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Contributions of foot muscles and plantar fascia morphology to foot posture

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1 **Abstract**

2 *Background:* The plantar foot muscles and plantar fascia differ between different foot postures.
3
4 However, how each individual plantar structure contribute to foot posture has not been explored. The
5 purpose of this study was to investigate the associations between static foot posture and morphology
6 of plantar foot muscles and plantar fascia and thus the contributions of these structures to static foot
7 posture.
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10 *Methods:* A total of 111 participants were recruited, 43 were classified as having pes planus and 68 as
11 having normal foot posture using Foot Posture Index assessment tool. Images from the flexor
12 digitorum longus (FDL), flexor hallucis longus (FHL), peroneus longus and brevis (PER), flexor
13 hallucis brevis (FHB), flexor digitorum brevis (FDB) and abductor hallucis (AbH) muscles, and the
14 calcaneal (PF1), middle (PF2) and metatarsal (PF3) regions of the plantar fascia were obtained using a
15 Venue 40 ultrasound system with a 5–13 MHz transducer.
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18 *Results:* In order of decreasing contribution, PF3>FHB>FHL>PER>FDB were all associated with FPI
19 and able to explain 69% of the change in FPI scores. PF3 was the highest contributor explaining 52%
20 of increases in FPI score. Decreased thickness was associated with increased FPI score. Smaller cross
21 sectional area (CSA) in FHB and PER muscles explained 20% and 8% of increase in FPI score.
22 Larger CSA of FDB and FHL muscles explained 4% and 14% increase in FPI score respectively.
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25 *Conclusion:* The medial plantar structures and the plantar fascia appear to be the major contributors to
26 static foot posture. Elucidating the individual contribution of multiple muscles of the foot could
27 provide insight about their role in the foot posture.
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38 **Keywords:** Foot muscles, Plantar fascia, Morphology, Ultrasound, Pes planus, Foot Posture Index
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2 **Introduction**

3 Forces produced by intrinsic and extrinsic foot muscles, and transmitted by the plantar fascia, act
4 across the numerous rear, mid and forefoot joints and are thus assumed to contribute to foot posture.
5 Differences in foot posture are associated with altered plantar pressure patterns [1] with likely
6 alteration of external joint moments as well as kinaesthesia inputs [2]. Motor responses to the altered
7 sensory inputs could thereafter affect muscle function and the foot mechanics associated with that foot
8 posture [2, 3]. Indeed, muscle strength and function have been shown to be related to foot posture [4]
9 and different foot kinematics exhibited between cavus, planus and normal foot postures [5].
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16 Muscle morphology (cross sectional area (CSA) and thickness) can be indicative of muscle
17 performance, including strength [6], and has been used to investigate relationships between foot
18 muscles and foot posture. Murley et al. [7] reported an association between flat-arched feet and
19 thicker peroneus longus muscle and tibialis anterior tendon, and thinner Achilles tendon
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24 Furthermore, increased navicular drop, indicative of a more pronated foot posture, has been shown to
25 occur after impairing intrinsic muscles using anaesthesia and a fatigue protocol. Consequently,
26 electrically stimulated plantar intrinsic muscles have shown to produce sufficient forces to reduce
27 longitudinal arch deformation under load [8]. This suggests variation in foot posture may be due to
28 variation in muscle function [9].
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34 Flexor hallucis longus (FHL) and flexor digitorum longus (FDL) are known contributors to the shape
35 of the medial longitudinal arch and act by resisting midfoot dorsiflexion associated with foot
36 pronation [10]. We have previously shown that the CSA of these two extrinsic muscles is greater in
37 pes planus than normal foot posture [11], although the intrinsic supinator muscles were smaller in pes
38 planus. These extrinsic and intrinsic muscles might be expected to change morphology in a similar
39 way since they create the same moments around many foot joints. According to Hintermann et al.
40 [10], and using the tibialis posterior moment arm as reference (1.00), average inverter moment arms
41 were 0.75 for flexor digitorum longus, and 0.62 for flexor hallucis longus. Perhaps in pes planus the
42 different foot posture reduces the FHL and FDL moment arm at the rearfoot [12] so that they need to
43 generate greater forces to contribute the required moments to resist external pronation moments and
44 facilitate normal sagittal plane ankle function. This may result in hypertrophy as seen in posterior
45 tibial tendon dysfunction induced pes planus [13], and reduced demand for forces from intrinsic
46 supinators, hence the CSA of extrinsic muscles would be greater and that of intrinsic muscles
47 reduced. Murley et al. [14] reported decreased peroneal muscle activity in flatfeet which would be
48 complementary to greater inverter activity associated with their greater CSA in pes planus.
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1 The plantar fascia, particularly the forefoot portion, was also reported to be thinner in pes planus foot
2 types [11], perhaps via a similar mechanism. However, its function is also coupled to transmission of
3 Achilles tendon forces to the forefoot during walking and thus is not solely concerned with foot
4 posture [15] and also toe flexion/extension.
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8 There is emerging evidence that intrinsic and extrinsic muscles and plantar fascia differ between
9 different foot postures. The multiple muscles of the foot differ from each other in terms of size
10 (longus/brevis) but also location (intrinsic/extrinsic, medial/lateral) and are therefore likely to
11 contribute to foot posture in different ways. However, how individual plantar structures contribute to
12 foot posture has not been explored. Understanding major and minor contributors could be relevant in
13 the design and evaluation of interventions for foot muscle strength and clinical pathologies associated
14 with specific foot types. The purpose of this study, therefore, was to investigate any associations be-
15 tween foot posture and measures of intrinsic and extrinsic foot muscles and plantar fascia and thus the
16 contributions of these structures to foot posture.
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24 **Methods**

