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Effects of new military footwear on knee loading during running

Jonathan Sinclair[a]*, Paul John Taylor[b] and Stephen Atkins[a]

Q1 [a]*Centre for Applied Sport and Exercise Science, University of Central Lancashire, Preston, United Kingdom;* [b]*School of Psychology,*
Q2 *University of Central Lancashire, Preston, United Kingdom*

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Military recruits are known to be susceptible to chronic injuries. The knee is the most common injury site and patellofemoral pain has been demonstrated as the leading mechanism for medical military discharge. Military boots have been cited as a key mechanism responsible for the high incidence of chronic injuries. The British Army has therefore introduced two new footwears – a cross-trainer and running shoe to reduce the incidence of chronic injuries. The aim of this study was to compare knee joint kinetics of the cross-trainer and running shoe in relation to conventional military boots. Twelve male participants ran at 4.0 m s^{-1} in each footwear condition. Knee joint kinetics was obtained and
Q3 contrasted using repeated-measures ANOVAs. The results showed that patellofemoral load was significantly greater in the military boots. However, peak knee abduction moment was significantly greater in the running shoes. On the basis of the findings from this study, it is recommended that recruits who are susceptible to injuries mediated through excessive knee loads select the cross-trainer for their running activities.

Keywords: biomechanics; knee injuries; patellofemoral pain; running; army boots

Introduction

Chronic injuries in military populations result in a large number of missed training days at a significant monetary cost to the military itself (Hauret, Jones, Bullock, Canham-Chervak, & Canada, 2010; Sinclair & Taylor, 2014). Clinical reports show an occurrence rate of 13% to
Q4 31% in male recruits (Bensel & Kish, 1983; Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999; Ross 1993a, 1993b). High-volume running activities have been proposed as one of the primary physical mechanisms for chronic injury incidence in military recruits (Ross, 1993a, 1993b; Ross & Allsopp 2002).

Patellofemoral pain syndrome has been demonstrated as the most common chronic injury in runners (Taunton
Q5 et al., 2002). Patellofemoral disorders are associated with pain which initiates as a result of the contact of the distal end of the femur with the posterior surface of the patella during dynamic activities (Besier, Gold, Beaupre, & Delp, 2005). Patellofemoral pain is debilitating and has also been shown to be a precursor to the initiation and progression of osteoarthritis (Crossley 2014; Thomas, Wood, Selfe, & Peat, 2010). Although several biomechanical/anatomical parameters are proposed as being implicated in the aetiology of patellofemoral pain, excessive and habitual loading of the patellofemoral joint (Ho,
Q6 Blanchette, & Powers, 2012; La Bella, 2004; Messier, Davis, Curl, Lowery, & Pack, 1991) as well as increased internal knee abduction moments (Myer et al., 2015; Sigward, Pollard, & Powers, 2012) are traditionally linked to the initiation and progression of patellofemoral symptoms.

It has been established in the aetiological studies of military personnel that patellofemoral pain is a frequent complaint in recruits (Boling et al., 2009; Jones, Perrotta, Canham-Chervak, Nee, & Brundage, 2000; Milgrom et al., 1988). Importantly, chronic patellofemoral pain has been shown to be the leading mechanism for medical discharge from basic military training (Gemmell, 2002). Conservative management of patellofemoral disorders is desirable as opposed to operative interventions, and the efficacy of different clinical approaches has been explored (Barton, Lack, Hemmings, Tufail, & Morrissey, 2015). Despite this, however, there is a paucity of information in biomechanical literature regarding treatment mechanisms designed to reduce the loads experienced by the patellofemoral joint, indicating that there is a requirement for further study of this area.

Traditional military boots have been cited as a key extrinsic parameter responsible for the high incidence of injuries in recruits. Military boots are associated with poor impact attenuation and high foot plantar pressures (House, Waterworth, Allsopp, & Dixon, 2002; Nunns, Stiles, & Dixon, 2012; Paisis, Hanley, Havenetidis, & Bissas, 2013; Sinclair & Taylor, 2014), but malalignment of the lower

*Corresponding author. Email: JKSinclair@uclan.ac.uk

extremities have also been observed when running in these footwear (Sinclair & Taylor, 2014). The British military has recently introduced two new footwear models, a cross-trainer (PT-03) and running shoe (PT1000), which are now provided to each new recruit. These new footwears are designed to reduce the high incidence of chronic injuries associated with running activities.

