot posture on midfoot kinematics during barefoot walking in an adolescent population. J Foot Ankle Res 2018;11:1–9. ***3.*** 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. ***4***. 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. ***5.*** Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An KN. Validation of shear wave elastography in skeletal muscle. J Biomech 2013;46:2381–7. ***6.*** Kelly JP, Koppenhaver SL, Michener LA, Proulx L, Bisagni F, Cleland JA. Characterization of tissue stiffness of the infraspinatus, erector spinae, and gastrocnemius muscle using ultrasound shear wave elastography and superficial mechanical deformation. J Electromyogr Kinesiol 2018;38:73–80. ***7.*** Le Sant G, Nordez A, Andrade R, Hug F, Freitas S, Gross R. Stiffness mapping of lower leg muscles during passive dorsiflexion. J Anat 2017;230:639–50. ***8.*** Creze M, Nordez A, Soubeyrand M, Rocher L, Maître X, Bellin M. Shear wave sonoelastography of skeletal muscle : basic principles, biomechanical concepts, clinical applications, and future perspectives 2017. ***9.*** Koppenhaver S, Kniss J, Lilley D, Oates M, Fernández-de-las-peñas C, Maher R, et al. Reliability of ultrasound shear-wave elastography in assessing low back musculature elasticity in asymptomatic individuals. J Electromyogr Kinesiol 2018;39:49–57. ***10.*** Dubois G, Kheireddine W, Vergari C, Bonneau D, Thoreux P, Rouch P, et al. Reliable Protocol for Shear Wave Elastography of Lower Limb Muscles at Rest and During Passive Stretching. Ultrasound Med Biol 2015;41:2284–91. ***11.*** Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control Trans Ultrason Ferroelectr Freq Control 2004;51:396–409. ***12.*** Mendes B, Firmino T, Oliveira R, Neto T, Infante J, Vaz JR. Hamstring stiffness pattern during contraction in healthy individuals : analysis by ultrasound-based shear wave elastography. Eur J Appl Physiol 2018;0:0. ***13.*** Saeki J, Ikezoe T, Nakamura M, Nishishita S, Ichihashi N. The reliability of shear elastic modulus measurement of the ankle plantar flexion muscles is higher at dorsiflexed position of the ankle. J Foot Ankle Res 2017;10:1–6. ***14.*** Saeki J, Nakamura M, Nakao S, Fujita K, Yanase K, Ichihashi N. Muscle stiffness of posterior lower leg in runners with a history of medial tibial stress syndrome. Scand J Med Sci Sport 2018;28:246–51.

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Appendix J - Tibialis posterior muscle stiffness analysis, by ultrasound-based Shear-Wave Elastography

Joel Marouvo[1,2,*], Filipa Sousa[3,4], Maria Alexandra André[5], Maria António Castro[6,7]

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ANNUAL MEETING
2021 | 17-19 junho

ID27721

Tibialis posterior muscle stiffness analysis, by ultrasound-based Shear-Wave Elastography

MAROUVO J[1,2], SOUSA F[3,4], ANDRÉ MA[5], CASTRO MA[6,7]

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INTRODUCTION

The most affected muscle concerning flatfoot condition is the ***Tibialis Posterior*** that can further lead to developing medial tibial stress syndrome or muscle and tendon pathologies. It presents two layers that can be evaluated, the deep and superficial layer. ***Ultrasound based Shear-Wave Elastography*** was developed to assess in real-time, in vivo muscle stiffness to quantify elasticity and stiffness. Thereby, it can provide a localized estimation of muscle stiffness and can be useful to assess injuries risk factors.

OBJECTIVES

The aim of this study was to analyze the association between ***Tibialis posterior deep*** and ***superficial layers*** stiffness.

METHODOLOGY

An observational descriptive study was carried out at the *RoboCorp Laboratory – Physiotherapy*, at the *Polytechnic Institute of Coimbra*. The sample was composed by 18 subjects (22.7±4.5 years) after meeting several inclusion criteria. All participants realized a ***Tibialis posterior*** stiffness assessment with the help of ***Ultrasound base Shear-Wave Elastography*** (*Acuson Sequoia Ultrasound System 2018, Siemens Healthcare GmbH, Germany*). Data were statistically processed with the *IBM SPSS Statistics 25.0* software *(IBM Corporation, New York, USA)* where association between ***Tibialis Posterior deep*** and ***superficial layer*** were determined by *Pearson's* correlation analysis (95% ICC).

