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The biomechanical effects of pronated foot function on gait. An experimental study

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The relationship between foot kinematics and the development of lower extremity musculoskeletal disorders (MSD) has been the focus of recent attention. However, most studies evaluated static foot type and not dynamic foot function. The purpose was to compare lower limb and foot kinematics, and plantar pressures during gait in physically active individuals with pronated and non-pronated foot function. Foot function in 154 adult participants was documented as pronated (n = 63) or neutral (n = 91) using 2 established methods: The Foot Posture Index and the Center of Pressure Excursion Index. Difference between the groups in triplanar motion of the lower limb during barefoot gait was evaluated using a 3D motion capture system incorporating the Oxford Foot Model. Dynamic parameters of plantar pressure were recorded using a pressure platform. Anterior-posterior pelvic tilt range of motion (ROM), peak knee internal rotation, forefoot dorsiflexion ROM, peak forefoot abduction, and rearfoot eversion were all increased in those with pronated foot function. Hallux contact time and time to peak force under the medial forefoot were increased with pronated foot function, and maximal force under the lateral forefoot was reduced. Pronated foot function affected the whole lower limb kinematic chain during gait. These kinematic alterations could increase the risk of developing MSD. Further studies should elucidate the relationship between pronated foot function and MSD, and, if confirmed, foot function should be evaluated in clinical practice for patients with lower limb and low back pain.

KEYWORDS
foot function, foot pronation, gait kinematic, injury, multi-segment foot model, plantar pressure

1 | INTRODUCTION

There is an ongoing debate in the literature regarding the relationships between static foot posture, dynamic foot function, and lower limb musculoskeletal disorders.[1,2] One reason for this debate is the common confusion between foot posture, which is static, and foot function, which is dynamic.[3]

Foot pronation (FP) designates a movement of the whole foot.[4] It has been defined as "a range of motion within the foot that makes the foot more prone to the support surface that is greater than that required by the individual to adjust to morphology or to adapt to the forces placed in the musculoskeletal system by kinetic and kinematic events within gait or another given action." [3] A few studies have evaluated the effect of different types of foot function on gait kinematics.

Foot pronation is commonly associated with the flat foot (FF) static foot posture,[3] and several studies have reported a relationship between FP and FF.[5,6] The static FF posture has been widely studied and is largely associated with musculoskeletal disorders (MSD), such as medial tibial stress syndrome,[7] patellofemoral pain,[8] or low back pain.[9] The effect of FF on gait kinematics [10-15] and plantar pressure distribution [16,17] has been well-documented. However, the relationship between foot posture and foot function has recently been questioned,[18,19] raising doubts regarding the kinematic link between FF and FP and thus between FP and MSD.

Therefore, the primary aim of this study was to determine whether FP function modifies lower limb kinematics during gait. Secondary aims were to describe the kinematics of the foot and plantar pressure distributions in FP function.

Based on previous studies, we hypothesized that there would be increases in (a) knee and hip internal rotation and anterior pelvic tilt, (b) hindfoot eversion and forefoot supination, and (c) pressure underneath the medial heel and the medial forefoot would be increased in FP.

2 | METHODS

2.1 | Participants

Participants were recruited from the Normandy fire-brigade as part of an ongoing project into the prevention of MSD in collaboration with the brigade health physicians. Fire-fighters are considered at risk of MSD and low back pain due to their hazardous working conditions and the intense physical stress they are exposed to.[20] Participants had to be aged between 20 and 50 years. Two hundred and ninety-five fire-fighters were initially screened by a podiatrist, and of these, 141 were excluded due to the presence of a current or previous lower limb injury (during the previous 12 months), leg-length discrepancy, supinated foot function, obvious muscle weakness, or known neurovascular disease; thus, 154 were included. Each participant was evaluated by an experienced podiatrist. All participants provided written informed consent before participation, in accordance with the Declaration of Helsinki. The study was approved by the ethical research committee of the university of Rouen (Ethics ID: 2018-03-A).

To increase the validity of the results, foot function was classified using two established methods: 1) the static, 6-item Foot Posture Index (FPI) and 2) the dynamic Center of Pressure Excursion Index (CPEI). The FPI-6 has been shown to have good inter-examiner reliability when performed by experienced clinicians (weighted kappa (Kw) = 0.86) [21] and high intra-examiner reliability.[22] In this study, the same experienced podiatrist rated the FPI-6 for all participants. The scores of the 6 items were combined to give a final score between −12 and 12; a score above 5 indicated FP.

The CPEI was computed from data collected from 2 pressure distribution platforms during gait (see experimental protocol). This index is reliable with an ICC above 0.95 [23] and is a very useful tool for the assessment of foot function during gait both in clinical practice and research.[24-26] It is calculated from the concavity of the center of pressure curve in the metatarsal head region, normalized to foot width,[23] and represents the mediolateral deviation of the center of pressure under the one-third trisection of the foot. A cutoff of 19.4% was used to determine the foot type [23,27]; values below this percentage indicated FP and values above indicated a neutral or supinated foot. Foot function was only classified as pronator (FP) if the FPI was greater than 5 and the CPEI was less than 19.4%. Neutral (FN) subjects were classified as having an FPI between 0 and 5 and a CPEI above 19.4%.