The effects of these new footwears on the kinetics and kinematics of running have been considered previously. Sinclair and Taylor (2014) demonstrated that impact loading was significantly greater when running in the military boot compared with the cross-trainer and running shoe, which the authors attributed to a lack of midsole cushioning in the military boot. The kinematic analysis indicated that, in comparison with the cross-trainer and running shoe, running in military boots was associated with significantly greater eversion and tibial internal rotation. The effects of different footwear on the loads experienced by the patellofemoral joint have also been examined previously. Sinclair (2014) demonstrated that barefoot and barefoot-inspired footwear significantly reduced patellofemoral loads in comparison to the conventional footwear. Similarly, Bonacci, Vicenzino, Spratford, and Collins (2013) showed that running barefoot mediated significant reductions in the load experienced by the patellofemoral joint. However, the influence of military footwear on the loads experienced by the patellofemoral joint has yet to be examined.

This study aims to examine patellofemoral joint loading when running in military boots, when compared to cross-trainer and running shoe conditions using a biomechanical modelling approach. This study tests the hypothesis that knee load will be significantly greater when running in military boots.

Methods

Participants

Twelve male participants volunteered to take part in this study. The participants mean characteristics were age 26.3 ± 5.9 years, height 175.6 ± 6.1 cm and body mass 73.9 ± 5.2 kg. Participants were recreational runners who trained at least three times per week and had a minimum of three years of running experience. The sample size was selected on the basis of previous work investigating the mechanics of running in military footwear (Nunns et al., 2012; Paisis et al., 2013; Sinclair, Hobbs, Taylor, Currigan, & Greenhalgh, 2014). All participants were right-foot dominant and considered to exhibit a rearfoot strike pattern as they demonstrated a clear first peak in their vertical ground reaction force time-curve (Cavanagh & Lafortune, 1980). All reported as being free from musculoskeletal pathology at the time of data collection and provided a written informed consent. Ethical approval was provided by the University of Central Lancashire, in accordance with the procedures outlined in the Declaration of Helsinki.

Procedure

The participants ran across a 22 m biomechanics laboratory at 4.0 m s^{-1} ± 5%. The participants struck a piezoelectric force platform (Kistler Instruments, Model 9281CA), collecting at 1000 Hz, with their dominant foot (Sinclair, Hobbs et al., 2014). The stance phase of the running cycle was delineated as the time over which more than 20 N of vertical force was applied to the force platform. Running speed was controlled using timing gates (SmartSpeed Ltd UK). Three-dimensional (3D) kinematic information was captured with a frequency of 250 Hz, using a 10 camera motion analysis system (Qualisys Medical AB, Goteburg, Sweden). Kinematic and kinetic data were obtained synchronously and interfaced using Qualisys Track Manager software. Participants completed five trials in each of the three footwear conditions. The order in which participants performed in each footwear condition was counterbalanced. As the experimental footwear were novel to participants they were given a period to familiarize prior to the commencement of data collection. This involved 5 minutes of running through the testing area without concern for striking the force platform in accordance with the protocol of Sinclair, Greenhalgh, Brooks, Edmundson, and Hobbs (2013).

3D kinematics was quantified using the calibrated anatomical systems technique (Cappozzo, Catani, Leardini, Benedeti, & Della, 1995). The anatomical frames of the shank and thigh were defined using retroreflective markers positioned onto the greater trochanter, medial and lateral femoral epicondyles and medial and lateral malleoli. Additional markers were also positioned bilaterally onto the anterior superior iliac spines (ASIS). The distal and proximal aspects of the shank were delineated as the midpoint between the malleoli and femoral epicondyle markers (Sinclair, Hebron, & Taylor, 2015). The proximal aspects of the thigh were delineated using the positions of the ASIS markers (Sinclair, Hobbs et al., 2014). 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 both segments. The carbon-fibre clusters had dimensions in accordance with Cappozzo, Cappello, Della-Croce, and Pensalfini (1997) recommendations. Static calibration trials were obtained allowing the positions of the anatomical markers to be referenced in relation to the tracking clusters. Previous work has confirmed that the reliability of this marker configuration for the quantification of joint kinetics and moments is very high (Sinclair et al., 2012).