RESULTS

Regarding the layers correlation, no statistically significant result was found (p=0.194 / r=-0.225).

Conclusion

This study related the stiffness correlation regarding the ***deep*** and ***superficial layer*** of the ***Tibialis Posterior*** muscle. Stiffness analysis correlation among intramuscular layers cannot be considered as an important indicator to analyze globally this muscular complex.

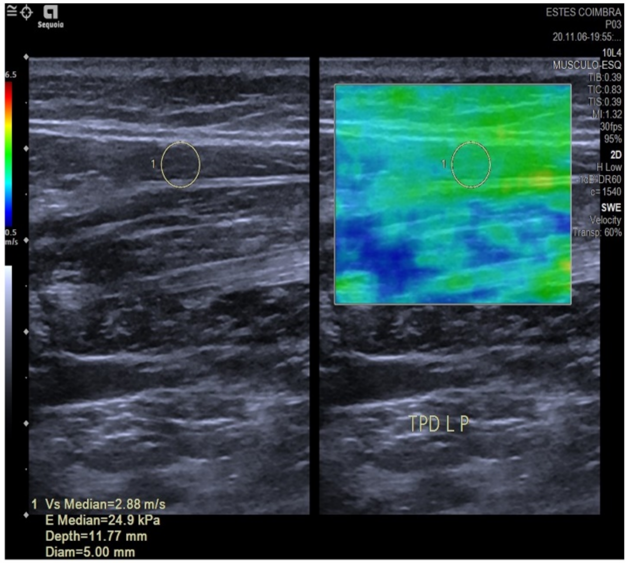

Figure 1: Tibialis Posterior Superficial Layer assessment

References: ***1***. 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. ***2.*** Caravaggi P, Sforza C, Leardini A, Portinaro N, Panou A. Effect of plano-valgus foot posture on midfoot kinematics during barefoot walking in an adolescent population. J Foot Ankle Res 2018;11:1–9. ***3.*** 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. ***4***. 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. ***5.*** Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An KN. Validation of shear wave elastography in skeletal muscle. J Biomech 2013;46:2381–7. ***6.*** Kelly JP, Koppenhaver SL, Michener LA, Proulx L, Bisagni F, Cleland JA. Characterization of tissue stiffness of the infraspinatus, erector spinae, and gastrocnemius muscle using ultrasound shear wave elastography and superficial mechanical deformation. J Electromyogr Kinesiol 2018;38:73–80. ***7.*** Le Sant G, Nordez A, Andrade R, Hug F, Freitas S, Gross R. Stiffness mapping of lower leg muscles during passive dorsiflexion. J Anat 2017;230:639–50. ***8.*** Creze M, Nordez A, Soubeyrand M, Rocher L, Maître X, Bellin M. Shear wave sonoelastography of skeletal muscle : basic principles, biomechanical concepts, clinical applications, and future perspectives 2017. ***9.*** Koppenhaver S, Kniss J, Lilley D, Oates M, Fernández-de-las-peñas C, Maher R, et al. Reliability of ultrasound shear-wave elastography in assessing low back musculature elasticity in asymptomatic individuals. J Electromyogr Kinesiol 2018;39:49–57. ***10.*** Dubois G, Kheireddine W, Vergari C, Bonneau D, Thoreux P, Rouch P, et al. Reliable Protocol for Shear Wave Elastography of Lower Limb Muscles at Rest and During Passive Stretching. Ultrasound Med Biol 2015;41:2284–91. ***11.*** Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control Trans Ultrason Ferroelectr Freq Control 2004;51:396–409. ***12.*** Mendes B, Firmino T, Oliveira R, Neto T, Infante J, Vaz JR. Hamstring stiffness pattern during contraction in healthy individuals : analysis by ultrasound-based shear wave elastography. Eur J Appl Physiol 2018;0:0. ***13.*** Saeki J, Ikezoe T, Nakamura M, Nishishita S, Ichihashi N. The reliability of shear elastic modulus measurement of the ankle plantar flexion muscles is higher at dorsiflexed position of the ankle. J Foot Ankle Res 2017;10:1–6. ***14.*** Saeki J, Nakamura M, Nakao S, Fujita K, Yanase K, Ichihashi N. Muscle stiffness of posterior lower leg in runners with a history of medial tibial stress syndrome. Scand J Med Sci Sport 2018;28:246–51.

