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THE EFFECTS OF VARIOUS RUNNING INCLINES ON THREE-SEGMENT FOOT MECHANICS AND PLANTAR FASCIA STRAIN

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ABSTRACT
Purpose. There has yet to be a combined analysis of three-dimensional multi-segment foot kinematics and plantar fascia strain in running gait at various degrees of inclination. The aim of the current study was therefore to investigate the above during treadmill running at different inclines (0°, 5°, 10° and 15°). **Methods.** Twelve male participants ran at $4.0 \text{ m} \cdot \text{s}^{-1}$ in the four different inclinations. Three-dimensional kinematics of the foot segments and plantar fascia strain were quantified for each incline and contrasted using one-way repeated measures ANOVA. **Results and conclusions.** The results showed that plantar fascia strain increased significantly as a function of running incline. Given the projected association between plantar fascia strain and the aetiology of injury, inclined running may be associated with a greater incidence of injury to the plantar fascia.

Key words: running, incline, biomechanics

Introduction

Recreational and competitive running has been linked to a significant number of clinical benefits [1]. However, aetiological analyses indicate that chronic injuries are extremely common in runners, with an occurrence rate of around 70% per year [2]. Both retrospective and prospective studies have explored the biomechanical mechanisms responsible for chronic running injuries [3–7]. Malalignment of the foot segments during the stance phase of running have been implicated in the aetiology of a number of chronic foot and ankle pathologies [8]. Excessive coronal and transverse plane motions of foot segments have been associated with the progression of various pathologies such as tibial stress syndrome and Achilles tendonitis [9]. In addition to this, atypical foot-segment mechanics are also linked to the aetiology of plantar fasciitis, which has been shown to affect in excess of 10% of runners [10].

The kinematics of incline running have been previously examined by those interested in the biomechanical study of human locomotion. Using an overground protocol, Roberts and Belliveau, [11] demonstrated progressive increases in hip joint moments and powers at inclines of 0°, 6° and 12°. It was proposed that this was due to a poorer mechanical advantage of this joint for producing force and that increases in hip mechanical work were necessary to provide propulsion in the latter part of the stance phase. Telhan et al. [12] demonstrated that no significant differences in three-dimensional (3-D) joint moments of the lower extremities were present when comparing a 4° incline to flat running using a treadmill protocol. Swanson and Caldwell [13] showed that flexion of the lower extremity joints was greater at initial contact during inclined running. They also demonstrated that EMG amplitude of the gastrocnemius, soleus, rectus femoris, vastus lateralis and gluteus maximus muscles was greater while hamstring amplitudes were lower when running at a 30% gradient. Sinclair et al. [14] showed that both hip and knee flexion decreased linearly with running inclines. It was also demonstrated that peak tibial internal rotation was larger during flat running and proposed as being linked to the aetiology of injury.

Running at an incline may be beneficial in that it induces a larger physiological response than flat running and mediates increased training adaptations [15]. Incline running forms a key component in both training and competition [15]. However, despite the frequent utilization of incline running training, there is no known research that has directly measured the effects of different treadmill inclines on 3-D multi-segment foot kinematics and plantar fascia strain during running. The aim of the current study was therefore to investigate the influence of treadmill running at various inclines (0°, 5°, 10° and 15°) on foot kinematics and plantar fascia strain during the stance phase of running.

Material and methods

Twelve male participants (age 25.33 ± 3.47 years, height 1.79 ± 0.11 m and body mass 75.22 ± 6.97 kg) volunteered to take part in the current investigation. All were free from musculoskeletal pathology at the time of data collection and provided informed consent. Ethics approval was obtained from the local University Ethics Committee and the procedures outlined in the Declaration of Helsinki were followed.