25 *Participants*

26 A total of 111 subjects (61 males, 50 females) aged between 18 and 47 years were recruited from
27 university communities. They were free of lower extremity injuries in the past 12 months and had no
28 history of lower extremity surgery and visual or vestibular disorders. The study was approved by the
29 institutional ethical committee. Each participant provided informed consent before participating in the
30 study.
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38 *Foot posture assessment*

39 The Foot Posture Index (FPI) was employed for quantitative assessment of foot posture by an
40 experienced physiotherapist (worked in musculoskeletal care for 8 years). Both feet of each
41 participant were assessed for the six FPI criteria. The six individual scores were then combined to
42 give a composite score between -12 and+12. A composite score between 0 and 5 indicated a normal
43 foot posture, ≥ 6 a pes planus posture.
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50 *Measurement of the muscle cross-sectional area and plantar fascia thickness*

51 Ultrasound can be used to reliably measure foot muscle and plantar fascia features [16, 17] and was
52 the method chosen for this study. Muscle CSA and PF thickness were scanned by the Chief
53 Investigator (SA), who has had extensive training on foot and ankle musculoskeletal ultrasound
54 scanning. The scanning took place one week after the FPI assessment and the assessor was blind to
55 the FPI Score. A Venue 40 musculoskeletal ultrasound system (GE Healthcare, UK) with a 5–13
56 MHz wideband linear array probe with 12.7 mm to 47.1 mm surface area was used to image CSA of
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1 each structure and thickness of the plantar fascia in the right foot of each participant . Details of probe
2 position and orientation for each structure, and all other aspects of the protocol are explained
3 elsewhere [11, 16].
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6 Each participant lay in the prone position for scanning PF, FHB and FDB muscles, and in the supine
7 position for scanning the AbH, FDL, FHL, and PER muscles. The medial part of the PF was scanned
8 longitudinally at three different regions: calcaneal part (PF1); middle part (PF2); and metatarsal part
9 (PF3) attached to the second MTP joint based on where the highest pressure was previously found
10 during push-off [18]. All scans were performed with the ankle joint in the neutral position. The CSA
11 and thickness measures were taken by the ultrasound user (SA), who remained blind to the FPI scores,
12 using Image J software (National Institute for Health, Bethesda, USA) and as described in the
13 previous studies. The mean value was derived from three images.
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21 *Data analysis*

22 Rasch transformation of the raw FPI values described by Keenan et al. [27] was used for conversion
23 of the raw FPI categorical data to continuous data for parametric statistical tests. Data from the right
24 foot was analyzed in order to satisfy the independence assumption of statistical analysis [19].
25 Variables with skewed distributions were log transformed.
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31 Univariate Pearson correlation coefficients were calculated for transformed FPI and the ultrasound
32 variables. The ultrasound variables that significantly correlated with transformed FPI were input as
33 independent variables into a multiple regression analysis to find major contributors to the FPI. The
34 linear regression analysis was run following the backward stepwise elimination procedure based on
35 the probability of F determined as a stepping method criteria. A significance level of $P < 0.05$ was
36 required for entry into the model, and $P > 0.06$ was the criterion for removal . The maximum value of
37 variance inflation factor (VIF) was determined as 5.0 for multicollinearity. All statistical analysis was
38 performed using IBM SPSS software version 20.0 (IBM Corporation, Armonk, NY, USA).
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46 **Results**