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Appendix K - Muscle stiffness differences regarding foot posture by ultrasound-based Shear-Wave Elastography.

Joel Marouvo[1,2,*], Maria António Castro[3,4], Maria Alexandra André[5], Rui Mendes[1,6,7], and Filipa Sousa[8,9].

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ANNUAL MEETING
2021 | 17-19 junho

ID27789

Muscle stiffness differences regarding foot posture by ultrasound-based Shear-Wave Elastography

MAROUVO J[1,2], CASTRO MA[1,3,4], ANDRÉ MA[5], MENDES R[1,6,7], SOUSA F[8,9]

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INTRODUCTION

Foot posture, through altered lower limb motion pattern can induce injuries and have been associated with abnormal foot motion during gait. In late stance-early swing, ***Rectus Femoris*** muscle activity increase to control knee flexion. Muscle stiffness assessment can help in the injuries risk factors identification while coupling with ***Ultrasound based Shear-Wave Elastography*** for its management.

OBJECTIVES

This study aims to investigate the muscle stiffness differences between regarding foot posture.

METHODOLOGY

The observational descriptive study was carried out at *RoboCorp Laboratory – Physiotherapy*, at the *Coimbra Health School*, at the *Polytechnic Institute of Coimbra*. The sample consisted of 18 participants (22.7±4.5 years). Subjects were allocated in the flatfoot group if they presented a bilateral ***Navicular Drop Test*** score of >9mm. The remaining participants represented the neutral-foot group. All participants were submitted to bilateral ***Rectus Femoris*** stiffness assessment with the help of ***Ultrasound base Shear-Wave Elastography*** (*Acuson Sequoia Ultrasound System 2018, Siemens Healthcare GmbH, Erlangen, Germany*). Data were statistically processed with the *IBM SPSS Statistics 27.0* software (*IBM Corporation, New York, USA*). Group differences were assessed using the *T- test for independent samples* (*95% ICC*).

RESULTS

Regarding both groups, no statistically significant differences between groups were found (p=0.249 / d=0.83).

Conclusion

This study related the stiffness differences among the Rectus Femoris muscle regarding foot posture. However, we did not find differences between groups, i.e., stiffness analysis cannot be considered as an important indicator to analyze Rectus Femoris stiffness among flatfoot subjects.