Participants ran at $4.0 \text{ m} \cdot \text{s}^{-1}$ on a Woodway high-power treadmill (ELG, Germany) at four different gradients 0°

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(flat), 5°, 10° and 15°. Five trials were recorded for each inclination without stopping the treadmill and the order in which the different gradients were undertaken was randomized. As force information was not available, the instances of footstrike and toe-off were determined using kinematic information. Footstrike was determined as the point at which the vertical velocity of the calcaneus marker changed from negative to positive and toe-off was delineated using the second instance of peak knee extension.

The calibrated anatomical systems technique (CAST) procedure for modelling and tracking segments was followed [16]. Markers were placed on anatomical landmarks in accordance with the Leardini et al. [17] foot model protocol to define the anatomical frames of the rearfoot (Rear), midfoot (Mid) and forefoot (Fore). 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 (Pro Grid Guide II, Saucony, USA).

Markers were digitized using Qualisys Track Manager (Qualisys Medical AB, Sweden) and exported to Visual 3D software (C-motion, USA). Retroreflective marker trajectories were filtered at 12 Hz using a zero-lag low-pass Butterworth filter. Euler angles were used to quantify 3-D rotations of the foot segments relative to one another. Stance phase angles were computed using an XYZ sequence of rotations between the rearfoot–tibia (Rear–Tib), midfoot–rearfoot (Mid–Rear), forefoot–midfoot (Fore–Mid) and forefoot–rearfoot (Fore–Rear). The medial longitudinal arch (MLA) angle was calculated in accordance with the protocol documented by Tome et al. [18] as the angle created by the lines from the calcaneus marker to the navicular tuberosity and from the first metatarsal to the navicular tuberosity. Discrete 3-D kinematic measures which were extracted for statistical analysis included 1) angle at footstrike, 2) angle at toe-off, 3) range of motion (ROM) from footstrike to toe-off during stance, 4) peak angle during stance and 5) relative ROM (representing the angular displacement from footstrike to peak angle). Plantar fascia strain was quantified by calculating the distance between the first metatarsal and calcaneus markers and quantified by the relative position of the markers. Plantar fascia strain was then calculated as the change in length during the stance phase divided by the original length.

Descriptive statistics (means and standard deviations) of the above measures were calculated for each incline condition. Differences in 3-D kinematic and plantar fascia strain parameters were examined using one-way repeated measures ANOVA with statistical significance accepted at $p < 0.05$ [19]. Post-hoc pairwise comparisons were conducted using a Bonferroni correction to control for type I error. Shapiro–Wilk tests were used to screen the data for normality, finding that the normality assumption was not violated. Effect sizes for all statistical main effects were calculated using partial eta^2 (pη^2). Statistical procedures were undertaken using SPSS ver. 21 (IBM, USA).

Results

The results indicate that whilst the multi-segment foot kinematic waveforms measured as a function of different inclines were quantitatively similar, significant differences were found between the various inclinations. Figures 1 and 2 present the 3-D multi-segment foot kinematics and MLA angles from the stance phase. Tables 1–5 present the results of the statistical analyses conducted on the measures of multi-segment foot kinematics.

Plantar fascia strain and temporal parameters

A significant main effect was shown for plantar fascia strain; $F(3, 33) = 5.99$, $p < 0.05$, p$\eta^2 = 0.40$ (Table 1). Post-hoc analysis showed that plantar fascia strain was significantly smaller in the flat condition compared with the 10° and 15° incline conditions. A significant main effect was found for stance duration; $F(3, 33) = 6.68$, $p < 0.05$, p$\eta^2 = 0.44$. Post-hoc analysis showed that stance duration was longer in the flat condition compared with the 15° and 10° inclines. It was also shown that stance duration was longer in the 5° incline compared with 15°. A significant main effect was found for stride frequency; $F(3, 33) = 7.02$, $p < 0.05$, p$\eta^2 = 0.47$. Post-hoc analysis showed that stride frequency was greater in the 15° incline compared with the flat condition.