47 Forty-three individuals (38%) had pes planus (18 females) with mean FPI of 7.86 ± 1.58 (range 6 –
48 11) and Rasch transformed means of 5.55 ± 1.21 (range 3.81 – 7.77). The remaining 68 had normal
49 feet (32 females) with mean FPI of 1.41 ± 1.44 (range 0 – 5) and Rasch transformed mean FPI of 0.78
50 ± 0.97 (range -0.21 – 3.81). Demographics of the participants are shown in Table 1.
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56 *<Insert Table 1 about here>*

57 As a result of the correlation analysis (see Table 2), PF1 was identified as the only variable that was
58 not significantly correlated to FPI and therefore excluded from the regression analysis. All other
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1 variables were included in the multiple regression analysis. Higher transformed FPI scores (i.e. a
2 more pes planus foot type) were correlated with smaller CSA of the AbH ($r = -0.42$, $p < 0.0001$), FHB
3 ($r = -0.44$, $p < 0.0001$) and PER ($r = -0.28$, $p = 0.003$) muscles. Higher transformed FPI scores were
4 also correlated with thinner PF2 ($r = -0.54$, $p < 0.0001$) and PF3 ($r = -0.72$, $p < 0.0001$). Higher
5 transformed FPI scores were also correlated with larger CSA of FDB ($r = 0.19$, $p = 0.045$), FDL ($r =$
6 0.35 , $p < 0.0001$) and FHL ($r = 0.37$, $p < 0.0001$). Distribution of PF thickness and cross-sectional area
7 of the muscles are represented in Table 3.
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13 *<Insert Table 2 about here>*

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15 *<Insert Table 3 about here>*
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18 A total of eight variables that significantly correlated to FPI were narrowed to five as AbH, FDL and
19 PF2 were excluded from the final model based on the stepping method criteria [28]. The resulting
20 five-variable model ($F = 47.48$; $p < 0.0001$) had an $r = 0.83$, $r^2 = 0.69$, and variance inflation factor
21 (VIF) < 3.0 (Table 4). The five variables in the final model accounted for 69% of variance in the FPI
22 score. Of the individual independent variables, decreased thickness of PF3 was the highest contributor
23 explaining 52% ($\beta = -0.51$) of increases in FPI. Smaller CSA in FHB and PER muscles explained
24 20% ($\beta = -0.23$) and 8% ($\beta = -0.16$) of increases in FPI respectively. Larger CSA of FDB and FHL
25 muscles explained 4% ($\beta = 0.33$) and 14% ($\beta = 0.32$) of increases in FPI respectively.
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33 *<Insert Table 4 about here>*
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36 Measured mean FPI was 2.63 ± 2.56 and the predicted FPI mean based on the CSA of the muscles
37 and PF3 thickness in the model was 2.63 ± 2.13 (Figure 1).
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44 **Discussion**