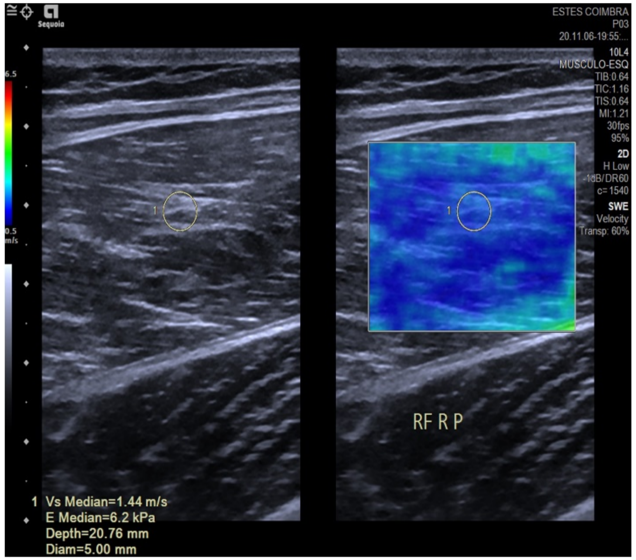

Figure 1: Rectus Femoris assessment

References: ***1.*** 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. ***2.*** Caravaggi P, Sforza C, Leardini A, Portinaro N, Panou A. Effect of plano-valgus foot posture on midfoot kinematics during barefoot walking in an adolescent population. J Foot Ankle Res 2018;11:1–9. ***3.*** 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. ***4***. 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. ***5.*** Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An KN. Validation of shear wave elastography in skeletal muscle. J Biomech 2013;46:2381–7. ***6.*** Kelly JP, Koppenhaver SL, Michener LA, Proulx L, Bisagni F, Cleland JA. Characterization of tissue stiffness of the infraspinatus, erector spinae, and gastrocnemius muscle using ultrasound shear wave elastography and superficial mechanical deformation. J Electromyogr Kinesiol 2018;38:73–80. ***7.*** Le Sant G, Nordez A, Andrade R, Hug F, Freitas S, Gross R. Stiffness mapping of lower leg muscles during passive dorsiflexion. J Anat 2017;230:639–50. ***8.*** Creze M, Nordez A, Soubeyrand M, Rocher L, Maître X, Bellin M. Shear wave sonoelastography of skeletal muscle : basic principles, biomechanical concepts, clinical applications, and future perspectives 2017. ***9***. Koppenhaver S, Kniss J, Lilley D, Oates M, Fernández-de-las-peñas C, Maher R, et al. Reliability of ultrasound shear-wave elastography in assessing low back musculature elasticity in asymptomatic individuals. J Electromyogr Kinesiol 2018;39:49–57. ***10.*** Dubois G, Kheireddine W, Vergari C, Bonneau D, Thoreux P, Rouch P, et al. Reliable Protocol for Shear Wave Elastography of Lower Limb Muscles at Rest and During Passive Stretching. Ultrasound Med Biol 2015;41:2284–91. ***11.*** Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control Trans Ultrason Ferroelectr Freq Control 2004;51:396–409. ***12.*** Mendes B, Firmino T, Oliveira R, Neto T, Infante J, Vaz JR. Hamstring stiffness pattern during contraction in healthy individuals : analysis by ultrasound-based shear wave elastography. Eur J Appl Physiol 2018;0:0. ***13.*** Saeki J, Ikezoe T, Nakamura M, Nishishita S, Ichihashi N. The reliability of shear elastic modulus measurement of the ankle plantar flexion muscles is higher at dorsiflexed position of the ankle. J Foot Ankle Res 2017;10:1–6. ***14.*** Saeki J, Nakamura M, Nakao S, Fujita K, Yanase K, Ichihashi N. Muscle stiffness of posterior lower leg in runners with a history of medial tibial stress syndrome. Scand J Med Sci Sport 2018;28:246–51.