Table 1. Plantar fascia strain and temporal parameters as a function of different inclines

	0° (flat)		5°		10°		15°	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Stance time (ms)	188.37	16.44	178.05	15.14	172.87	11.20	168.76	13.25
Stride frequency (Hz)	2.82	0.22	2.95	0.21	3.07	0.22	3.16	0.25
Plantar fascia strain	5.63	2.25	6.37	2.53	6.60	2.32	6.78	2.56
Peak MLA angle (°)	115.41	7.40	116.79	7.80	116.51	7.30	117.48	6.90
MLA relative ROM (°)	6.00	2.31	7.37	1.99	5.71	2.22	6.48	2.18
MLA ROM (°)	27.23	3.12	36.87	3.46	32.90	3.21	21.61	3.33

Table 2. Rearfoot–Tibia kinematics as a function of different inclines

	0° (flat)		5°		10°		15°	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Sagittal plane								
Angle at footstrike	1.33	9.70	0.45	8.84	–3.11	13.67	–3.34	10.61
Angle at toe–off	–16.92	7.91	–19.47	9.57	–20.47	10.24	–20.69	8.96
Peak dorsiflexion	17.63	7.93	16.43	7.07	15.54	6.19	13.46	5.64
ROM	22.06	7.83	20.93	8.37	18.13	6.51	13.58	5.28
Relative ROM	16.80	10.50	18.65	12.36	15.98	7.01	16.31	7.33
Coronal plane								
Angle at footstrike	2.93	4.33	3.67	5.84	2.21	4.22	1.91	4.51
Angle at toe–off	2.82	5.08	2.84	4.89	2.92	5.52	2.89	4.96
Peak eversion	–7.41	3.94	–7.54	4.24	–7.88	4.39	–7.98	4.44
ROM	3.87	2.15	4.38	3.99	4.75	3.10	5.47	3.12
Relative ROM	10.34	3.92	11.21	5.59	10.10	4.01	9.89	4.16
Transverse plane								
Angle at footstrike	–1.15	2.19	0.13	4.65	–1.12	3.78	–1.15	4.05
Angle at toe–off	2.11	3.55	2.35	3.87	2.80	3.98	2.98	3.40
Peak external rotation	–6.79	3.28	–6.62	3.73	–6.90	4.97	–6.71	4.81
ROM	3.85	2.75	4.27	3.00	4.33	3.00	4.67	3.82
Relative ROM	5.64	3.03	6.75	4.63	5.79	4.70	5.57	5.36

Table 3. Midfoot–Rearfoot kinematics as a function of different inclines

	0° (flat)		5°		10°		15°	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Sagittal plane								
Angle at footstrike	1.80	2.78	2.45	4.49	2.09	2.49	2.14	2.68
Angle at toe–off	–1.11	3.71	–1.86	4.57	–2.08	3.91	–2.38	5.00
Peak dorsiflexion	6.24	2.10	6.88	4.46	6.39	3.10	6.87	3.64
ROM	4.49	2.56	4.54	2.36	4.27	2.30	5.01	2.55
Relative ROM	4.43	3.00	4.43	2.22	4.30	2.02	4.73	2.18
Coronal plane								
Angle at footstrike	–1.61	2.08	–3.40	4.40	–2.00	2.52	–1.93	2.84
Angle at toe–off	–2.19	3.42	–3.03	3.65	–2.65	4.51	–2.21	4.00
Peak eversion	–0.08	2.56	–0.95	2.53	–0.55	3.14	0.09	3.15
ROM	2.43	1.88	3.37	4.16	2.65	2.17	3.29	2.40
Relative ROM	1.53	2.51	2.45	4.56	1.44	2.31	2.02	2.96
Transverse plane								
Angle at footstrike	1.46	1.15	1.15	1.41	1.10	1.57	1.31	1.86
Angle at toe–off	2.23	1.69	2.00	1.93	1.91	1.77	1.84	1.73
Peak external rotation	–0.65	1.27	–0.67	1.25	–0.66	1.29	–0.68	1.34
ROM	1.30	1.25	1.34	1.05	1.32	1.30	0.95	0.61
Relative ROM	2.11	1.35	1.81	0.84	1.75	0.80	1.99	0.88

