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# Influence of minimalist footwear on knee and ankle loads during the squash lunge

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**Abstract.** Squash is associated with a high incidence of knee and ankle joint injuries. The aim of this work was to examine the effects of squash specific, running shoes and minimalist footwear on knee and ankle loads during the lunge movement in squash players. Twelve male squash players performed lunge movements whilst wearing squash specific, running shoes and minimalist footwear. The loads experienced by the knee and ankle joints were calculated. Patellofemoral forces were significantly greater in running shoes (5.10 B.W) compared to minimalist footwear (4.29 B.W). Achille tendon forces were significantly larger in the minimalist footwear (3.10 B.W) compared to the running shoes (2.64 B.W) and squash specific footwear (2.88 B.W). This shows that whilst minimalist footwear may reduce the incidence of knee pathologies in squash players corresponding increases in ankle loading may induce an injury risk at this joint.

**Key words:** Biomechanics, squash, knee, ankle, footwear

**Résumé. Influence de la chaussure minimaliste sur les charges du genou et de la cheville lors de la fente de squash.**

La pratique du squash est associée à des lésions articulaires au niveau du genou et de la cheville. Le but de ce travail était d'examiner les effets du port de chaussures de course à pied, de chaussures spécifiques de squash et de chaussures minimalistes sur les contraintes au niveau du genou et de la cheville pendant le mouvement de fente chez des joueurs de squash. Les contraintes aux articulations du genou et de la cheville ont été calculées pour douze joueurs de squash avec les différents types de chaussures. Les forces fémoro-patellaires étaient significativement plus grandes avec les chaussures de course ( $5,10 \times$  poids de corps) par rapport aux chaussures minimalistes ( $4,29 \times$  poids de corps). Les forces au niveau du tendon d'Achille étaient significativement plus grandes avec les chaussures minimalistes ( $3,10 \times$  poids de corps) par rapport aux chaussures de course ( $2,64 \times$  poids de corps) et aux chaussures spécifiques de squash ( $2,88 \times$  poids de corps). En conclusion, les chaussures minimalistes pourraient réduire les pathologies du genou chez les joueurs de squash, cependant une augmentation des contraintes au niveau du tendon d'Achille pourrait induire parallèlement un risque de blessure au niveau de l'articulation de la cheville.

**Mots clés :** Biomécanique, squash, genou, cheville, chaussures

## 1 Introduction

2 Squash is an extremely popular sport with millions of  
 3 players in over 100 countries worldwide. Competitive  
 4 squash is a physically demanding sport characterised by  
 5 a series of accelerations and decelerations which involve  
 6 both lunging and side-stepping (Vuckovic & James, 2010).

The repetitive nature and intensity of squash means that  
 squash players are at risk from injuries.

Injuries of a chronic nature are commonplace in both  
 recreational and competitive squash players (Clavisi &  
 Finch, 2000), with an occurrence rate of 45% (Berson,  
 Rolnick, Ramos, & Thornton, 1981). Chronic musculo-skeletal pathologies in squash players occur in both the

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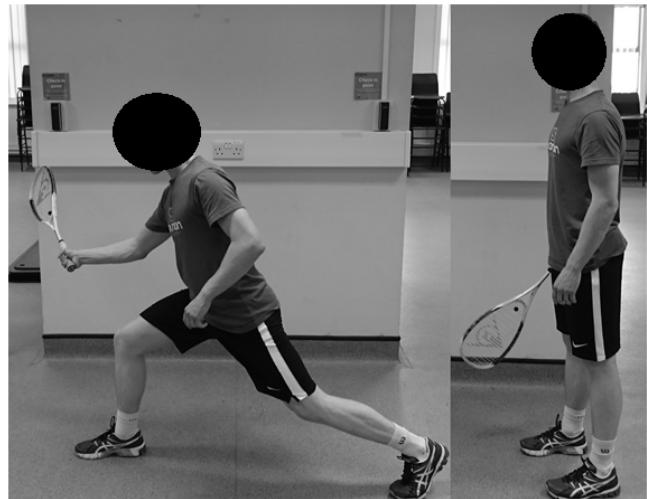
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1 upper and lower limbs and also the lower back (Finch  
2 & Eime, 2001). Lower extremities injuries are most com-  
3 mon, with the knee and ankle joints being the most com-  
4 monly injured sites (Finch & Eime, 2001).