2.2 | Experimental protocol

A 3-dimensional motion analysis system was used to assess the kinematic variables (Qualisys AB, Goteborg, Sweden). Ten cameras were used to capture kinematic data at a frequency of 150 Hz. A total of thirty-eight reflecting markers were fixed to both limbs of each subject (supplementary Figure S1). Of those, twenty-four were positioned on the feet according to the Oxford Foot Model. The fourteen other markers were positioned on the anterior-superior and posterior-superior iliac spines, the most prominent part of the greater trochanters, the lateral femoral condyles, the heads of the fibulae, the tibial tuberosities, and the lateral malleoli.

Two Zebris pressure distribution platforms (FDM-3, Zebris Medical GmbH, Germany, frequency = 120 Hz), 2x314x62cm mounted flush in the middle of a 15m runway carpet, were used to record plantar pressures.

TABLE 1 Participant characteristics

Variable	Pronated	Neutral	*P* value
Population			
Age (years)	35.5 ± 4.7	36.4 ± 4.9	.36
Height (m)	1.76 ± 0.06	1.78 ± 0.07	.14
Weight (kg)	76.5 ± 8.1	78.0 ± 9.0	.38
BMI (kg/m^2)	24.5 ± 2.4	24.6 ± 2.0	.86
Measures			
CPEI (%)	16.2 ± 5.2	22.2 ± 1.7	<.001
FPI	7.7 ± 1.8	2.6 ± 1.5	<.001
Foot length (m)	0.276 ± 0.011	0.277 ± 0.012	.55
Spatiotemporal			
Velocity (m/s)	1.2 ± 0.1	1.2 ± 0.1	.92
Step length (m)	1.3 ± 0.1	1.3 ± 0.1	.52
Cadence (step/min)	104.8 ± 6.5	105.9 ± 7.3	.37

TABLE 2 Peak and ROM values for the lower limb kinematics

	Peak values (°)					ROM values (°)				
Variable	**FPg**	**CTRg**	**Mean Difference (95% CI)**	**Effect Size**	***p* values**	**FPg**	**CTRg**	**Mean Difference (95% CI)**	**Effect Size**	***p* values**
Pelvic										
(+) Anterior tilt	9.8 (4.9)	9.8 (5.2)	0.0 (−2.1 to 1.2)	0	.94	**2.4 (0.7)**	**1.6 (0.7)**	0.8 (0.4 to 1.0)	>0.8	**<.001**
(−) Posterior tilt	7.4 (4.5)	8.2 (4.9)	−0.8 (−2.6 to 0.5)	0.2	.19					
(+) Upward tilt	2.6 (2.3)	2.5 (2.2)	0.1 (−0.8 to 0.6)	0.1	.90	4.3 (1.5)	4.7 (1.5)	−0.4 (−0.9 to 0.2)	0.3	.12
(−) Backward tilt	−1.7 (1.7)	−2.2 (1.9)	0.5 (−0.3 to 0.9)	0.3	.10					
(+) Internal rotation	4.3 (3.4)	4.4 (4.5)	−0.1 (−1.3 to 1.4)	0.1	.93	**8.3 (3.1)**	**7.4 (2.5)**	0.9 (0.1 to 1.9)	0.3	**.04**
(−) External rotation	−4.0 (5.4)	−3.0 (6.0)	−1.0 (−3.1 to 1.0)	0.2	.32					
Hip										
(+) Adduction	5.0 (2.7)	4.5 (3.3)	0.5 (−1.6 to 0.7)	0.1	.41	6.1 (1.9)	6.4 (2.5)	−0.3 (−1.2 to 0.4)	0.2	.37
(−) Abduction	−2.7 (4.5)	−3.5 (4.4)	0.8 (−0.7 to 2.1)	0.1	.33	7.7 (1.8)	8.1 (2.7)	−0.4 (−1.4 to 0.4)	0.2	.23
(+) Internal rotation	2.2 (7.3)	2.4 (6.9)	−0.2 (−2.4 to 2.1)	0.1	.87	5.7 (3.4)	5.6 (3.3)	0.1 (−1.1 to 1.1)	0.1	.97
(+) External rotation	−6.8 (7.1)	−7.0 (7.3)	0.2 (−1.9 to 2.7)	0.1	.78	9.0 (4.5)	9.4 (4.2)	−0.4 (−1.7 to 1.2)	0.1	.56
Knee										
(−) Abduction	0.1 (3.8)	0.0 (3.5)	0.1 (−0.5 to 2.0)	0	.21	4.2 (1.6)	4.4 (2.3)	−0.2 (−0.9 to 0.5)	0	.69
(+) Internal rotation	**−7.3 (9.1)**	**−11.3 (8.0)**	4.0 (1.0 to 6.7)	0.5	**.01**	12.6 (4.3)	12.9 (4.4)	−0.3 (−1.6 to 0.9)	0.1	.63

Note: Bold values represent significant results ($P < .05$).