Experimental footwear

The shoes utilized during this study consisted of a regulation military boot (combat scale 95), army issue cross-trainer (PT-03, UK running shoe (PT1000, UK gear, Warwickshire, UK) (Figure 1). The military boots feature a polyurethane midsole and have heel and forefoot heights of 24 and 13 mm. The PT-03 features an EVA midsole and has a heel and forefoot heights of 38 and 23 mm. The PT1000 feature an EVA midsole and have heel and forefoot heights of 32 and 20 mm. The shoes were the same for all runners; they differed in size only (UK sizes 7–10 in men's shoe).

Data processing

Dynamic running trials were digitized using Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files in to Visual 3D (C-Motion Inc., Germantown, MD, USA). Kinetic and kinematic information were filtered at 50 and 12 Hz, respectively using a Butterworth low-pass fourth-order zero-lag filter (Sinclair, 2014). Knee kinematics was calculated using an XYZ cardan sequence of rotations and kinematic curves were normalized to 100% of the stance phase. Knee joint kinetics was computed using Newton–Euler inverse-dynamics allowing net internal joint moments to be calculated. Net knee joint moments were normalized to body mass by dividing by body mass (N m/kg).

The load experienced by the knee joint was quantified initially using the peak knee extensor and abduction moments. Patellofemoral contact force (PTCF) and patellofemoral contact pressure (PTCP) were estimated using the knee flexion angle (KFA) and knee extensor moment (KEM) as input parameters into the biomechanical model of Ho et al. (2012). This technique has been adopted previously to resolve differences in PTF and PP when wearing different footwear (Bonacci et al., 2013; Sinclair, 2014). The effective moment arm of the quadriceps muscle (QMA) was calculated as a function of KFA using a non-linear equation, based on cadaveric information presented by van Eijden, Kouwenhoven, Verburg, and Weijs (1986):

$$\mathrm{QMA} = 0.00008\ \mathrm{KFA}^3 - 0.013\ \mathrm{KFA}^2 + 0.28\ \mathrm{KFA} + 0.046.$$

Quadriceps force (FQ) was calculated using the below formula

$$\mathrm{FQ} = \mathrm{KEM}/\mathrm{QMA}.$$

PTCF was estimated using the FQ and a constant (C):

$$\mathrm{PTCF} = \mathrm{FQ}\ C.$$

The C was described in relation to KFA using the equation described by van Eijden et al. (1986):

$$C = (0.462 + 0.00147\ \mathrm{KFA}^2 - 0.0000384\ \mathrm{KFA}^2)/$$
$$(1 - 0.0162\ \mathrm{KFA} + 0.000155\ \mathrm{KFA}^2 - 0.000000698\ \mathrm{KFA}^3).$$

PTCP (MPa) was calculated using the PTCF divided by the patellofemoral contact area. The contact area was delineated by fitting a second-order polynomial curve to the data of Powers, Lilley, and Lee (1998) showing patellofemoral contact areas at varying levels of KFA (83 mm^2 at 0°, 140 mm^2 at 15°, 227 mm^2 at 30°, 236 mm^2 at 45°, 235 mm^2 at 60°, and 211 mm^2 at 75°).

$$\mathrm{PTCP} = \mathrm{PTCF}/\text{contact area}.$$

PTCF was normalized to bodyweight (B.W) by dividing by participants' bodyweight. PTCF loading rate (B.W s^{-1}) was calculated as a function of the change in PTCF force from initial contact to peak force divided by the time taken to peak force.