5 Clavisi & Finch (2000) proposed that inappropriate  
6 footwear is a potential contributing factor to the aeti-  
7 ology of lower extremity injuries in squash players. In-  
8 deed Shorten (1993) suggests that through appropriate  
9 footwear design/ selection athletes may be able to regu-  
10 late their susceptibility to chronic injuries. There is cur-  
11 rently a lack of published research investigating the effects  
12 of different footwear on the biomechanical parameters  
13 linked to the aetiology of injury development in squash.  
14 There is a trend in a number of sporting disciplines for  
15 athletes to choose minimalist footwear as opposed to  
16 sport specific or running shoes (Sinclair, Atkins, Taylor,  
17 & Vincent, 2015a), based on the supposition that running  
18 in minimalist footwear is associated with a reduced inci-  
19 dence of lower extremity injuries (Sinclair, Greenhalgh,  
20 A., Brooks, Edmundson, & Hobbs, 2013a).

21 Research in other sports has examined the effects of  
22 minimalist footwear on the loads experienced by the knee  
23 and ankle joints. Sinclair (2014) investigated the effects of  
24 barefoot and minimalist footwear on knee and ankle loads  
25 during running compared to running shoes. Running  
26 barefoot and in minimalist footwear reduced the loads  
27 experienced by the knee but also increased the loads on  
28 the ankle compared to running shoes. Bonacci, Vicenzino,  
29 Spratford, & Collins (2013) showed that running bare-  
30 foot reduced the loads experienced by the knee com-  
31 pared to running in conventional running shoes. Sinclair,  
32 Chockalingam, Naemi, & Vincent (2015b) showed that  
33 minimalist footwear reduced the loads experienced by the  
34 knee during depth jumping compared to running shoes,  
35 but there were no differences in ankle loads. Finally Sin-  
36 clair, Hobbs, & Selfe (2015c) showed that minimalist  
37 footwear reduced the load on the knee but increased the  
38 load experienced by the ankle compared to netball spe-  
39 cific footwear. However, there is currently no research  
40 which has investigated the effects of different footwear  
41 in squash players. This indicates further study regarding  
42 the effects of different footwear on the loads experienced  
43 by the knee and ankle joints in squash specific movements  
44 is warranted.

45 The lunge is a movement that is used regularly in  
46 competitive squash, and the ability to quickly execute a  
47 controlled lunge is a key component of the game (Cronin,  
48 McNair, & Marshall, 2003). The aim of the current in-  
49 vestigation was therefore to examine the effects of squash  
50 specific, running shoes and minimalist footwear on the  
51 loads experienced by the knee and ankle during the  
52 squash lunge. An investigation of this nature may pro-  
53 vide key information to squash players regarding selection  
54 of appropriate footwear. This study tests the hypothesis  
55 that the minimalist footwear will be associated with de-  
56 creased knee loading in comparison to the squash specific  
57 and running shoes



**Fig. 1.** Example of the squash lunge movement.

## 2 Methods

### 2.1 Participants

Twelve male participants (Age  $21.59 \pm 2.28$  years; height  $1.74 \pm 0.07$  m; mass  $68.12 \pm 4.54$  kg) volunteered to take part in the current investigation. Participants were all competitive university level squash players. Ethical approval for this project was obtained from the University ethics committee, and each participant provided written consent in accordance with the declaration of Helsinki.

### 2.2 Procedure

Participants completed five lunges in each footwear condition starting from a stationary position facing forward (Fig. 1). Following each lunge they were required to return to a starting point which was determined by each participant prior to the commencement of data collection. This allowed the lunge distance to be maintained for each condition. Participants were also required to contact a force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) embedded into the floor of the biomechanics laboratory with their right (lead) foot. The force platform sampled at 1000 Hz. The lunge movement was considered to begin at the point of foot contact, this was taken as the point at which  $> 20$  N of vertical force was applied to the force platform. The end of the lunge movement was taken as the point of maximum knee flexion (Sinclair & Bottoms, 2013). The peak linear velocity (m/s) of the lunge movement was quantified using the centre of mass of the pelvis segment (Sinclair, Toth, & Hobbs, 2015d).