TABLE 3 Lower limb kinematics at foot strike, midstance and toe-off

Variable	Foot strike values (°)					Midstance values (°)	
	FPg	CTRg	Mean Difference (95% CI)	Effect Size	*P* values	FPg	CTRg
Pelvic							
(+) Anterior tilt	8.8 (4.6)	8.9 (4.8)	−0.1 (−1.5 to 1.5)	0.1	.98	7.9 (4.5)	8.4 (4.9)
(+) Upward tilt	−0.6 (3.0)	−1.0 (2.9)	0.4 (−0.1 to 0.9)	0.1	.10	0.4 (1.4)	0.5 (1.8)
(+) Internal rotation	3.5 (5.1)	3.8 (5.6)	−0.3 (−1.5 to 2.0)	0.1	.72	2.1 (5.0)	2.5 (5.4)
Hip							
(+) Adduction	−1.1 (3.0)	−1.8 (2.8)	0.7 (−1.6 to 0.2)	0.2	.12	4.4 (3.1)	3.7 (2.9)
(+) Internal rotation	−3.6 (7.2)	−3.2 (7.4)	−0.4 (−2.4 to 2.2)	0.1	.93	−2.0 (7.5)	−1.8 (6.9)
Knee							
(+) Adduction	1.0 (3.0)	0.8 (2.9)	0.2 (−0.7 to 1.2)	0.1	.65	1.0 (3.5)	0.9 (3.3)
(+) Internal rotation	**−19.9 (10.2)**	**−24.2 (9.7)**	4.3 (0.8 to 7.2)	0.4	**.01**	**−11.0 (9.3)**	**−14.4 (9.2)**

Note: Midstance and toe-off. Bold values represent significant results ($P < .05$).

TABLE 4 Foot kinematic results for peak values

Variable	Peak values (°)				
	FPg	CTRg	Mean Difference (95% CI)	Effect Size	*P* values
Forefoot/ Hindfoot					
(+) Dorsiflexion	6.6 (5.1)	6.6 (5.7)	0.0 (−1.9 to 1.6)	0	.89
(−) Plantarflexion (toe-off)	−12.1 (6.5)	−11.1 (5.6)	−1.0 (−2.6 to 0.6)	0.2	.23
(+) Supination	9.2 (5.8)	8.5 (5.5)	0.7 (−1.0 to 2.5)	0.1	.43
(−) Eversion	1.4 (5.0)	1.4 (4.9)	0.0 (−1.5 to 1.6)	0	.92
(+) Adduction	**5.0 (6.2)**	**8.5 (6.9)**	−3.5 (−5.6 to −1.3)	0.6	**.001**
(−) Abduction	**−2.5 (6.0)**	**−0.1 (6.5)**	−2.4 (−4.5 to −0.4)	0.4	**.02**
Forefoot/ Tibia					
(+) Dorsiflexion	15.8 (5.4)	16.3 (4.7)	−0.5 (−2.2 to 1.8)	0.1	.55
(−) Plantarflexion (toe-off)	−16.8 (7.4)	−16.5 (6.2)	−0.3 (−1.9 to 1.5)	0.1	.85
(−) Flexion plantaire (loading response)	**−4.7 (5.1)**	**−2.0 (4.6)**	−2.7 (−4.5 to −1.1)	0.6	**.001**
(+) Supination	13.7 (5.3)	14.4 (5.0)	−0.7 (−2.2 to 1.0)	0.1	.42
(−) Eversion	0.9 (5.7)	1.7 (4.8)	−0.8 (−2.6 to 0.7)	0.2	.27
(+) Adduction	**16.8 (8.4)**	**20.2 (7.7)**	−3.4 (−6.0 to −0.8)	0.4	**.01**
(−) Abduction	**3.3 (8.9)**	**6.5 (7.6)**	−3.2 (−5.9 to −0.5)	0.4	**.02**
Hindfoot/ Tibia					
(+) Dorsiflexion	10.5 (5.0)	10.6 (4.4)	−0.1 (−1.6 to 1.5)	0.1	.82
(−) Plantarflexion (toe-off)	−4.6 (4.7)	−4.6 (5.4)	0.0 (−1.8 to 1.7)	0	.97
(−) Flexion plantaire (loading response)	−0.6 (5.1)	−0.0 (4.8)	−0.6 (−2.1 to 0.9)	0.1	.46
(+) Supination	3.1 (5.4)	4.8 (5.0)	−1.7 (−3.2 to 0.1)	0.2	.06
(−) Eversion	**−2.8 (4.9)**	**0.0 (4.4)**	−2.8 (−4.4 to −1.5)	0.6	**<.001**
(+) Internal rotation	**11.0 (7.9)**	**14.2 (9.6)**	−3.2 (−6.2 to −0.4)	0.4	**.03**
(−) External rotation	0.0 (9.0)	2.5 (9.4)	−2.5 (−5.4 to 0.5)	0.3	.11
Hallux					
(+) Dorsiflexion	29.1 (11.1)	31.3 (10.2)	−2.2 (−5.5 to 1.2)	0.2	.23
(−) Plantarflexion	−0.3 (9.2)	1.8 (10.6)	−2.1 (−5.3 to 0.9)	0.3	.17

Note: Bold values represent significant results ($P < .05$).