Rearfoot–Tibia

In the sagittal plane, the results showed a significant main effect for the angle at footstrike; $F(3, 33) = 4.54$, $p < 0.05$, $p\eta^2 = 0.30$ (Table 2). Post-hoc pairwise comparisons showed that this angle was significantly more dorsiflexed in the flat and 5° conditions compared with the 10° and 15° conditions. The results also showed a significant main effect for the peak dorsiflexion angle; $F(3, 33) = 5.76$, $p < 0.05$, $p\eta^2 = 0.3$. Post-hoc pairwise comparisons showed that peak dorsiflexion was significantly greater in the flat and 5° conditions than at 15°. Finally, a significant main effect was found for sagittal plane ROM; $F(3, 33) = 12.67$, $p < 0.05$, $p\eta^2=0.54$. Post-hoc pairwise comparisons showed that peak dorsiflexion was significantly greater in the flat, 5° and 10°

Table 4. Forefoot–Midfoot kinematics as a function of different inclines

	0° (flat)		5°		10°		15°	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Sagittal plane								
Angle at footstrike	4.48	6.17	5.17	7.56	3.93	7.64	4.04	8.81
Angle at toe–off	13.51	11.77	14.23	8.62	12.35	9.16	12.28	9.67
Peak dorsiflexion	19.32	9.44	20.68	10.61	20.33	10.73	20.37	10.59
ROM	11.50	4.36	9.06	3.55	8.70	3.49	8.74	2.53
Relative ROM	14.83	4.15	15.51	5.08	16.40	5.08	16.33	3.69
Coronal plane								
Angle at footstrike	0.11	1.28	–0.84	2.42	–0.12	0.98	–0.64	0.72
Angle at toe–off	1.61	2.12	–0.22	3.08	0.94	1.70	0.85	2.02
Peak eversion	2.27	2.14	0.61	2.85	1.72	1.82	1.52	2.12
ROM	1.83	1.26	1.26	0.85	1.40	1.29	1.68	1.65
Relative ROM	2.16	1.54	1.45	1.22	1.84	1.58	2.16	1.95
Transverse plane								
Angle at footstrike	0.14	1.73	–0.03	1.74	0.28	1.47	0.24	1.83
Angle at toe–off	1.38	1.16	0.04	1.89	0.58	2.21	1.26	2.62
Peak external rotation	2.81	1.48	1.96	1.98	2.31	2.15	2.91	2.30
ROM	2.53	1.68	1.31	0.89	1.38	0.98	1.65	1.60
Relative ROM	2.67	1.24	1.99	1.50	2.03	1.19	2.67	1.63

Table 5. Forefoot–Rearfoot kinematics as a function of different inclines

	0° (flat)		5°		10°		15°	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Sagittal plane								
Angle at footstrike	6.17	5.87	7.38	8.10	5.89	6.92	5.85	7.97
Angle at toe–off	12.41	9.34	12.02	8.26	10.15	9.74	9.64	9.31
Peak dorsiflexion	18.42	8.44	19.60	9.82	19.25	9.30	18.81	8.21
ROM	7.57	3.97	6.23	4.35	5.65	3.41	5.22	2.28
Relative ROM	12.25	5.01	12.22	5.26	13.36	5.07	12.96	3.16
Coronal plane								
Angle at footstrike	–1.11	3.33	–2.50	5.69	–1.58	3.61	–1.37	4.76
Angle at toe–off	–1.56	4.54	–0.78	3.68	–1.46	4.34	–1.50	5.18
Peak eversion	1.37	3.15	1.03	3.38	0.60	4.12	0.62	4.53
ROM	3.97	3.55	3.28	4.61	2.10	2.04	2.30	2.42
Relative ROM	2.48	3.19	3.54	4.75	2.18	2.37	1.99	2.87
Transverse plane								
Angle at footstrike	1.23	2.10	0.23	3.19	0.70	2.25	0.35	2.00
Angle at toe–off	2.41	2.73	1.19	4.07	2.02	2.22	1.70	2.00
Peak external rotation	–1.05	1.44	–2.05	3.11	–1.14	2.00	–1.16	1.99
ROM	2.36	1.67	2.18	1.16	1.96	1.45	1.66	0.70
Relative ROM	2.28	2.11	2.28	1.68	1.84	1.48	1.51	1.27