Kinematic information was obtained using an eight camera optoelectric system capture system (Qualisys Medical AB, Goteburg, Sweden) using a capture frequency of 250 Hz. Kinematics and force platform data were synchronized using an analogue to digital interface

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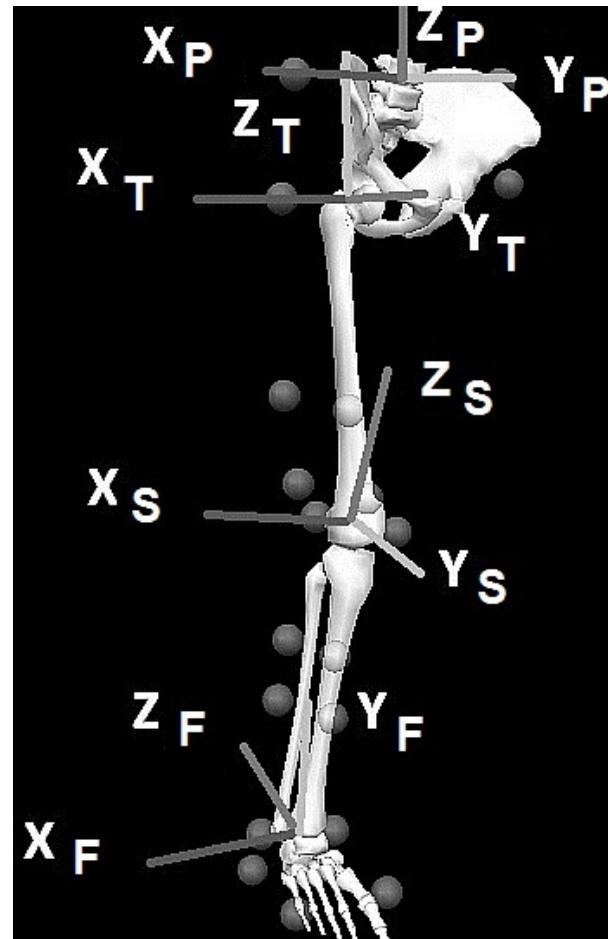
board. To model the lower extremity segments in six degrees of freedom the calibrated anatomical systems technique was utilized (Cappozzo, Catani, Leardini, Benedetti, & Della, 1995). To define the segment co-ordinate axes of the right; foot, shank and thigh, retroreflective markers were placed unilaterally onto 1st metatarsal, 5th metatarsal, calcaneus, medial and lateral malleoli, medial and lateral epicondyles of the femur. To define the pelvic segment, additional markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. The centres of the ankle and knee joints were delineated as the mid-point between the malleoli and femoral epicondyle markers (Graydon, Fewtrell, Atkins, & Sinclair 2015; Sinclair Hebron, & Taylor 2015e). The hip joint centre was delineated using a regression equation in accordance with Sinclair, Taylor, Currigan, & Hobbs (2014a) (Fig. 2).

The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right hand rule and was oriented from medial to lateral. Carbon fibre tracking clusters were positioned onto the shank and thigh segments. The foot was tracked using the 1st metatarsal, 5th metatarsal and calcaneus markers. Static calibration trials were obtained allowing for the anatomical markers to be referenced in relation to the tracking markers/clusters. Previous work has confirmed that the reliability of this marker configuration is very high (Sinclair, *et al.*, 2012).

### 2.3 Data processing

Ground reaction force (GRF) and marker data were filtered at 50 Hz and 12 Hz using a low-pass Butterworth 4th order filter and processed using Visual 3-D (C-Motion, Germantown, MD, USA). Joint kinetics were computed using Newton-Euler inverse-dynamics, allowing net knee and ankle joint moments to be calculated. To quantify joint moment's segment mass, segment length, GRF and angular kinematics were utilized using the procedure previously described by Sinclair (2014).

Knee loading was examined through extraction of peak knee extensor/ abduction moments, peak patellofemoral contact force (PTCF) and peak patellofemoral contact pressure (PTS). PTCF during the lunge was estimated using knee flexion angle (*kfa*) and knee extensor moment (KEM) through the biomechanical model of Ho Blanchette, and Powers (2012). This model has been utilized previously to resolve differences in PTCF and PTS in during the lunge movement and when different footwear (Bonacci, *et al.*, 2013; Sinclair, 2014; Sinclair & Bottoms, 2015). In addition to this previous work has confirmed the robustness of this model through sensitivity analyses for each of the measures (Sinclair, Taylor, & Atkins, 2015f).



**Fig. 2.** Pelvic, thigh, tibial and foot segments, with anatomical axes. P = Pelvis, S = Shank, T = tibia and F = foot.

