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Gender differences in multi-segment foot kinematics and plantar fascia strain during running

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This study aimed to determine whether there are gender differences in multi-segment foot kinematics and plantar fascia strain during running. Fifteen male and fifteen female participants ran at 4.0- m.s^{-1}. Multi-segment foot kinematics and plantar fascia strain were quantified using a motion capture system and compared between genders using independent samples t-tests. The results showed that plantar fascia strain was significantly greater in males (0.09 ± 0.04) compared to females (0.06 ± 0.03). Furthermore male runners (-9.72 ± 3.09) were also associated with a significantly larger peak calcaneal eversion angle compared to females (-6.03 ± 2.33). Given the proposed relationship between high levels of plantar fascia strain as well as excessive coronal plane rotations of the foot segments and the etiology of injury, it is likely that the potential risk of the developing running injuries in relation to these mechanisms is higher in males.

Keywords: Running, gender, biomechanics

Recreational distance running is currently an extremely popular pastime for both males and female alike [1]. Although regular running activities offer a plethora of physiological benefits [2], the susceptibility of runners to degenerative chronic injuries is also well documented [3]. In their retrospective analysis of chronic running injuries, Taunton et al [4] demonstrated that patellofemoral pain, iliotibial band syndrome, and plantar fasciitis were the most commonly experienced chronic pathologies. Female runners have been shown to be at greater risk from chronic injuries due to running in comparison to age matched males [5].

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It has been frequently hypothesized, in addition to anatomical variances, that differences in lower extremity running biomechanics may be a causative mechanism that explains why females sustain different injury patterns in comparison to males [1,6,7]. Analyses investigating the prevalence of pathologies indicate females are twice as likely to sustain a chronic injury related to running compared to males [5].

Gender differences in lower extremity kinematics have been examined previously in biomechanical literature. Sinclair et al [7] determined that female runners exhibited significantly greater peak knee abduction and rotation angles in comparison to males. Similarly, Ferber et al. [6] showed a significantly greater peak hip internal rotation and adduction angle and a significantly larger peak knee abduction angle in female runners. Sinclair & Taylor [1] compared gender differences in tibiocalcaneal kinematics during the stance phase of running. They showed that peak eversion and tibial internal rotation angles were significantly greater in female runners. These studies display a clear pattern in terms of the gender differences in running biomechanics showing that differences primarily occur in the coronal and transverse planes, which may explain the increased susceptibility of female runners to chronic injuries. Each of the aforementioned investigations utilized a single segment foot model however, and did not quantify plantar fascia strain as part of their experimental protocol. Therefore, there is currently a paucity of information regarding the potential gender differences in multi-segment foot kinematics and strain experienced by the plantar fascia during running.

This study aims to determine whether there are gender differences in multi-segment foot kinematics and plantar fascia strain during the stance phase of running. A study of this nature may be beneficial to the biomechanics and clinical communities as it may provide further insight into the mechanisms by which male and female runners suffer from distinct chronic injury patterns.

Methods

Participants

Fifteen male (age 26.98 years SD 2.87, height 1.74 m SD 0.15, mass 71.66 kg SD 4.74) and fifteen female (age 24.22 years SD 2.56, height 1.68 m SD 0.16, mass 64.22 kg SD 3.79) participants volunteered to take part in this study. All were free from musculoskeletal pathology at the time of data collection and provided informed consent in written form. Ethical approval was obtained from a University ethical committee in accordance with the declaration of Helsinki.