conditions compared with 15°. In addition, ROM was shown to be significantly larger in the flat condition compared with 10°.

Midfoot–Rearfoot

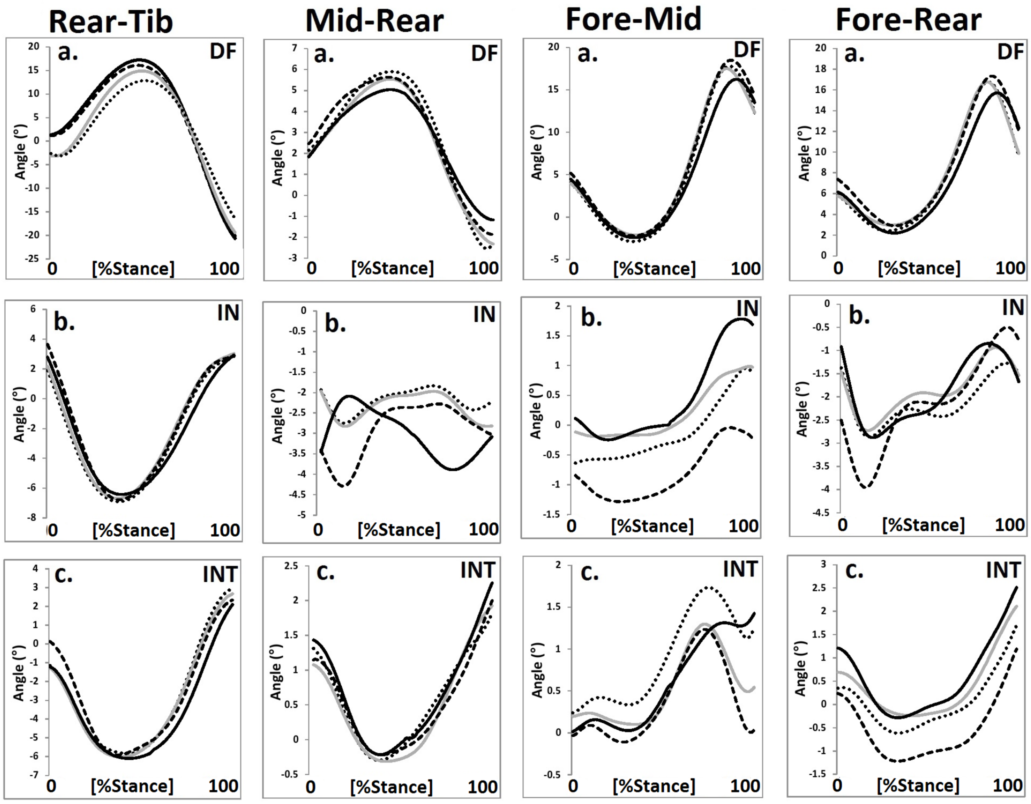
No significant ($p > 0.05$) differences were observed (Table 3, Figure 1).

Forefoot–Midfoot

No significant ($p > 0.05$) differences were observed (Table 4, Figure 1).

Forefoot–Rearfoot

No significant ($p > 0.05$) differences were observed (Table 5, Figure 1).