45 We have found, in order of decreasing contribution, PF3>FHB>FHL>PER>FDB were all associated
46 with FPI ($r = 0.83$), and were able to explain 69% of the change in FPI scores (Figure 1). Among
47 these variables, plantar fascia was the main contributor to change in FPI scores, contributing more
48 than the other four factors combined. The role of these five variables in foot posture agrees with prior
49 studies that have investigated the function of these structures [11, 20] but their relative contributions
50 have not been described before.
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58 This cross-sectional analysis describes static foot posture and relates it to muscle features that are
59 assumed to infer the dynamic function of the muscle e.g. larger CSA equates to greater muscle
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1 strength and therefore greater forces during gait [21]. The muscle forces in standing and thus during
2 our foot posture measures would be different than those during gait. We cannot ascertain whether a
3 change in any of the structures evaluated would lead to a change in foot posture and therefore cannot
4 infer a cause-and-effect relationship between the foot structures and foot posture. However, within the
5 context of this limitation, we have identified apparent different contributions of the selected muscles
6 and plantar fascia to foot posture.
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11 Plantar fascia thickness at the metatarsal region (PF3) was the greatest contributor to change in FPI
12 (52%). That fascia was found to contribute more than muscles could perhaps relate to the fact we
13 assessed posture statically, during which perhaps passive structures rather than muscle forces are
14 relied upon. However, if this were true then PF1 and PF2 might have also been significant
15 contributors and they were not. The plantar fascia has been reported to contribute as much as 80% of
16 the force resisting lowering of the medial arch [20]. In their cadaveric study, Huang et al. [22] found
17 that the plantar fascia was highest contributor (55.6%) to arch stability among the other static
18 structures, and their simulated model showed that there was little muscle activity during standing
19 posture.
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28 That both extrinsic (FHL, PER) and intrinsic (FHB, FDB) muscles were contributors in the final
29 regression model perhaps reflects their shared function in determining foot posture. However, there
30 was no pattern in contribution in terms of muscle size and thus assumed muscle forces and foot
31 posture. FHB was second greatest contributor yet is smaller in muscle volume and tendon thickness (a
32 surrogate measure of forces born) than FHL and PER. Whilst the shortening capacity of FHB is
33 certainly smaller than that of extrinsic muscles [23], Hashimoto et al. [4] found increased medial
34 longitudinal arch (MLA) height after use of exercises strengthening intrinsic flexor muscles including
35 FHB. Decreased FPI scores and increased MLA height with exercises targeting intrinsic muscles have
36 also been reported [24]. However, muscles associated with the hallux and medial side of the foot
37 (FHB and FHL) were ranked 2nd and 3rd contributors, and the main contributor, PF3, was measured
38 on the medial side of the foot too. FHL and FHB together contributed 34% to the FPI scores whereas
39 PER and FDB contributed only 12%. FHB contributed 14% whereas the more lateral FDB
40 contributed 4% to the FPI scores. The contribution from medial structures might therefore be more
41 important to foot posture. Measures of lateral plantar fascia and flexor digiti minimi muscle would be
42 required to clarify relative contributions of other lateral/medial structures.
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55 Thinner fascia could mean higher loads if those loads lengthened the fascia. However, it could be
56 speculated that the PF could not stretch uniformly throughout its length. Morphologically, PF3 is
57 thinner and could be more sensitive to tensile forces compared to other regions (PF1 and PF2). As the
58 highest tension load was found at the PF3 region during the push off [25] this may indicate elongation
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1 [26, 27] and further decrease thickness of the plantar fascia at the metatarsal region (PF3). However,
2 given the weakness of some correlations it is not clear why there may be increased CSA in some
3 muscles with apparently contradictory smaller CSA in muscles with similar function. This could be
4 related to the so called windlass mechanism. Hicks concluded that the toes are forced into an extended
5 position in toe-standing and walking by the action of body weight, and the arch is caused to rise by
6 the windlass mechanism (tensile forces in the plantar fascia) without direct action of any muscle [28].
7 Other studies have also revealed that whilst plantar fascia provides passive stiffness to the
8 longitudinal arch, plantar intrinsic and extrinsic muscles continuously regulate this stiffness [26, 29].
9 The windlass mechanism also works in a reverse direction when the foot is loaded. As the MLA
10 flattens in pes planus foot, tensional force increases in the plantar fascia [29], the reverse windlass
11 mechanism therefore pulls the metatarsophalangeal (MTP) joints into flexion [29, 30]. This action is
12 normally shared by plantar fascia and plantar intrinsic muscles. This could also mean that a reverse
13 windlass mechanism lessens the intrinsic muscle activity required for MTP joint flexion.
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23 This work poses several new questions. Does increased load in the plantar fascia lead to thinner fascia
24 or hypertrophy? Thicker fascia in cases of heel pain may suggest the latter, but this is equally likely to
25 be the effects of inflammation as much as tissue hypertrophy. Also, the rationale for using extrinsic
26 rather than intrinsic muscles is not clear, nor is the use of lesser toe rather than hallux muscles. How
27 and why these mechanisms are used to control foot behaviour remains unclear and points to the need
28 for research that explains how the body uses the duplication in foot and ankle musculature and plantar
29 fascia to vary foot stiffness and how this leads to differences in static foot posture. A mechanism
30 clearly exists since we were able to explain 69% of variation in the FPI scores by a combination of 5
31 measures of muscle and fascia structure. However, PF data explained more than 50% of the variance
32 in FPI scores and so is clearly the starting point for any explanation. The relationship between plantar
33 fascia morphology and its dynamic behaviour requires further clarification.
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43 There are several limitations that need to be acknowledged. The age and BMI differences between our
44 groups were not considered in the analysis values were similar in both groups. However, these
45 factors may influence the muscle morphology. The gender balance in each group was not equal, and
46 may also affect muscle size. Whilst ultrasound has a good to excellent inter-rater reliability it is user
47 dependent. We did not directly test the intra-rater reliability of the operator, although the values for all
48 structures measured are in line with prior literature. Finally, cavus foot types have not been included
49 in the study and thus one end of the foot posture spectrum is absent. It is also acknowledged that only
50 FPI values for normal and planus feet have been included in the multiple regression analysis
51 compared to total range from planus foot (-12) to cavus foot (+12). Further research is required to
52 confirm our findings over the full range of foot postures.
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In conclusion, we have demonstrated the contribution of the plantar muscles and fascia structure to FPI scores. The medial plantar structures appear to be the major contributors to foot posture with the PF alone contributing 52% of changes in FPI. Elucidating the individual contribution of multiple muscles that differ from each other in terms of size and location, and plantar fascia structure, provide insight about their role in foot posture. Further studies are warranted to explore the interactions between the individual structures and how they each and collectively contribute to differences in dynamic foot function and static foot posture.