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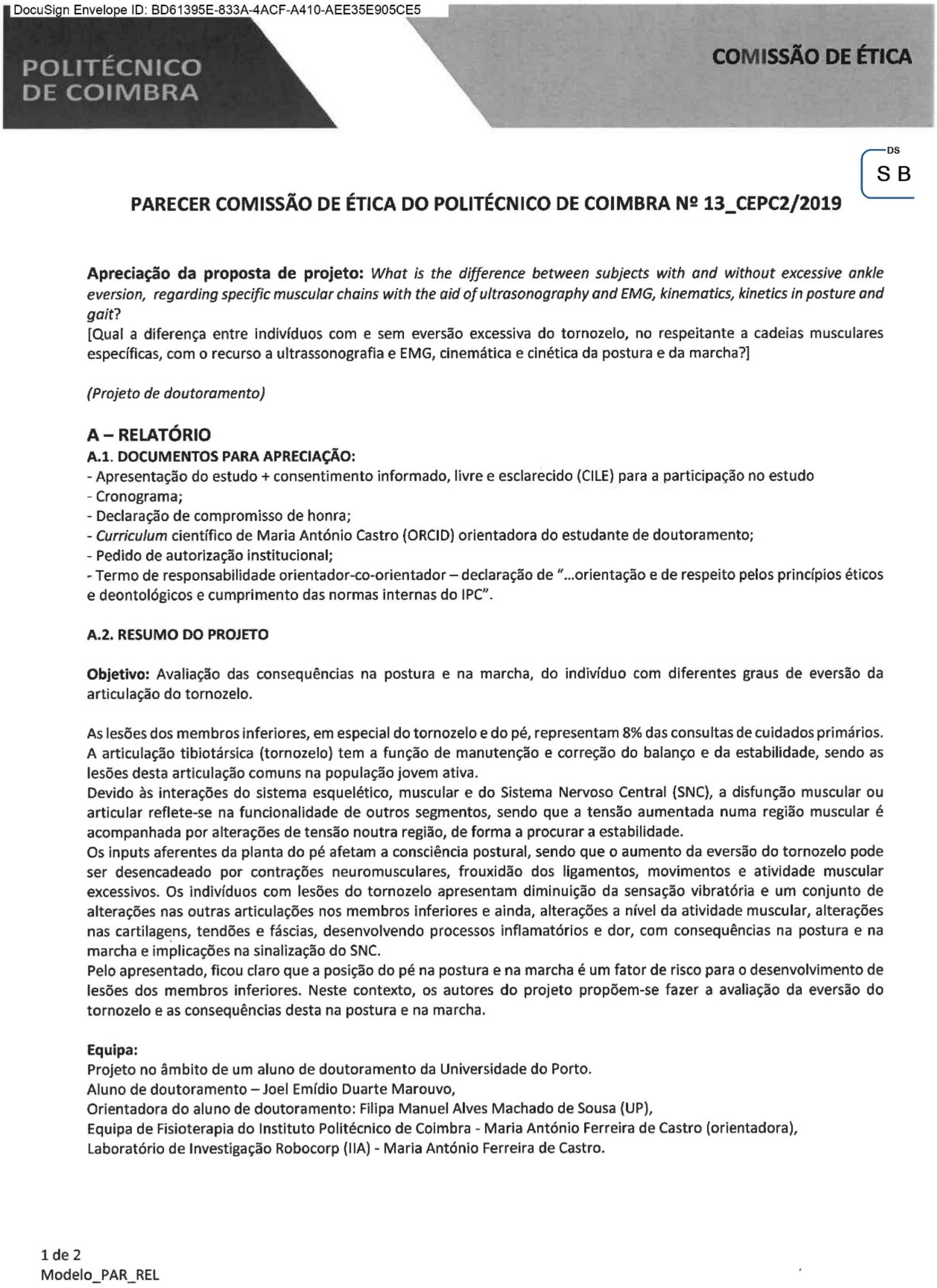
Annex A - The local Faculty Ethics Committee approved the research (13_CEP2/2019)



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POLITÉCNICO
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COMISSÃO DE ÉTICA

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S B

PARECER COMISSÃO DE ÉTICA DO POLITÉCNICO DE COIMBRA Nº 13_CEPC2/2019

Apreciação da proposta de projeto: *What is the difference between subjects with and without excessive ankle eversion, regarding specific muscular chains with the aid of ultrasonography and EMG, kinematics, kinetics in posture and gait*?
[Qual a diferença entre indivíduos com e sem eversão excessiva do tornozelo, no respeitante a cadeias musculares específicas, com o recurso a ultrassonografia e EMG, cinemática e cinética da postura e da marcha?]

(Projeto de doutoramento)

A – RELATÓRIO

A.1. DOCUMENTOS PARA APRECIAÇÃO:

- Apresentação do estudo + consentimento informado, livre e esclarecido (CILE) para a participação no estudo
- Cronograma;
- Declaração de compromisso de honra;
- *Curriculum* científico de Maria António Castro (ORCID) orientadora do estudante de doutoramento;
- Pedido de autorização institucional;
- Termo de responsabilidade orientador-co-orientador – declaração de "...orientação e de respeito pelos princípios éticos e deontológicos e cumprimento das normas internas do IPC".

A.2. RESUMO DO PROJETO

Objetivo: Avaliação das consequências na postura e na marcha, do indivíduo com diferentes graus de eversão da articulação do tornozelo.

As lesões dos membros inferiores, em especial do tornozelo e do pé, representam 8% das consultas de cuidados primários.
A articulação tibiotársica (tornozelo) tem a função de manutenção e correção do balanço e da estabilidade, sendo as lesões desta articulação comuns na população jovem ativa.
Devido às interações do sistema esquelético, muscular e do Sistema Nervoso Central (SNC), a disfunção muscular ou articular reflete-se na funcionalidade de outros segmentos, sendo que a tensão aumentada numa região muscular é acompanhada por alterações de tensão noutra região, de forma a procurar a estabilidade.
Os inputs aferentes da planta do pé afetam a consciência postural, sendo que o aumento da eversão do tornozelo pode ser desencadeado por contrações neuromusculares, frouxidão dos ligamentos, movimentos e atividade muscular excessivos. Os indivíduos com lesões do tornozelo apresentam diminuição da sensação vibratória e um conjunto de alterações nas outras articulações nos membros inferiores e ainda, alterações a nível da atividade muscular, alterações nas cartilagens, tendões e fáscias, desenvolvendo processos inflamatórios e dor, com consequências na postura e na marcha e implicações na sinalização do SNC.
Pelo apresentado, ficou claro que a posição do pé na postura e na marcha é um fator de risco para o desenvolvimento de lesões dos membros inferiores. Neste contexto, os autores do projeto propõem-se fazer a avaliação da eversão do tornozelo e as consequências desta na postura e na marcha.