			Toe-off values (°)				
Mean Difference (95% CI)	Effect Size	P values	FPg	CTRg	Mean Difference (95% CI)	Effect Size	P values
−0.5 (−2.5 to 0.6)	0.1	.53	7.9 (4.6)	8.5 (4.9)	−0.6 (−2.1 to 0.9)	0.1	.45
−0.1 (−0.4 to 0.7)	0.1	.48	−1.7 (1.5)	−2.2 (1.9)	0.5 (−0.3 to 0.9)	0.3	.10
−0.4 (−2.1 to 1.4)	0.1	.65	−4.2 (7.3)	−2.5 (7.2)	−1.7 (−4.1 to 0.6)	0.3	.12
0.7 (−0.2 to 1.6)	0.2	.13	−2.7 (4.5)	−3.5 (4.4)	0.8 (−0.7 to 2.1)	0.1	.33
−0.2 (−2.5 to 2.2)	0.1	.88	−6.4 (7.1)	−6.6 (7.3)	0.2 (−1.9 to 2.7)	0.1	.78
0.1 (−1.1 to 1.3)	0.1	.95	0.2 (4.3)	0.1 (4.1)	0.1 (−1.4 to 1.4)	0.1	.91
3.4 (0.4 to 6.8)	0.4	**.03**	**−18.7 (9.0)**	**−21.4 (8.2)**	2.7 (0.4 to 6.1)	0.3	**.02**

TABLE 5 Foot kinematic results for ROM values

	ROM values (°)				
Variable	FPg	CTRg	Mean Difference (95% CI)	Effect Size	P values
Forefoot/ Hindfoot					
(+) Dorsiflexion	**12.6 (3.3)**	**10.7 (3.7)**	1.9 (0.7 to 3.2)	0.5	**.001**
(−) Plantarflexion	18.7 (5.3)	17.7 (5.7)	1.0 (−0.5 to 2.3)	0.2	.16
(+) Supination	7.8 (3.3)	7.0 (2.8)	0.8 (−0.2 to 1.6)	0.3	.13
(−) Eversion	5.7 (3.4)	4.7 (4.0)	1.0 (−0.2 to 2.1)	0.3	.08
(+) Adduction	7.6 (5.5)	8.6 (5.3)	−1.0 (−2.7 to 0.8)	0.2	.24
(−) Abduction	6.4 (3.7)	5.4 (3.6)	1.0 (−0.1 to 2.1)	0.3	.08
Forefoot/ Tibia					
(+) Dorsiflexion	**20.4 (5.6)**	**18.3 (4.8)**	2.1 (0.4 to 3.8)	0.4	**.01**
(−) Plantarflexion	32.6 (6.2)	32.8 (6.7)	−0.2 (−1.7 to 1.4)	0.1	.84
(+) Supination	5.5 (6.2)	6.0 (6.7)	−0.5 (−2.6 to 1.5)	0.2	.61
(−) Eversion	12.8 (3.7)	12.7 (3.7)	0.1 (−1.1 to 1.3)	0.1	.91
(+) Adduction	10.3 (4.3)	10.0 (4.2)	0.3 (−1.0 to 1.6)	0.1	.64
(−) Abduction	13.6 (6.1)	13.6 (5.0)	0.0 (−1.8 to 1.8)	0.1	.94
(−) Abduction	8.7 (3.6)	8.1 (2.9)	0.6 (−0.4 to 1.6)	0.2	.24
Hindfoot/ Tibia					
(+) Dorsiflexion	11.1 (4.1)	10.6 (3.8)	0.5 (−0.7 to 1.8)	0.1	.38
(−) Plantarflexion (toe-off)	15.1 (5.2)	15.2 (5.0)	−0.1 (−1.7 to 1.5)	0.1	.89
(−) Plantarflexion (loading response)	4.8 (3.8)	5.0 (3.1)	−0.2 (−2.2 to 1.6)	0.1	.74
(+) Supination	5.9 (3.9)	4.8 (3.8)	1.1 (−0.1 to 2.4)	0.3	.07
(−) Eversion	5.7 (3.7)	4.6 (3.7)	1.1 (−0.1 to 2.4)	0.3	.06
(+) Internal rotation	11.0 (3.7)	11.7 (4.4)	−0.7 (−2.0 to 0.6)	0.2	.32
(−) External rotation	6.7 (3.5)	5.6 (3.3)	1.1 (−0.1 to 2.3)	0.3	.06
Hallux					
(+) Dorsiflexion	29.3 (8.9)	29.5 (9.3)	−0.2 (−3.0 to 2.6)	0.1	.90
(−) Plantarflexion	11.4 (7.8)	10.6 (6.5)	0.8 (−1.3 to 2.7)	0.1	.49

Note: Bold values represent significant results ($P < .05$).