The robustness of the biomechanical model was examined by conducting a sensitivity analysis. This was undertaken by calculating PTCF and PTCP values when individually varying the two key input parameters KFA and KEM from their minimum to maximum value. Sensitivity index values were calculated in accordance with Hamby (1994) and showed values for PTCF of 0.18 and 0.19 B.W and for PTCP of 0.15 and 0.19 MPa as a function of KFA and KEM scores, respectively.

Figure 1. Footwear used in this study: (1) cross-trainer, (2) running shoe, and (3) military boot.

Statistical analysis

Differences in peak KEM, knee abduction moment, PTCF, PTCP and PTCF loading rate between footwear conditions were examined using one-way repeated measures ANOVAs. The alpha level required to denote statistical significance was adjusted to $P \leq 0.01$ using a Bonferroni correction to control type I error. Post-hoc pairwise comparisons were conducted on all significant main effects. Effect sizes were calculated using partial Eta^2 ($p\eta^2$). All statistical procedures were conducted using SPSS 21.0 (SPSS Inc., Chicago, USA).

Results

Table 1 and Figure 2 present the patellofemoral kinetics obtained as a function of footwear. The results indicate that the experimental footwear significantly influenced patellofemoral kinetics.

A significant main effect ($F_{(2,\ 22)} = 8.56$, $P < 0.01$, $p\eta^2 = 0.60$) was observed for peak KEM. Post-hoc analysis showed that KEM was significantly greater in the military boot in comparison to the running shoe and cross-trainer conditions (Table 1, Figure 2(a)). In addition, a significant main effect ($F_{(2,\ 22)} = 11.49$, $P < 0.01$, $p\eta^2 = 0.66$) was observed for PTCF. Post-hoc analysis showed that PTCF was significantly greater in the military boot in comparison to the running shoe and cross-trainer conditions (Table 1, Figure 2(c)). A significant main effect ($F_{(2,\ 22)} = 12.08$, $P < 0.01$, $p\eta^2 = 0.67$) was observed for PTCP. Post-hoc analysis showed that PTCP was significantly greater in the military boot in comparison to the running shoe and cross-trainer conditions (Table 1, Figure 2(b)). Finally, a significant main effect ($F_{(2,\ 22)} = 15.37$, $P < 0.01$, $p\eta^2 = 0.72$) was also observed for the magnitude of knee abduction moment. Post-hoc analysis showed that the peak abduction moment was significantly greater in the running shoe condition compared to the cross-trainer and military boot conditions (Table 1, Figure 2(d)).

Discussion

This study aimed to determine whether running in three different types of military footwear resulted in differential

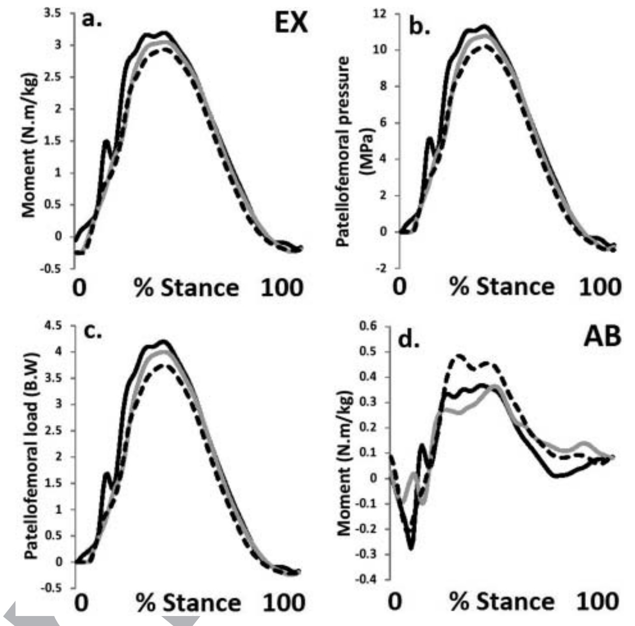

Figure 2. Knee kinetics and kinematics as a function of footwear; black = military boot, grey = cross-trainer, dash = running shoe (a = sagittal knee moment, b = PTCP, c = PTCF, d = coronal knee moment) (EXT = extension and AB = abduction). Q9

levels of loading of the knee. To the authors' knowledge, this study represents the first investigation to examine the influence of military footwear on the load experienced by the knee joint during running, a common activity engaged in during basic training.