Equipa:
Projeto no âmbito de um aluno de doutoramento da Universidade do Porto.
Aluno de doutoramento – Joel Emídio Duarte Marouvo,
Orientadora do aluno de doutoramento: Filipa Manuel Alves Machado de Sousa (UP),
Equipa de Fisioterapia do Instituto Politécnico de Coimbra - Maria António Ferreira de Castro (orientadora),
Laboratório de Investigação Robocorp (IIA) - Maria António Ferreira de Castro.

1 de 2
Modelo_PAR_REL

Metodologias:
Avaliar em cadeias musculares específicas o comportamento cinemático de todo o corpo, o comportamento cinético, a atividade neuromuscular (Electromiografia) e a Ultrassonografia musculoesquelética (Ecografia) dos membros inferiores e da coluna lombar.
Estudo transversal, observacional.

- Local onde decorre o estudo: Laboratório Robocorp; Escola Superior de Tecnologia da Saúde de Coimbra.
- Caracterização da amostra: indivíduos voluntários entre os 18 e 40 anos de idade; com eversão unilateral ou bilateral do tornozelo.
- Critério de exclusão: indivíduos com toma de medicamentação que afete a marcha e a atividade muscular.
- Duração da aplicação das metodologias no participante: 60 minutos e 1 só vez/participante.

Procedimentos: i) Apresentação e explicação dos procedimentos ao participante; ii) Avaliação da eversão do tornozelo; iii) Consentimento informado.

Colheita de dados por: i) Goniometria (avaliação da restrição do movimento); ii) Qualise (sistema de captura do movimento); iii) Plataforma de força e plataforma de pressão plantar; iv) Electromiografia de superfície; iv) Ultrassonografia musculoesquelética.

Cronograma: O projeto decorrerá desde setembro de 2019 a junho de 2021.

B – IDENTIFICAÇÃO DAS QUESTÕES COM EVENTUAIS IMPLICAÇÕES ÉTICAS
B.1. Os métodos não são dolorosos, não existem riscos para a saúde do participante.
B.2. Identificação dos participantes por código; dados protegidos por palavra passe.
B.3. Dados utilizados apenas para este estudo; não há contrapartida monetária para os participantes.
Estudo sem financiamento.

C – CONCLUSÕES
O projeto está claramente explicado.
As metodologias a serem aplicadas não são dolorosas nem invasivas.
As implicações éticas estão salvaguardadas e a confidencialidade dos resultados está assegurada.

Estando salvaguardados os pressupostos éticos relacionados com a investigação, de acordo com o disposto no n.º 2 do art.º 7.º do Regulamento da Comissão de Ética do IPC, não tem esta CEIPC nada a opor quanto ao desenvolvimento do referido projeto.

DECISÃO: DEFERIDO, por unanimidade, em 7 de outubro de 2019.

O/A Relator/a: Maria Antónia P. Conceição

Maria Antónia P. Conceição

O/A Presidente da CEIPC: Sónia Brito-Costa

DocuSigned by:
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10/9/2019

Annex B – Certificate of Congresso Nacional de Biomecânica - Appendix A / B

CNB FF

19-20 Fevereiro 2021 | Porto

Congresso Nacional de Biomecânica

ciência em movimento

CERTIFICADO DE PARTICIPAÇÃO

Certifica-se que,

Joel Marouvo

participou no 9º Congresso Nacional de Biomecânica, nos dias 19 e 20 de fevereiro de 2021

A comissão organizadora:

Jorge Belinha
José Carlos Reis Campos
Elza Fonseca
Mª Helena Figueiral
Fernanda Gentil
Susana Oliveira
Arcelina Marques

Annex C - Certificate of Health and Well-being Congress - Appendix C

2nd Health
& Well-Being
Intervention
INTERNATIONAL
CONGRESS

International Conference
on Human Kinesiology

CERTIFICATE

This is to certify that oral communication titled Flat foot condition diagnosis regarding different methods By Joel Marouvo, Maria António Castro, Filipa Sousa, Carlos Santos was presented at the 2nd International Congress of Health and Well-being Intervention (ICHWBI 2021), organized by the RECI (Research in Education and Community Intervention) and the Jean Piaget Health School (ESS) / Viseu and 1st International Conference on Human Kinesiology (ICOHK), organized by the KinesioLab and the Piaget Institute which was held at the University Campus of Viseu of the Piaget Institute, Viseu, Portugal, on May 28 & 29, 2021 (www.healthwellbeingcongress.ipiaget.org).

Gustavo Desouzart
ICHWBI 2021 *President of the Organizing Committee*

ORGANIZAÇÃO
INSTITUTO PIAGET | VISEU

Annex D - Certificate of Annual Meeting 2021 Coimbra Health School – Appendix D

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Maria António Castro

Presented the Oral Communication entitled

Postural stability assessment in flatfoot subjects trough Lyapunov Exponent analysis.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Maria António Castro; Nelson Azevedo; Filipa Sousa; Orlando Fernandes

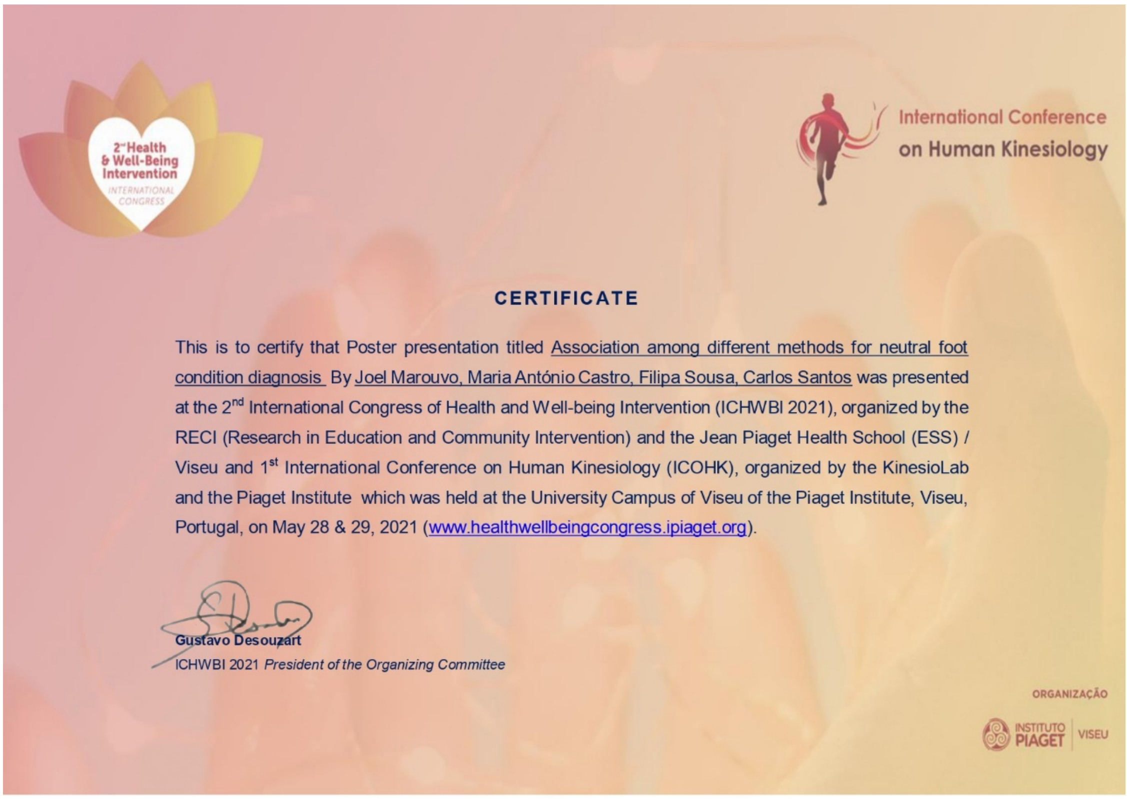
João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Martins
Coordinator