The effective moment arm distance (m) of the quadriceps muscle (QM) was calculated as a function of *kfa* using a non-linear equation, based on information presented by Van Eijden, Kouwenhoven, Verburg, & Weijns (1986):

$$QM = 0.00008 kfa^3 - 0.013 kfa^2 + 0.28 kfa + 0.046 \quad 60$$

The force (N) of the quadriceps (QF) was calculated using the below formula:

$$QF = KEM/QM \quad 63$$

Net PTCF was estimated using the QF and a constant (*C*):

$$PTCF = QF * C \quad 66$$

The *C* was described in relation to *kfa* using a curve fitting technique based on the non-linear equation described by Van Eijden, *et al.* (1986):

$$C = (0.462 + 0.00147 * kfa^2 - 0.0000384 * kfa^2) / (1 - 0.0162 * kfa + 0.000155 * kfa^2 - 0.000000698 * kfa^3) \quad 71$$

**Table 1.** Abbreviations of input parameters for knee and ankle load models.

Key	
Patellofemoral contact force	PTCF
Patellofemoral contact pressure	PTS
Knee flexion angle	kfa
Knee extensor moment	KEM
Quadriceps moment arm	QM
Quadriceps force	QF
Constant	C
Achilles tendon force	ATF
Ankle plantarflexor moment	MPF
Achilles tendon moment arm	mat
Sagittal ankle angle	ak

1 PTS (MPa) was calculated using the net PTCF divided  
 2 by the patellofemoral contact area. The contact area was  
 3 described using the Ho, *et al.* (2012) recommendations by  
 4 fitting a 2<sup>nd</sup> order polynomial curve to the data of Powers,  
 5 Lilley, & Lee (1998) showing patellofemoral contact areas  
 6 at varying levels of kfa.

7 PTS = PTCF / contact area  
 8 Ankle loading was examined through extraction of the  
 9 peak plantar flexion moment and peak Achilles tendon  
 10 force (ATF). ATF was determined by dividing the plan-  
 11 tarflexion moment (MPF) by the estimated Achilles ten-  
 12 don moment arm (mat). The moment arm was quantified  
 13 as a function of the ankle sagittal plane angle (ak) using  
 14 the procedure described by Self & Paine (2001):

$$15 \quad ATF = MPF / mat$$

$$16 \quad mat = -0.5910 + 0.08297 ak - 0.0002606 ak^2$$

17 The net joint moments were normalized by dividing by  
 18 body mass (Nm/kg). PTCF and ATF were also normal-  
 19 ized by dividing by body weight (B.W). These variables  
 20 were extracted from each of the five trials and the data  
 21 was then averaged within participants for statistical anal-  
 22 ysis. In accordance with Sinclair, Isherwood, & Taylor  
 23 (2014b) GRF's in all three axes and sagittal knee/ an-  
 24 kle angles at the instances of peak PTCF and ATF were  
 25 also obtained. GRF's were normalized by dividing by  
 26 bodyweight.

## 27 2.4 Experimental footwear

28 The footwear used during the current investigation con-  
 29 sisted of a running shoe (New balance 1260 v2), mini-  
 30 malist footwear (Vibram five-fingers, ELX) and squash  
 31 specific shoe (Asics Mens GEL Rocket 7 Indoor), (shoe  
 32 size 8-10 UK men's).

## 33 2.5 Statistical analysis

34 Differences between footwear were examined using one-  
 35 way repeated measures ANOVA with significance ac-  
 36 cepted at the  $p \leq 0.05$  level (Sinclair, Taylor, & Hobbs,

2013b). Post-hoc pairwise comparisons were conducted on  
 all significant main effects using a Bonferroni adjustment.  
 Effect sizes were calculated for each significant main effect  
 using partial eta<sup>2</sup> ( $p\eta^2$ ). The normality assumption was  
 calculated using a Shapiro-Wilk test, which confirmed  
 that all data were normally distributed. All statistical  
 procedures were conducted using SPSS v22.0 (SPSS Inc,  
 Chicago, USA).

## 3 Results

Figure 3 and Tables 2–3 show GRFs and knee/ ankle  
 loads as a function of footwear. The statistical findings  
 indicate that both knee and ankle loads were significantly  
 influenced as a function of footwear.