TABLE 6 Foot kinematics at foot strike, midstance and toe-off.

	Foot strike values (°)					Midstance values (°)	
Variable	FPg	CTRg	Mean Difference (95% CI)	Effect Size	*P* values	FPg	CTRg
Forefoot/ Hindfoot							
(+) Dorsiflexion	−6.0 (6.0)	−4.1 (5.8)	−1.9 (−3.8 to 0.1)	0.3	.06	−0.6 (4.8)	0.2 (5.4)
(+) Supination	7.1 (5.3)	6.1 (5.7)	1.0 (−0.8 to 2.6)	0.2	.29	2.8 (5.1)	2.6 (5.5)
(+) Adduction	3.9 (5.3)	5.3 (5.3)	−1.4 (−3.2 to 0.5)	0.3	.16	0.3 (4.9)	1.6 (5.4)
Forefoot/ Tibia							
(+) Dorsiflexion	**0.8 (5.7)**	**4.0 (5.3)**	−3.2 (−5.0 to −1.5)	0.6	**<.001**	**6.2 (5.6)**	**8.9 (5.1)**
(+) Supination	11.2 (5.0)	11.7 (5.4)	−0.5 (−2.3 to 1.1)	0.1	.47	2.0 (5.6)	3.0 (5.6)
(+) Adduction	**12.1 (8.1)**	**14.6 (5.1)**	−2.5 (−4.6 to −0.4)	0.4	**.02**	**6.3 (8.7)**	**8.9 (7.4)**
Hindfoot/ Tibia							
(+) Dorsiflexion	4.2 (5.3)	5.1 (5.2)	−0.9 (−2.6 to 0.8)	0.2	.30	7.0 (5.4)	7.2 (4.7)
(+) Inversion	2.9 (5.3)	4.5 (4.7)	−1.6 (−3.3 to 0.1)	0.4	.06	**−1.8 (4.0)**	**1.0 (5.0)**
(+) Rotation interne	6.7 (7.5)	8.1 (7.2)	−1.4 (−3.8 to 0.9)	0.2	.24	**3.9 (7.8)**	**6.6 (6.7)**
Hallux							
(+) Dorsiflexion	11.0 (9.9)	12.4 (10.3)	−1.4 (−4.8 to 1.7)	0.1	.44	0.4 (9.5)	2.1 (10.7)

Note: Midstance and toe-off. Bold values represent significant results ($P < .05$).

TABLE 7 Foot pressures results for percentage of contact time, maximal force, and time to reach peak force

Variable	Contact time (%)					Maximal force (N)	
	FPg	CTRg	Mean Difference (95% CI)	Effect Size	*P* values	FPg	CTRg
Toes	**78.9 (6.1)**	**76.4 (7.4)**	−2.5 (−4.6 to −0.5)	0.4	**.02**	213.8 (50.2)	193.0 (57.8)
Medial forefoot	79.6 (3.4)	78.9 (3.5)	−0.7 (−1.7 to 0.3)	0.1	.15	167.9 (40.9)	163.7 (41.9)
Lateral forefoot	84.2 (2.4)	83.9 (2.5)	−0.3 (−1.0 to 0.4)	0.1	.39	**154.9 (35.2)**	**174.3 (41.1)**
Inner forefoot	85.1 (2.3)	85.0 (2.3)	0.1 (−0.6 to 0.8)	0.1	.94	365.8 (63.2)	366.2 (59.9)
Midfoot	74.1 (3.9)	74.6 (4.0)	0.5 (−0.7 to 1.7)	0	.53	161.0 (71.5)	164.6 (69.8)
Medial Heel	58.8 (7.2)	59.1 (7.2)	0.3 (−2.0 to 2.5)	0	.97	315.3 (50.9)	315.7 (50.2)
Lateral Heel	59.4 (7.0)	59.3 (7.0)	−0.1 (−2.3 to 2.1)	0	.77	274.3 (42.9)	273.3 (45.4)

Note: Bold values represent significant results ($P < .05$).