Procedure

Participants completed five trials running at 4.0 $m.s^{-1}$ ± 5%. Multi-segment foot kinematics and plantar fascia strain were quantified using an eight-camera motion analysis system (Qualisys Medical, Sweden) with a sample rate of 250 Hz. Participants struck an embedded force platform (Kistler 9281CA, Kistler Instruments, UK) sampling at 1000 Hz with their dominant foot [8]. The stance phase of running was determined as the time over which >20 N of force in the axial direction was applied to the force platform [9]. The calibrated anatomical systems technique (CAST) procedure for modelling and tracking segments was adhered to [10]. Markers were placed on anatomical landmarks in accordance with the Leardini et al. [11] foot model protocol allowing the anatomical frames of the calcaneus (Cal), midfoot (Mid), and forefoot (Fore) to be defined. Markers were positioned on the medial and lateral femoral epicondyles to allow the anatomical frame of the tibia (Tib) to be delineated and a rigid tracking cluster was also positioned on the tibia. Participants wore the same footwear throughout (Saucony Pro Grid Guide II, Saucony, USA) in sizes 5-10 men's UK.

Data processing

Retroreflective marker trajectories were identified using Qualisys track manager and then exported to Visual 3D (C-motion, Germantown USA). Marker trajectories were filtered at 12 Hz using a low pass zero-lag Butterworth filter. Cardan angles were used to calculate 3-D articulations of the foot segments. Stance phase angles were computed using an XYZ cardan sequence of rotations between the calcaneus-tibia (Cal-Tib), midfoot-calcaneus (Mid-Cal), forefoot-midfoot (Fore-Mid), and forefoot-calcaneus (Fore-Cal). 3-D kinematic parameters which were extracted for statistical analysis were 1) angle at footstrike, 2) angles at toe-off, 3) range of motion from footstrike to toe-off during stance, 4) peak angle during stance, and 5) relative range of motion (representing the angular displacement from footstrike to peak angle). Plantar fascia strain was determined by calculating the distance between the first metatarsal and calcaneus markers and quantified as the relative position of the markers was altered. Plantar fascia strain was calculated as the change in length during the stance phase divided by the original length [12].

Statistical analysis

Descriptive statistics were calculated for both the orthotic and no-orthotic conditions. Differences in kinematic and plantar fascia strain parameters were examined using independent samples t-tests with significance accepted at the $p<0.05$ level. A Shapiro-Wilk test was used to screen the data for normality, it was confirmed that the normality assumption was not violated. Effect sizes for all statistical main effects were calculated using a Cohen's *D*. Statistical procedures were undertaken using SPSS v21 (IBS, SPSS INC USA).