### 3.1 Lunge velocity

No significant ( $p > 0.05$ ) differences in lunge velocity were  
 found between running shoe ( $1.65 \pm 0.32$  m/s), minimalist  
 ( $1.63 \pm 0.32$  m/s) and squash specific footwear ( $1.64 \pm$   
 $0.27$  m/s).

### 3.2 Ground reaction forces and joint angles

No significant ( $p > 0.05$ ) differences in GRF's at the instances  
 of PTCF or ATF were shown between footwear. A significant  
 main effect was shown ( $P < 0.05$ ,  $p\eta^2 = 0.33$ ) for knee  
 flexion angle at the instance of PTCF. Post-hoc  
 pairwise comparisons showed that knee flexion was signif-  
 icantly larger in the running shoes ( $P = 0.014$ ) compared  
 to the minimalist condition.

### 3.3 Knee loads

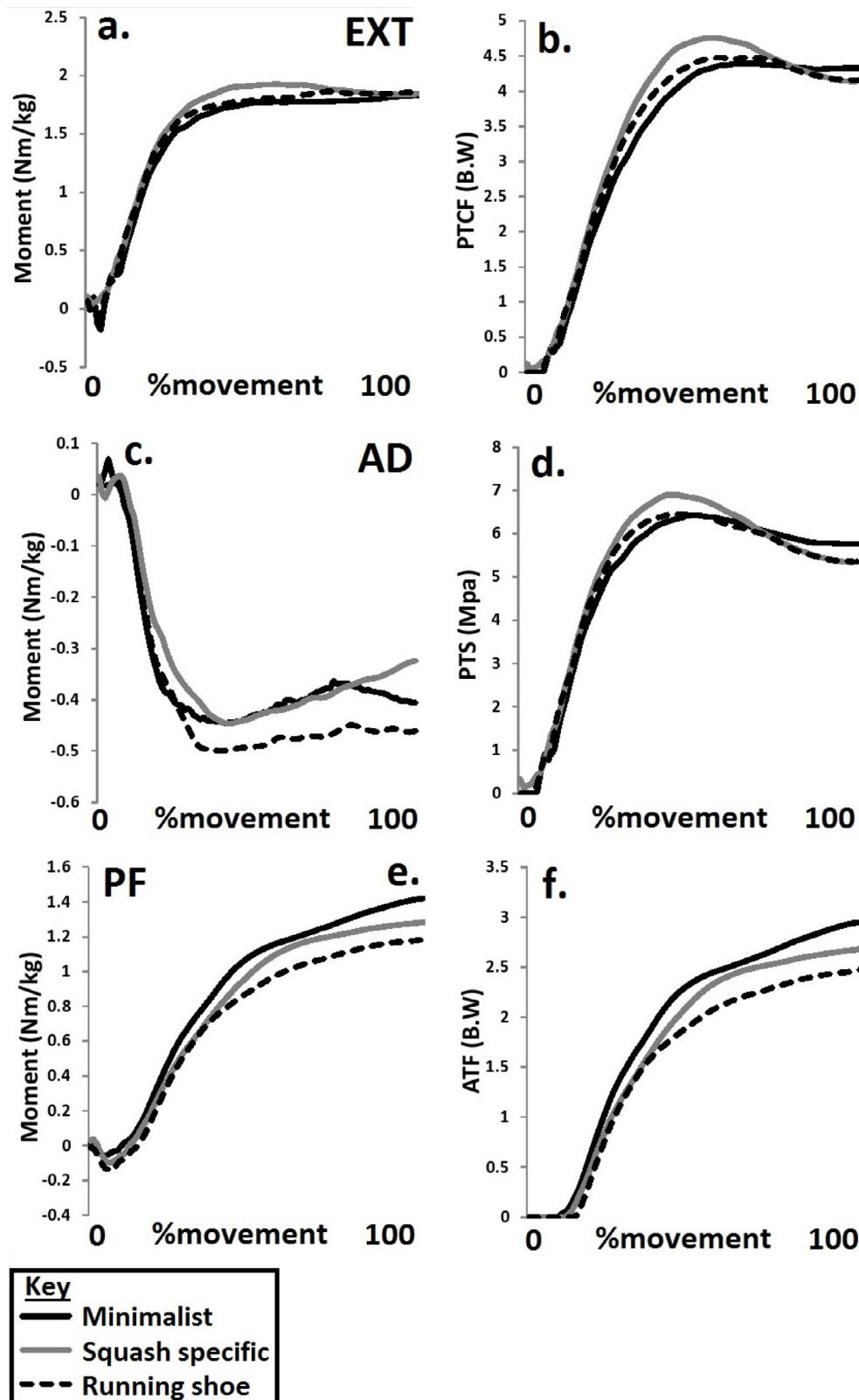
A significant main effect was shown ( $P < 0.05$ ,  $p\eta^2 =$   
 $0.32$ ) for peak knee extensor moment. Post-hoc pairwise  
 comparisons showed that peak extensor moment was sig-  
 nificantly larger in the running shoes ( $P = 0.04$ ) com-  
 pared to the minimalist condition. In addition a sig-  
 nificant main effect was found for PTCF ( $P < 0.05$ ,  
 $p\eta^2 = 0.42$ ). Post-hoc analysis indicated that PTCF was  
 significantly larger in the running shoes ( $P = 0.03$ ) com-  
 pared to the minimalist condition. Finally a significant  
 main effect was found for PTS ( $P < 0.05$ ,  $p\eta^2 = 0.41$ ).  
 Post-hoc analysis indicated that PTS was significantly  
 larger in the running shoes ( $P = 0.03$ ) compared to the  
 minimalist condition.