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Table 1: Demographic features of the groups

	Pes Planus		Normal Feet		<i>p</i>
	Mean	\pm SD	Mean	\pm SD	
Age	23.74	\pm 4.87	24.79	\pm 6.38	0.331
Body Weight	69.30	\pm 13.16	69.84	\pm 13.70	0.838
Body height	171.65	\pm 8.31	171.66	\pm 8.38	0.995
Body Mass Index	23.36	\pm 3.25	23.60	\pm 3.67	0.725

Table 2: Correlation coefficients between FPI and cross-sectional area of the muscles and plantar fascia thickness

Variables	r	p
AbH	-0.42	< 0.0001
FDB	0.19	= 0.045
FDL	0.35	= 0.0002
FHB	-0.44	< 0.0001
FHL	0.37	< 0.0001
PER	-0.28	=0.003
PF1	-0.01	=0.925*
PF2	-0.54	< 0.0001
PF3	-0.72	< 0.0001

*Not significant

AbH, Abductor hallucis; FDB, flexor digitorum brevis; FDL, Flexor digitorum longus; FHB, Flexor hallucis brevis; FHL, Flexor hallucis longus, PER, peroneus longus and brevis; PF1, plantar fascia (calcaneal part); PF2 plantar fascia (middle part); PF3, plantar fascia (metatarsal part)

Table 3: Distribution of the PF thickness and CSA of the muscles based on the FPI.

FPI	N	AbH-CSA Mean±SD	FDB-CSA Mean±SD	FDL-CSA Mean±SD	FHB-CSA Mean±SD	FHL-CSA Mean±SD	PER-CSA Mean±SD	PF1-T Mean±SD	PF2-T Mean±SD	PF3-T Mean±SD
0-5	68	2.71±0.36	2.06±0.55	2.43±0.62	3.20±0.47	2.84±0.67	3.68±0.82	0.33±0.05	0.19±0.03	0.13±0.01
6-12	43	2.28±0.43	2.19±0.48	2.75±0.60	2.69±0.44	3.31±0.69	3.21±0.66	0.33±0.05	0.16±0.02	0.10±0.02
Total	111	2.54±0.44	2.11±0.53	2.56±0.64	3.00±0.52	3.03±0.71	3.50±0.79	0.33±0.05	0.17±0.03	0.12±0.02