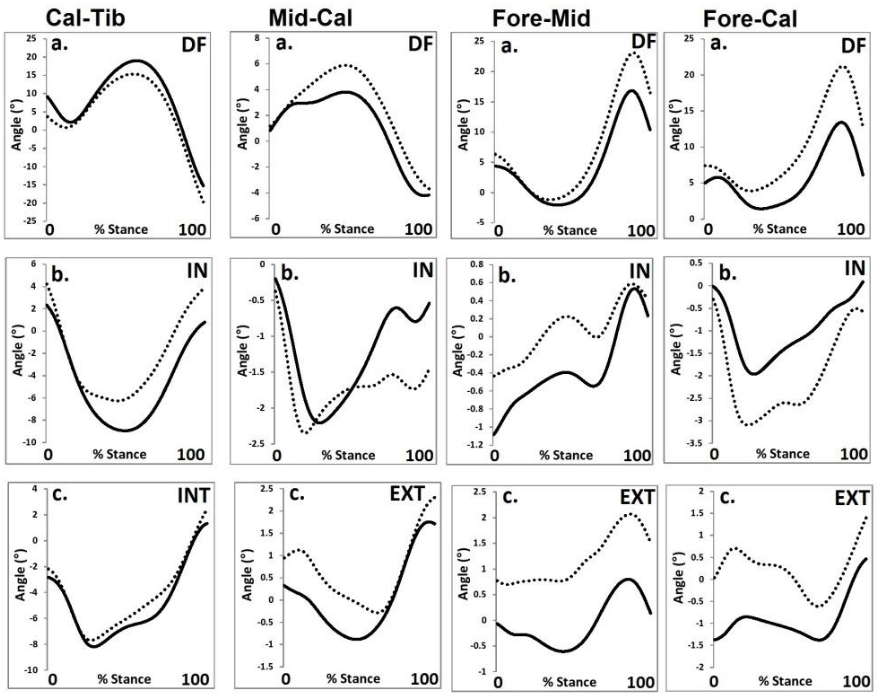

Figure 1: Multi-segment foot kinematics during running in the a. sagittal, b. coronal and c. transverse planes as a function of gender markers (Solid=male and Dot=female) (DF=dorsiflexion, IN=inversion, INT=internal, EXT=external) (Cal=calcaneus, Mid=midfoot, Fore=forefoot, Tib=tibia).

	Male		Female		
	Mean	**SD**	**Mean**	**SD**	
Sagittal plane					
Angle at footstrike	10.74	4.91	3.85	5.58	*
Angle at toe-off	-15.03	4.90	-19.69	6.39	
Peak angle	20.22	4.54	15.70	4.46	*
Range of motion	25.77	3.95	24.20	7.74	
Relative range of motion	9.48	3.61	11.85	4.92	
Coronal plane					
Angle at footstrike	2.20	2.77	4.25	2.83	
Angle at toe-off	0.26	4.38	3.94	3.58	*
Peak angle	-9.72	3.09	-6.03	2.33	*
Range of motion	2.70	2.87	3.75	2.59	
Relative range of motion	11.92	3.19	10.28	3.12	
Transverse plane					
Angle at footstrike	-3.30	4.58	-2.17	4.42	
Angle at toe-off	1.11	6.21	2.62	3.84	
Peak angle	-8.86	4.67	-8.49	4.39	
Range of motion	4.44	3.02	5.42	2.98	
Relative range of motion	5.57	2.76	6.32	2.51	

Table 1: Cal-Tib kinematics as a function of gender. (* =significant difference)

	Male		Female		
	Mean	**SD**	**Mean**	**SD**	
Sagittal plane					
Angle at footstrike	1.04	2.44	1.18	2.62	
Angle at toe-off	-4.05	1.92	-3.55	2.87	
Peak angle	3.29	2.05	6.10	2.74	*
Range of motion	5.09	1.12	4.76	1.86	
Relative range of motion	2.25	1.07	4.92	2.33	
Coronal plane					
Angle at footstrike	-0.42	1.09	-0.31	2.87	
Angle at toe-off	-0.79	1.28	-1.35	4.29	
Peak angle	-2.71	1.38	-3.44	4.00	
Range of motion	0.62	0.25	1.55	1.39	
Relative range of motion	2.29	0.68	3.12	2.37	
Transverse plane					
Angle at footstrike	0.50	0.98	0.86	1.94	
Angle at toe-off	1.86	1.16	2.20	1.87	
Peak angle	-0.60	1.18	-0.69	2.52	
Range of motion	1.39	0.82	1.54	0.95	
Relative range of motion	1.10	0.64	1.55	1.42	

Table 2: Mid-Cal kinematics as a function of gender. (* =significant difference)

	Male		Female		
	Mean	**SD**	**Mean**	**SD**	
Sagittal plane					
Angle at footstrike	4.33	1.17	6.24	5.41	
Angle at toe-off	9.96	2.28	16.08	9.47	*
Peak angle	16.92	2.79	23.70	8.84	*
Range of motion	5.63	1.55	9.84	5.03	*
Relative range of motion	12.59	2.27	17.46	5.35	*
Coronal plane					
Angle at footstrike	-1.17	0.67	-0.44	1.09	
Angle at toe-off	0.07	0.96	0.40	1.45	
Peak angle	0.53	1.16	1.27	1.10	
Range of motion	1.24	0.71	1.08	0.59	
Relative range of motion	1.70	0.97	1.68	0.55	
Transverse plane					
Angle at footstrike	-0.07	0.30	0.69	2.24	
Angle at toe-off	0.15	0.95	1.43	2.91	
Peak angle	1.36	0.98	3.05	2.44	
Range of motion	0.23	0.77	1.46	0.87	
Relative range of motion	1.23	0.79	2.36	1.56	