### 3.4 Ankle loads

A significant main effect was shown ( $P < 0.05$ ,  $p\eta^2 =$   
 $0.46$ ) for peak ankle plantarflexor moment. Post-hoc pair-  
 wise comparisons showed that peak plantarflexor moment

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**Fig. 3.** Knee and ankle loads as a function of footwear (a. = knee extensor moment, b. = PTCF, c. = knee abduction moment, d. = PTS, e. = plantarflexor moment, f. = ATF) (EXT = extensor, AD = adductor, PF = plantarflexor).

**Table 2.** GRF's and knee/ ankle angles as a function of footwear.

	Running shoe		Minimalist		Squash footwear	
	Mean	SD	Mean	SD	Mean	SD
Medial force at PTCF (B.W)	0.05	0.07	0.04	0.07	0.04	0.07
Anterior force at PTCF (B.W)	0.29	0.09	0.29	0.09	0.27	0.11
Vertical force at PTCF (B.W)	1.19	0.17	1.18	0.17	1.19	0.18
Knee angle at PTCF (°)	145.25	A	36.36	137.07	35.35	142.85
Medial force at ATF (B.W)	0.06	0.02	0.03	0.06	0.02	0.05
Anterior force at ATF (B.W)	0.22	0.10	0.24	0.10	0.26	0.09
Vertical force at ATF (B.W)	1.17	0.17	1.19	0.16	1.16	0.17
Ankle angle at ATF (°)	19.75	9.29	21.04	8.82	19.82	4.65

\* = significant main effect.

A = significantly different from minimalist.

**Table 3.** Knee and ankle loads as a function of footwear.

	Running shoe		Minimalist		Squash footwear		
	Mean	SD	Mean	SD	Mean	SD	
Peak knee extensor moment (Nm/kg)	2.16	A	0.58	2.03	0.52	2.13	0.56
Peak knee abduction moment (Nm/kg)	0.71	0.37	0.67	0.38	0.64	0.32	
Peak PTCF (B.W)	5.10	A	1.36	4.29	1.49	4.66	1.45
Peak PTS (Mpa)	6.94	A	2.10	5.67	2.38	6.04	2.24
Peak plantarflexor moment (Nm/kg)	1.26	A	0.21	1.49	0.29	1.38	A
Peak ATF (B.W)	2.64	A	0.47	3.10	0.63	2.88	A

\* = significant main effect.

A = significantly different from minimalist.

1 was significantly larger in the minimalist footwear com-  
 2 pared to the squash specific ( $P = 0.026$ ) and running  
 3 shoes ( $P = 0.005$ ). A significant main effect was also  
 4 found ( $P < 0.05$ ,  $p\eta^2 = 0.40$ ) for ATF. Post-hoc pairwise  
 5 comparisons showed that ATF was significantly larger in  
 6 the minimalist footwear compared to the squash specific  
 7 ( $P = 0.029$ ) and running shoes ( $P = 0.007$ ).

## 4 Discussion

9 The aim of the current investigation was to examine the  
 10 effects of different footwear on the loads experienced by  
 11 the knee and ankle joints during the squash lunge. This  
 12 represents the first investigation to study the effects of  
 13 different footwear on knee and ankle loads in squash play-  
 14 ers. As the knee and ankle joints are the most frequently  
 15 injured sites in squash players, this work may provide  
 16 important information to squash players regarding the  
 17 selection of appropriate footwear.