Participants were asked to walk barefoot at a self-selected speed between two lines positioned 4m before and 4m after the platforms. Five trials were recorded, and the mean values of all variables calculated were analyzed. All the analyses were carried out on the right foot in the neutral group and on the most pronated foot in the pronated group (lower CPEI score) to avoid statistical bias due to pooling right and left feet.[28]

2.3 | Data analysis and statistics

Raw kinematic data were exported to Visual 3D software (C-motion, Germantown, MD, USA), and segments were modeled following the ISB recommendations.[29] The following angles were calculated: (a) pelvis relative to the laboratory (X,Y,Z); (b) femur relative to pelvis (Y,Z); (c) tibia relative to femur (Y,Z); (d) rearfoot relative to tibia (X,Y,Z); (e) forefoot relative to rearfoot (X,Y,Z); (f) forefoot relative to tibia (X,Y,Z); and (g) hallux relative to forefoot (X). Processed data were low-pass filtered at 6Hz using a fourth-order Butterworth filter. The peaks and ranges of motion (ROM) were compared between groups for each angle during the stance phase based on the method of Hösl et al.[10] Mean values at foot strike, midstance, and toe-off were also compared (supplementary Figure S2). Gait events were detected according to the method proposed by Zeni et al based on the kinematic marker position of the foot (heel and toe)

Mean Difference (95% CI)	Effect Size	P values	Toe-off values (°) FPg	CTRg	Mean Difference (95% CI)	Effect Size	P values
−0.8 (−2.5 to 0.8)	0.2	.31	−12.1 (6.5)	−11.1 (5.6)	−1.0 (−2.6 to 0.6)	0.2	.22
0.2 (−1.5 to 1.9)	0.1	.82	8.0 (5.8)	7.3 (5.5)	0.7 (−1.0 to 2.5)	0.1	.42
−1.3 (−2.8 to 0.5)	0.3	.17	**5.0 (6.2)**	**8.5 (6.9)**	−3.5 (−5.6 to −1.3)	0.7	**.001**
−2.7 (−4.5 to −1.9)	0.5	**.001**	−16.8 (7.4)	−16.5 (6.2)	−0.3 (−1.9 to 1.5)	0.1	.85
−1.0 (−2.8 to 0.8)	0.2	.25	7.7 (5.3)	8.4 (5.3)	−0.7 (−2.3 to 1.0)	0.1	.45
−2.6 (−5.2 to −0.1)	0.3	**.04**	**16.8 (8.4)**	**20.2 (7.7)**	−3.4 (−6.0 to −0.8)	0.4	**.01**
−0.2 (−1.8 to 1.4)	0.1	.78	−4.6 (4.7)	−4.6 (5.4)	0.0 (−1.8 to 1.7)	0	.97
−2.8 (−4.2 to −1.2)	0.6	**<.001**	2.8 (5.4)	3.8 (5.1)	−1.0 (−2.7 to 0.7)	0.2	.22
−2.7 (−5.2 to −0.4)	0.4	**.03**	**7.7 (7.9)**	**10.7 (9.6)**	−3.0 (−5.8 to −0.1)	0.4	**.04**
−1.7 (−5.0 to 1.5)		.31	29.1 (11.1)	31.3 (10.2)	−2.0 (−5.5 to 1.2)	0.2	.23

Mean Difference (95% CI)	Effect Size	P values	Time to peak force (%) FPg	CTRg	Mean Difference (95% CI)	Effect Size	P values
20.8 (3.6 to 38.0)	0.2	.21	83.1 (2.2)	82.7 (2.6)	0.5 (−0.3 to 1.2)	0	.14
4.2 (−8.3 to 17.1)	0.1	.24	**71.9 (4.8)**	**74.1 (4.6)**	−2.1 (−3.6 to −0.7)	0.5	**.001**
−19.4 (−31.5 to −7.3)	0.5	**.001**	68.6 (7.7)	68.3 (6.0)	0.4 (−1.7 to 2.5)	0	.18
−0.3 (−19.5 to 18.8)	0	.55	74.2 (2.5)	74.1 (3.0)	0.1 (−0.7 to 0.9)	0	.99
−3.6 (−25.6 to 18.4)	0,1	.49	46.3 (10.0)	44.3 (8.9)	2.0 (−0.9 to 4.9)	0.2	.09
−0.4 (−16.2 to 15.4)	0	.840	18.8 (2.7)	19.6 (2.4)	−0.8 (−1.6 to 0.0)	0.1	.09
1.0 (−12.8 to 14.4)	0.1	.78	17.7 (3.4)	18.7 (3.0)	−1.1 (−2.1 to 0.0)	0.1	.39

and the pelvis.[30] Midstance was defined as 50% of the stance phase.

Zebris software was used to analyze plantar pressure data under the medial and lateral heel, medial, inner and lateral forefoot, and midfoot. Maximal force, contact time, and time to maximal force were compared between the groups.

Statistical analysis was carried out using SPSS version 17 (SPSS Inc). The data distribution was tested for skewness and kurtosis. Levene's test was used to test the equality of variance. Student's t tests were used to compare kinematic and plantar pressure data between groups. The effect size and mean difference were also calculated for each variable. $P < .05$ was considered significant in each case.

3 | RESULTS

Data from 154 subjects (91 in the control group (CTRg) and 63 in the FP group (FPg)) were included in the analysis. There were no significant differences between groups for age ($P = .36$), height ($P = .14$), weight ($P = .38$), body mass index ($P = .86$), or gait velocity (FPg = 1.2 ± 0.1 m/s; CTRg = 1.2 ± 0.1 m/s; $P = .92$) (Table 1).