Table 3: Fore-Mid kinematics as a function of gender. (* =significant difference)

	Male		Female		
	Mean	**SD**	**Mean**	**SD**	
Sagittal plane					
Angle at footstrike	5.15	2.90	7.33	6.70	
Angle at toe-off	5.81	2.90	12.45	9.80	*
Peak angle	13.68	3.88	22.08	8.65	*
Range of motion	1.77	1.05	5.42	4.27	*
Relative range of motion	8.52	2.90	14.75	4.55	*
Coronal plane					
Angle at footstrike	-0.31	1.34	-0.17	2.74	
Angle at toe-off	-0.28	1.84	-0.45	4.04	
Peak angle	-2.64	1.62	-4.11	2.69	
Range of motion	0.82	0.31	1.87	1.24	
Relative range of motion	2.33	0.60	3.94	2.50	
Transverse plane					
Angle at footstrike	-1.26	1.41	-0.05	1.94	
Angle at toe-off	0.59	1.13	1.33	1.88	
Peak angle	-1.75	1.19	-1.61	2.64	
Range of motion	1.85	0.62	1.91	1.08	
Relative range of motion	0.49	0.57	1.56	1.47	

Table 4: Fore-Cal kinematics as a function of gender. (* =significant difference)

Results

Although qualitative examination of the kinematic curves from males and females indicate that they predominately followed a similar pattern, significant differences were observed between genders. Figure 1 and Tables 1-4 present the mean multi-segment foot parameters and stance phase joint angle curves obtained as a function of gender.

Plantar fascia strain

Males (0.09 ± 0.04) were associated with a significantly ($t_{(28)}$=2.55, $p<0.05$, *D*=0.96) greater plantar fascia strain compared to females (0.06 ± 0.03).

Foot kinematics

Cal-Tib

In the sagittal plane, males were shown to exhibit significantly greater dorsiflexion at footstrike ($t_{(28)}$=3.35, $p<0.05$, *D*=1.27) and were also associated with a significantly larger peak dorsiflexion ($t_{(28)}$=2.56, $p<0.05$, *D*=0.97) compared to females. In the coronal plane, males were shown to exhibit significantly greater eversion at footstrike ($t_{(28)}$=2.35, $p<0.05$, *D*=0.89) and were also associated with a significantly larger peak eversion ($t_{(28)}$=2.51, $p<0.05$, *D*=0.95) compared to females.

Mid-Cal

In the sagittal plane, females were shown to exhibit significantly greater peak dorsiflexion ($t_{(28)}$=2.34, $p<0.05$, *D*=1.27) compared to males.

Fore-Mid

In the sagittal plane, females were shown to exhibit significantly greater dorsiflexion at toe-off ($t_{(28)}$=2.26, $p<0.05$, *D*=0.85) and were also associated with a significantly larger peak dorsiflexion ($t_{(28)}$=2.64, $p<0.05$, *D*=1.00) compared to males. In addition, females were also associated with a significantly greater range of motion ($t_{(28)}$=2.88, $p<0.05$, *D*=1.09) and relative range of motion ($t_{(28)}$=3.02, $p<0.05$, *D*=1.14) compared to males.

Fore-Cal

In the sagittal plane, females were shown to exhibit significantly greater dorsiflexion at toe-off ($t_{(28)}$=2.34, p<0.05, *D*=0.88) and were also associated with a significantly larger peak dorsiflexion ($t_{(28)}$=3.20, p<0.05, *D*=1.21) compared to males. In addition, females were also associated with a significantly greater range of motion ($t_{(28)}$=3.00, p<0.05, *D*=1.13) and relative range of motion ($t_{(28)}$=4.16, p<0.05, *D*=1.57) compared to males.