18 From these findings the first important observation  
 19 is that peak knee loads were significantly larger in the  
 20 running shoes in comparison to the minimalist footwear.  
 21 This observation concurs with previous work investigat-  
 22 ing knee loading in runners. Sinclair (2014), Bonacci,  
 23 *et al.* (2013), Sinclair, *et al.* (2015b, 2015c) each showed  
 24 that knee loading in runners was significantly larger in  
 25 running shoes footwear compared to barefoot and in min-  
 26 imalist footwear. This may be attributable to the signifi-  
 27 cant increase in peak knee extensor moment and decrease

in knee flexion angle at PTCF. Increases in knee flexion  
 28 are linked to a shortening of the quadriceps moment arm,  
 29 which ultimately leads to an increase in the load borne  
 30 by the patellofemoral joint (Sinclair, 2014). This finding  
 31 may have clinical significance regarding the aetiology of  
 32 injury in squash players as the consensus regarding the  
 33 development of knee pathologies is that symptoms are the  
 34 function of excessive knee joint kinetics (LaBella, 2004).  
 35 Therefore it appears that for squash players susceptible to  
 36 knee injuries that minimalist footwear may be more ap-  
 37 propriate than running shoes although they do not appear  
 38 to provide any advantage compared to squash footwear.  
 39

40 Of further importance is the finding that peak ankle  
 41 loads were significantly greater in the minimalist footwear  
 42 in comparison to the squash specific and running shoe  
 43 conditions. This observation also concurs with the find-  
 44 ings of Sinclair (2014) and Sinclair, *et al.* (2015c) who  
 45 showed in runners that ankle loading was significantly  
 46 larger when wearing minimalist footwear in comparison  
 47 to conventional athletic trainers. It is proposed that this  
 48 observation relates to the increase plantarflexion moment  
 49 contribution observed in minimalist footwear as no dif-  
 50 ferences in ankle angle were shown between footwear.  
 51 This finding may also have relevance clinically as the de-  
 52 velopment of Achilles tendon pathology is mediated by  
 53 excessive and habitual loading of the tendon during dy-  
 54 namic activities (Magnusson, Langberg, & Kjaer, 2010).  
 55 When the load experienced exceeds levels that are toler-  
 56 able by the tendon itself this causes degeneration of the  
 57 tendon.

1 tendon and eventually leads to injury (Selvanetti, Cipolla,  
2 & Puddu, 1997). Based on this observation this study in-  
3 dicates that for squash players who are predisposed to  
4 ankle pathologies, that squash specific and running shoes  
5 are most appropriate.

6 A potential drawback of the current study is that  
7 only male squash players were tested. Sinclair & Bottoms  
8 (2014), and Sinclair & Bottoms (2015) showed that knee  
9 loads were significantly larger in females and ankle loads  
10 were significantly greater in males during the lunge. As  
11 such it appears that the findings from this study may not  
12 be generalizable to female squash players. Future research  
13 should seek to repeat this study using a sample of female  
14 squash players. A further limitation is that only the lunge  
15 movement was investigated. The lunge was chosen as it  
16 represents a high impact movement (Sinclair, Bottoms,  
17 Taylor, & Greenhalgh, 2010), which exposes the mus-  
18 culoskeletal system to high forces. Competitive squash  
19 also requires other motions for success including sprint-  
20 ing, pivot turning and side stepping. Therefore future re-  
21 search should investigate the effects of different footwear  
22 when performing different squash movements.

23 In conclusion, the observations of the current investi-  
24 gation show that performing the lunge movement in min-  
25 imalist footwear produced significant reductions in knee  
26 loading compared to running shoes. Given the proposed  
27 relationship between knee loading and knee joint pathol-  
28 ogy, squash players may be able to attenuate their risk  
29 of the developing knee injuries by wearing minimalist  
30 footwear as opposed to running shoes. However, taking  
31 into account the corresponding increase in ankle loading  
32 in minimalist footwear in comparison to the running shoes  
33 and squash specific footwear, this may also enhance the  
34 likelihood of chronic ankle injuries. Additional analyses  
35 are required in order to expand the current investigation  
36 to squash specific movements in addition to the lunge.

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