3.1 | Lower limb kinematics

Peak knee internal rotation, ROM pelvic anterior-posterior tilt, and internal pelvic rotation ROM were all significantly

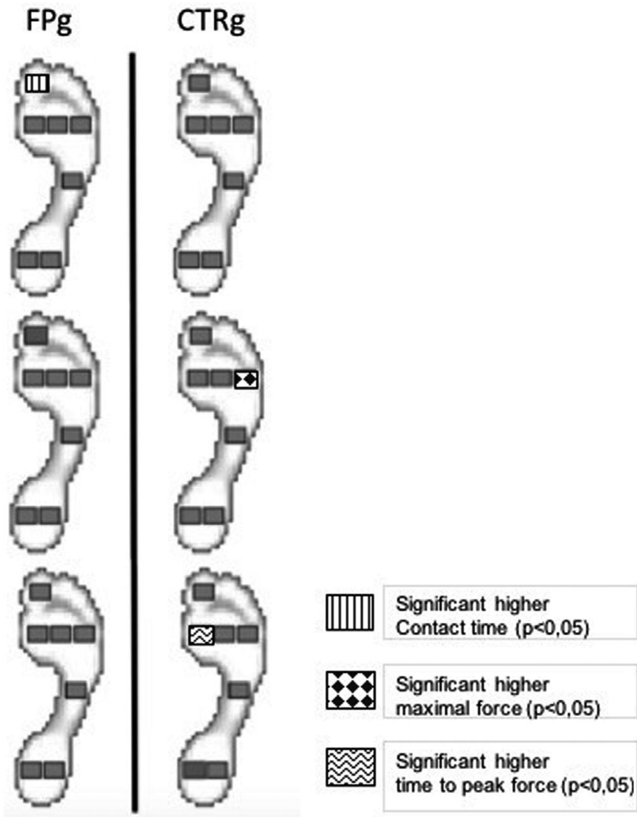

FIGURE 1 Comparison of foot pressure data during the stance phase between groups. Representation of a right foot

higher in the FPg than the CTRg (Tables 2,3). Peak knee internal rotation was also significantly higher in the FPg at foot strike, midstance, and toe-off (Table 3).

3.2 | Foot kinematics

In the FPg, peak forefoot abduction and plantarflexion relative to the tibia were significantly increased in early stance (Table 4-6). Forefoot dorsiflexion ROM (relative to the tibia and the hindfoot), peak forefoot abduction (relative to the tibia and the hindfoot), hindfoot eversion, and hindfoot internal rotation were also increased.

Peak forefoot adduction (relative to the hindfoot and the tibia) was reduced at toe-off, peak hindfoot supination was reduced at midstance (relative to the tibia), and peak hindfoot internal rotation was reduced at toe-off (Table 6).

3.3 | Plantar pressures

Hallux contact time was longer in the FPg, maximal force under the lateral forefoot was reduced, and time to peak force was longer under the medial forefoot (Figure 1; Table 7).

4 | DISCUSSION

This study revealed that pronated foot function alters lower limb and foot kinematics and plantar pressure distributions during gait. The diagnosis of FP was robust since two methods were used to determine foot function type.

4.1 | Effect of foot pronation function on lower limb kinematics during gait

Previous studies of healthy subjects walking with wedges to artificially induce FP have revealed alterations in lower limb kinematics [4,31-36]; however, artificial FP may not represent the true effects and adaptations to FP. Peak knee internal rotation, for example, was increased during the whole stance phase in the FPg compared with the CTRg in agreement with previous studies [4,31-34] and our hypothesis. However, the increase in hip adduction in the FPg was not significant, in contrast to Tateuchi et al, who reported a significant increase in hip adduction and internal rotation with FP.[35] Equally, unlike other reports, we did not find increases in FPg anterior pelvic tilt [4,32,36] or pelvic obliquity.[33,34] However, FPg pelvic ROM in the sagittal and transversal planes during stance was slightly, but significantly, greater in the FPg (with a large effect size in the sagittal plane, and a small effect size in the transverse plane), supporting our hypothesis and confirming the results of Resende et al[34] that showed an effect of FP on pelvic kinematics.[33,34,36] Nevertheless, these results should be interpreted with caution in view of the small differences in angle values between groups. These differences could be generated by a measurement error but could also represent a difference in the gait pattern due to the small ROM that occur at the pelvis.[37]

4.2 | Effect of PF function on foot kinematics

In the FPg, forefoot (relative to the hindfoot) adduction was reduced during the whole stance phase. Although FP has been associated with forefoot supination,[38] in the present study the increase in forefoot supination was, contrary to our hypothesis, not significant. Forefoot (relative to the tibia) dorsiflexion was decreased at the start of stance phase in the FPg, but forefoot dorsiflexion ROM was increased (relative to the tibia and the hindfoot) during the whole of the stance phase. An increase in forefoot dorsiflexion during gait has been associated with a lower degree of midfoot resistance torque, allowing more pronation to occur.[39]

Foot pronation is commonly associated with hindfoot eversion.[3] We found higher peak rearfoot eversion for the FPg during the stance phase and also at midstance, in agreement with our hypothesis. This confirms an association between hindfoot eversion and FP. Hindfoot motion in the transverse plane was also different between groups, with significantly less internal rotation at toe-off in the FPg. This mechanism of hindfoot external rotation and abduction of the forefoot seems likely to have induced more medial displacement of the center of pressure. The combined eversion and lateral displacement of the hindfoot could decrease the stability of the talus, leading to more internal tibial rotation in FP.