Discussion

The aim of the current investigation was to determine whether differences in multi-segment foot kinematics and plantar fascia strain are present between males and females. This represents the first comparative investigation to simultaneously examine multi-segment foot kinematics and plantar fascia strain in male and female runners.

The first key observation from the current investigation is that plantar fascia strain was shown to be significantly greater in male runners compared to female runners. This finding is likely to have clinical significance regarding the etiology of plantar fasciitis which is considered to be related to the magnitude of the strain imposed on the plantar fascia itself [13]. This provides further evidence to support the observations of Taunton et al. [4] who showed that males suffered a significantly higher rate of chronic injuries to the plantar fascia. The results from the current study therefore provide further insight into the biomechanical mechanisms behind the increased susceptibility of male runners to plantar fasciitis.

A further key finding from the present study is that significant gender differences were observed in the sagittal plane for all four foot articulations. Examination of the Cal-Tib articulation indicates that males were associated with a significantly greater peak dorsiflexion angle whereas at the more distal Mid-Cal, Fore-Mid, and Fore-Cal regions, larger peak dorsiflexion angles were observed in female runners. This finding opposes the results of Sinclair et al. [7] who showed using a single segment foot model that no sagittal plane differences in foot kinematics were present between genders. This observation may relate to differences in stride length characteristics between genders as males have been shown to be associated with significantly longer stride lengths than females [14]. Furthermore this finding may also be associated with differences in foot shape or structure. Wunderlich & Cavanagh [15] showed that allometrically scaled foot dimensions in runners differed between genders which could mediate alterations in foot mechanics during the stance phase.

In addition to differences in the sagittal plane, there were also significant alterations between genders in the coronal plane. Specifically, males were associated with increased peak Cal-Tib eversion. This finding disagrees with the observations of Sinclair et al. [7] who found using a single segment foot model that females were associated with significantly greater foot eversion compared to males. Given the proposed relationship between excessive coronal and transverse plane foot motions and the incidence of chronic running injuries, this finding may also have clinical relevance and suggests that males may be more susceptible to foot pathologies [13]. This observation in conjunction with the increase in plantar fascia strain opposes the current consensus in biomechanical literature, which suggests that female runners are more susceptible to chronic injury. The findings from the current study indicate that injury susceptibility may be site specific with females being more likely to suffer from chronic injuries at the hip and knee and males perhaps more susceptible to foot pathology.

There are some limitations associated with the current study. Firstly, plantar fascia strain was obtained using markers positioned onto the foot segment and the plantar fascia length itself was taken as the distance between calcaneus and first metatarsal locations. Whilst this procedure has been adopted in previous analyses to quantify the strain experienced by the plantar fascia [12], it is nonetheless a simplified practice for which there is likely to be some degree of error. Future analyses may wish to consider more direct fluoroscopic measurements in conjunction with 3-D motion capture to achieve accurate plantar fascia strain measurements. In addition, retroreflective markers placed onto the shoe in order to quantify foot articulations may also serve as a limitation as the foot is known to move relative to the shoe itself and thus the accuracy of this technique is questionable.

Previous analyses have investigated the variations in foot kinematics using markers placed onto the shoe and those placed onto the skin through holes cut into the shoe itself [16]. It was demonstrated that markers positioned onto the shoe may lead to errors particularly in the coronal and transverse planes. However, because cutting holes in the footwear reduced the structural integrity of the shoe upper and also influenced the runners' perception of the footwear, it was determined that the present technique is acceptable.

In conclusion, the current investigation provides information not previously available describing multi-segment foot kinematics and plantar fascia strain in male and female runners. Importantly, increased plantar fascia strain and peak non-sagittal angles of the Cal-Tib articulation were observed in male runners. Given the proposed relationship between high levels of plantar fascia strain as well as excessive coronal plane rotations of the foot segments and the etiology of injury, it is likely that the potential risk of the developing running injuries in relation to these mechanisms is higher in males.

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