João Lima
Coordinator

Annex E – Certificate of Health and Well-being Congress - Appendix E



2nd Health & Well-Being Intervention
INTERNATIONAL CONGRESS

International Conference
on Human Kinesiology

CERTIFICATE

This is to certify that Poster presentation titled Association among different methods for neutral foot condition diagnosis By Joel Marouvo, Maria António Castro, Filipa Sousa, Carlos Santos was presented at the 2nd International Congress of Health and Well-being Intervention (ICHWBI 2021), organized by the RECI (Research in Education and Community Intervention) and the Jean Piaget Health School (ESS) / Viseu and 1st International Conference on Human Kinesiology (ICOHK), organized by the KinesioLab and the Piaget Institute which was held at the University Campus of Viseu of the Piaget Institute, Viseu, Portugal, on May 28 & 29, 2021 (www.healthwellbeingcongress.ipiaget.org).

Gustavo Desouzart
ICHWBI 2021 *President of the Organizing Committee*

ORGANIZAÇÃO

INSTITUTO PIAGET | VISEU

Annex F - Certificate of Annual Meeting 2021 Coimbra Health School – Appendix F

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Joel Marouvo

Presented the Poster Presentation entitled

Bipedal weight-bearing stance postural kinematic analysis in flatfoot subjects.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Maria António Castro; Orlando Fernandes; Filipa Sousa; Nelson Azevedo

João José Joaquim
President of ESTeSC

Fernando Mendes President of the Congress	Diana Martins Coordinator	João Lima Coordinator

Annex G - Certificate of Annual Meeting 2021 Coimbra Health School – Appendix G

ANNUAL MEETING 2021
Global Health | New Trends

17 - 19 JUNE
VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Joel Marouvo

Presented the Poster Presentation entitled

Postural stability analysis in flatfoot subjects.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Maria António Castro; Orlando Fernandes; Filipa Sousa; Nelson Azevedo

João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Martins
Coordinator

João Lima
Coordinator

Annex H - Certificate of Annual Meeting 2021 Coimbra Health School – Appendix H

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Maria António Castro

Presented the Poster Presentation entitled

Postural stability assessment in flatfoot subjects trough Approximate Entropy analysis.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Maria António Castro; Nelson Azevedo; Filipa Sousa; Orlando Fernandes

João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Raquel Fernandes Martins
Diana Martins
Coordinator

João Pedro Marques Lima
João Lima
Coordinator

Annex I – Certificate of Annual Meeting 2021 Coimbra Health School – Appendix I

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Joel Marouvo

Presented the Poster Presentation entitled

Tibialis posterior muscle stiffness assessment regarding foot posture, by ultrasound based Shear-Wave Elastography.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Filipa Sousa; Alexandra André; Maria António Castro

João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Martins
Coordinator

João Lima
Coordinator

Annex J – Certificate of Annual Meeting 2021 Coimbra Health School – Appendix J

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

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Tibialis posterior muscle stiffness analysis, by ultrasound based Shear-Wave Elastography.

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Filipa Sousa; Alexandra André André; Maria António Castro

João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Raquel Fernandes Martins
Diana Martins
Coordinator

João Pedro Marques Lima
João Lima
Coordinator

Annex K – Certificate of Annual Meeting 2021 Coimbra Health School – Appendix K

ANNUAL MEETING 2021

Global Health | New Trends

17 - 19 JUNE

VIRTUAL

estesc
Politécnico de Coimbra

Certificate

We hereby certify that

Maria António Castro

Presented the Poster Presentation entitled

Muscle stiffness differences regarding foot posture by ultrasound-based Shear-Wave Elastography

inserted on the **Annual Meeting - Global Health: New Trends** that took place in a virtual format from the 17th to the 19th of June 2021

Authors: Joel Marouvo; Maria António Castro; Alexandra André; Rui Mendes; Filipa Sousa

João José Joaquim
President of ESTeSC

Fernando Mendes
President of the Congress

Diana Martins
Coordinator

João Lima
Coordinator