4.3 | Effect of pronated foot function on plantar pressure distribution

There were significant between-group differences in plantar pressure distribution, probably due to the different foot kinematics: Increased forefoot plantarflexion at the beginning of the stance phase in the FPg could have been caused by the more everted and plantarflexed position of the hindfoot at foot strike. The association of these motions could also explain the increased forefoot plantarflexion and subsequently increased hallux contact time, which reduced time to peak force at the medial forefoot in the FPg. The maximal force under the lateral forefoot was significantly lower in the FPg; however, this was unsurprising considering the pronation movement and increased medial foot pressure results from this group.[25]

4.4 | Differences between FF and FP

These results thus confirm that differences exist between FF and FP and they should not be confused.[18,19] Forefoot abduction [10-13] and hindfoot external rotation [10] have been shown to be increased in FF; FPg data from the present study supported this. Forefoot dorsiflexion, however, has not previously been reported as increased in FF [11,14,40] yet it was in the FPg. Similarly, forefoot supination has previously been reported as increased in FF [10,14,15] but this was not the case in the FPg. With regard to rearfoot eversion, findings in the literature are inconsistent [11-14,40]: Our results showed that rearfoot eversion was increased in the FPg compared with the CTRg. The divergent results reported for FF could be attributed to the large range of foot kinematics associated with this foot type. For example, peak hindfoot eversion may be greater in pronated FF than in non-pronated FF. Studies including foot posture tests (eg, navicular drop) and functional tests (eg, the CPEI) are necessary to identify different FF profiles and to clarify the inconsistent findings in the literature.

4.5 | Potential role of pronated foot function in MSD

The kinematic changes in the whole lower limb caused by FP might increase the risk of pathology in the lower limb joints and muscles.[3] Increased forefoot abduction, as found in the FPg, has recently been reported as a predictive factor for lower limb MSD.[12,41] Similarly, higher knee internal rotation (also found in the FPg) has been shown to be a risk factor for the development of MSD of the knee and tibia.[7,10,42] The increased pelvic ROM in the sagittal and transverse planes observed in the FPg could accentuate the lumbar lordosis and increase the risk of low back pain.[36,43] Therefore, although this study did not directly assess the relationship between FP and MSD, it seems reasonable to believe that FP might increase the risk of MSD due to the effects of FP on the whole kinematic chain. However, and despite a large effect size in the sagittal plane ROM, these results should be interpreted with caution in view of the small differences in joint angles between groups.

This study has several limitations: (a) It was carried out in a sample of very active men, thus the results may not be generalizable to more sedentary populations, (b) gait was assessed barefoot and the results may have differed for shod gait, (c) walking speed was not controlled and could have affected the kinematic results, and (d) this study was only conducted on men and the kinematics of women may be different.

In summary, this study demonstrated that pronated foot function not only affected the biomechanics of the whole foot, but also the lower limbs and pelvis. Both similarities and differences were found between FF and FP, demonstrating that static foot type and dynamic foot function are separate entities. Our results also confirmed that both the forefoot and rearfoot are involved in global foot pronation [3,41]: a combination which could increase knee internal rotation and alter pelvic motion during gait. These kinematic changes are consistent with biomechanical variables that have been shown to increase the risk of MSD. Further studies are therefore needed to examine the relationship between MSD and pronated foot function.

5 | PERSPECTIVE

This study has important clinical implications relating to the understanding of both foot and lower limb movement in individuals with pronated foot function. This work also confirmed the importance of studying transverse plane forefoot motion in pronated foot function. The results suggest that individuals with pronated foot function, though asymptomatic, may have a greater risk of lower limb MSD due to the increase in forefoot abduction.[12,41] Studies are therefore required to fully elucidate the relationship between FP and MSD. In addition, the increase in forefoot dorsiflexion in the FPg is a mechanism for foot collapse when the foot is in a flat position on the ground. This may indicate that in FP, there is an increased reliance on the flexible mode of foot function,[12] and a decreased use of the rigid propulsive mode. Strengthening of the intrinsic foot muscles could limit this phenomenon and could be a useful injury prevention strategy in asymptomatic pronators. Finally, although this result requires confirmation, pronated foot function could alter lower limb and pelvic kinematics and increase constraints on the knee and the lumbar region. We therefore suggest that foot function should be evaluated as part of a holistic assessment in the case of knee injury or low back pain.

CONFLICT OF INTEREST

We certify that none of the authors have any financial involvement in an organization or entity that has a direct financial interest in the subject matter or materials discussed in the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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