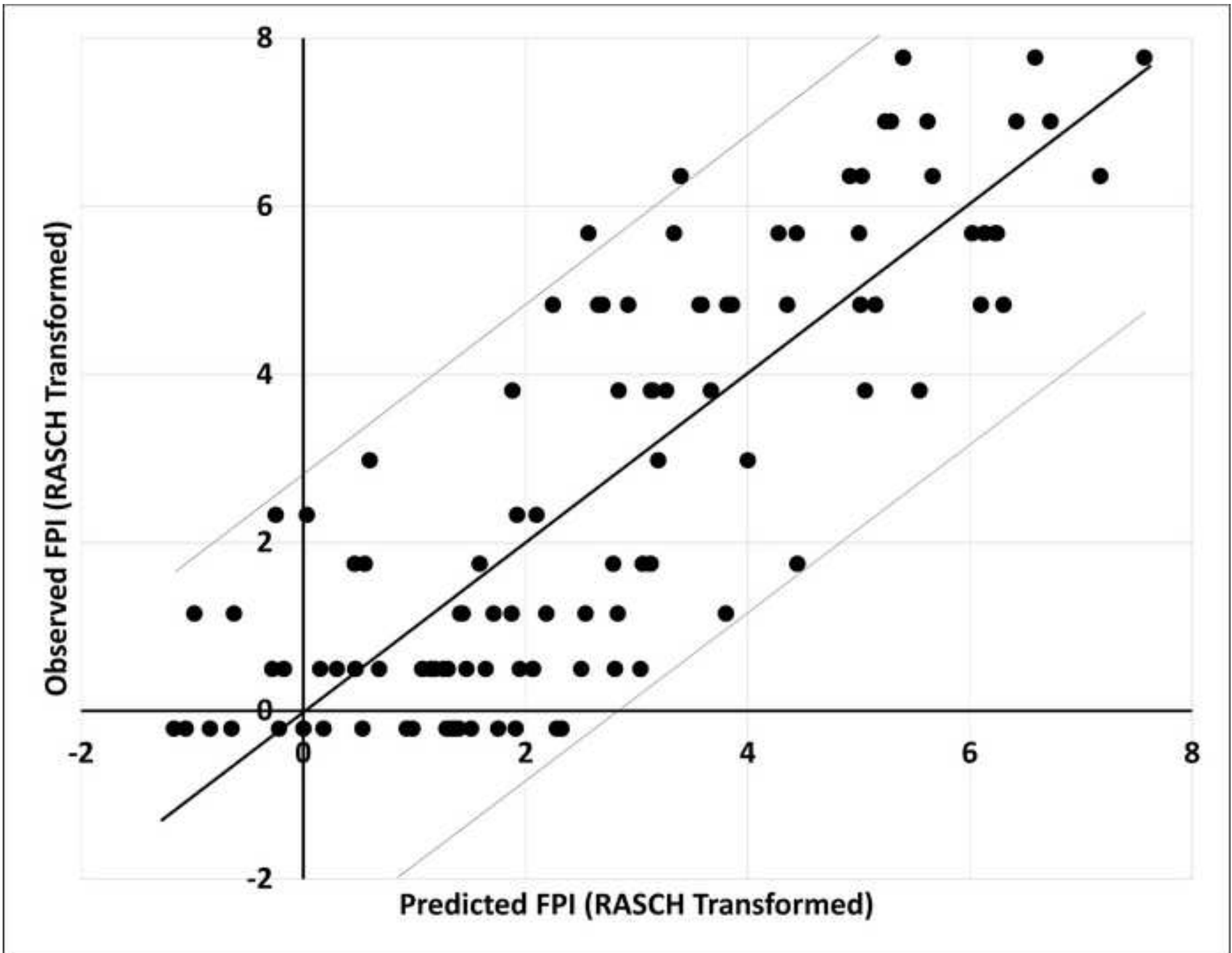
FPI: Foot Posture Index; Mean±SD: Mean (cm²) ±Standard Deviation; AbH: Abductor hallucis; FDB: Flexor digitorum brevis; FDL: Flexor digitorum longus; FHB: Flexor hallucis brevis; FHL: Flexor hallucis longus; PER: Peroneal muscles; PF (1,2,3): plantar fascia (calcaneal portion, middle portion, metatarsal portion); CSA: Cross-sectional area; T: Thickness

Table 4: Multiple regression between FPI and cross-sectional area of the muscles and plantar fascia thickness remained in the final model ($F = 47.48$; $r = 0.83$, $p < 0.0001$, $r^2 = 0.69$), and rank of contribution to FPI score.

Dependent	Independents	β -coefficient	r^2	p	VIF	Rank
FPI	FDB	0.33	0.04	$= 0.0006$	1.20	5
	FHB	-0.23	0.20	< 0.0001	2.05	2
	FHL	0.32	0.14	< 0.0001	2.28	3
	PER	-0.16	0.08	$= 0.001$	1.52	4
	PF3	-0.51	0.52	< 0.0001	2.96	1

FPI, Foot Posture Index; *FDB*, flexor digitorum brevis; *PER*, peroneus longus and brevis; *PF3*, plantar fascia (metatarsal part); *VIF*, variance inflation factor.

7. Figure(s)
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7. Figure(s)

Figure 1: Regression plot displaying the association ($F = 47.48$, $r = 0.83$; $r^2 = 0.69$) between observed FPI and predicted FPI using cross-sectional area of the muscles and plantar fascia thickness from the group of normal and pes planus feet.

*Research Highligts

- The medial plantar structures appear to be the major contributors to static foot posture.
- Plantar fascia is the main contributor among the plantar structures.
- Plantar muscles have less contribution on static foot posture.