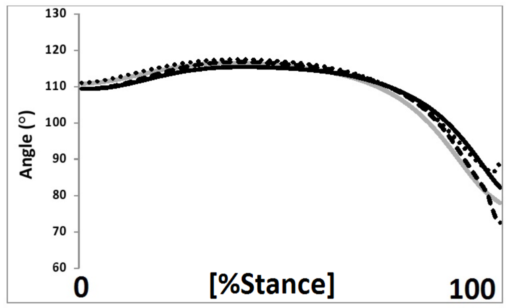


black – 0°, dash – 5°, grey – 10° and dot – 15°; DF – dorsiflexion, IN – inversion, INT – internal

Figure 1. Multi-segment foot kinematics as a function of different inclines

MLA angle

No significant ($p > 0.05$) differences were observed (Table 1, Figure 2).



black – 0°, dash – 5°, grey – 10° and dot – 15°

Figure 2. MLA angle as a function of different inclines

Discussion

The current investigation, as the first study on this subject, analysed the influence of treadmill running at various inclines (flat, 5°, 10° and 15°) on three-segment foot kinematics and plantar fascia strain during the stance phase of running.

The first key observation is that three-segment foot kinematics were shown to be significantly altered as a function of different running inclines. Specifically, it was shown that at footstrike the rearfoot exhibited significantly greater plantarflexion during the incline conditions. This concurs with the findings of Swanson and Caldwell [13] who also showed similar increases in plantarflexion during incline running. It is proposed that this observation relates to the increased stride frequencies noted in the incline running conditions. Increases in stride frequency are associated with reductions in step length, signifying that the ankle is required to plantarflex to a greater extent in order to reduce the linear distance from the foot to the centre of mass so as to maintain balance. This observation may also provide insight into the mechanism by which reductions in impact loading have been noted during incline running, as an increase in plantarflexion at footstrike have been shown to increase the duration of the impact phase in running [20, 21].

Another important observation from the current investigation is that plantar fascia strain was shown to be significantly greater with increased incline. This finding may be an important one regarding the aetiology of plantar fasciitis in runners. Plantar fasciitis itself is believed to be caused by excessive strain imposed on the plantar fascia [22]. The findings from this study may provide insight into the clinical differences between different running inclines and the susceptibility of runners to plantar fasciitis.

On the basis that increases in plantar fascia strain were observed during incline running, the results from the current study provide evidence to support the utilization of flat running for those susceptible to plantar fasci pathologies. These observations can be further contextualized by taking into account the observed increases in stride frequencies during the incline running conditions. Although increases in plantar fascia strain were shown for each individual step during inclined running, the amount of cumulative stress is likely to be further accentuated as the total number of required steps to achieve the same running velocity is greater. Thus, it can be concluded that the cumulative strain experienced by the plantar fascia during incline running conditions is likely to be considerably larger, placing runners at increased risk from plantar fascial pathologies.

A potential drawback of this study is that foot mechanics were quantified using a treadmill. As overground running is still the most common running modality, the generalizability of the findings is limited. Because running mechanics have been shown to differ between treadmill and overground locomotion [23], future work should seek to repeat the present study using an overground running protocol. In addition, the positioning of the retroreflective markers onto the shoe may not have quantified movement of the foot within the shoe. The accuracy of this method has been questioned, where previous analyses have demonstrated that markers positioned onto the shoe may lead to errors particularly in the coronal and transverse planes [8, 24]. However, these investigations showed that cutting holes in experimental footwear compromised the structural integrity of the shoe and affected footwear perception. Hence, it was determined that in the context of the current investigation that such a technique is acceptable.

Conclusions

The present study provides new information on multi-segment foot kinematics and plantar fascia strain at different running inclines. Of importance is that increased plantar fascia strain and alterations in the sagittal plane angles of rearfoot–tibial articulation were observed in the incline running conditions. Given the proposed relationship between high levels of plantar fascia strain and the aetiology of injury, it is likely that the potential risk of developing running injuries in relation to these mechanisms is higher during incline conditions.

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