In support of our hypothesis, the first key observation from the current investigation is that PTCF and PTCP load parameters were significantly greater when running in military boots. This observation concurs with the observations of Bonnaci et al. (2013) and Sinclair (2014), who also demonstrated that different footwear conditions can influence the magnitude of patellofemoral kinetics during running. The observed increases in patellofemoral loads may have clinical significance regarding the high incidence of patellofemoral disorders in military recruits as the aetiology of patellofemoral pain symptoms is considered to be linked to excessive patellofemoral loading during running (Ho et al., 2012; La Bella, 2004; Messier et al., 1991).

Table 1. Patellofemoral kinetics (Means ± SD's) as a function of footwear.

	Military boot		Cross-trainer		Running trainer	
	Mean	SD	Mean	SD	Mean	SD
Peak knee extensor moment (N.m/kg)	3.11	0.09	3.02A	0.18	2.82A	0.18*
Patellofemoral contact force (B.W)	4.08	0.13	3.84A	0.14	3.59A	0.35*
Patellofemoral loading rate (B.W.s^{-1})	33.64	1.08	29.58A	1.17	27.62A	2.92*
Patellofemoral pressure (MPa)	11.53	0.93	11.13A	0.66	10.38A	1.34*
Peak knee abduction moment (N.m/kg)	0.40B	0.16	0.37B	0.14	0.52	0.22*

* = significant main effect.
A = significantly different from military boot.
B = significantly different from running trainer.

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The current investigation may therefore provide new information regarding the selection of footwear with which to reduce patellofemoral loading. Given the proposed relationship between patellofemoral loading and the aetiology of patellofemoral pain symptoms, the findings from this work suggest that running in running shoe and cross-trainers may be beneficial for those who are susceptible or have previously presented with patellofemoral disorders. It is hypothesized that the increases in patellofemoral kinetics, demonstrated in the military boot, relates to the comparatively reduced midsole cushioning associated with the military boot in relation to the running shoe and cross-trainer (Sinclair & Taylor, 2014). When running with reduced midsole cushioning, runners utilize increased knee flexion throughout the stance phase (Lafortune, Hennig, & Lake, 1996). Sinclair and Taylor (2014) confirmed this observation as they showed that the military boot was associated with a significantly increased peak knee angle compared to the running shoe. Increases in knee flexion are however associated with a shortening of the patellofemoral joint moment arm, which leads to an increase in the contact force between the patella and femur (Ho et al., 2012).

A further important observation from this analysis is that the running shoe condition was associated with increased peak coronal plane internal abduction moment in comparison to both the military boot and cross-trainer. It is hypothesized that this observation related to distinct coronal plane knee kinematics observed between footwear. Indeed, Sinclair and Taylor (2014) confirmed that knee coronal plane profiles were significantly influenced as a function of different military specific footwear. Although the magnitude change in internal knee abduction moment was relatively small, this observation may also have clinical implications. Increases in internal knee abduction moments have been shown to be associated with augmented compartment loading of the medial aspect of the knee joint (Zhao et al., 2007), and also implicated into the development and progression of osteoarthritis at the medial tibio-femoral articulation (Miyazaki et al., 2002). In addition, it is postulated that increased internal knee abduction moments may also enhance progressive degeneration at the knee joint, possibly contributing to the development of pathologies at the knee (Myer et al., 2015; Sigward et al., 2012). Therefore, it appears that although the running shoe condition is able to attenuate sagittally dominated kinetics at the patellofemoral joint, they may expose runners to additional medio-laterally directed loads at the knee joint. This highlights the clinical benefits of investigating joint moments in the coronal and transverse planes.

Examination of the variability associated with each footwear condition indicates that the data distribution around the mean score for each parameter was much lower in the traditional military boot. Sensory information has been shown to be associated with alterations in movement variability during locomotive movements (Dingwell et al., 1999). Importantly, footwear midsole densities are known to influence the amount of sensory information the foot receives, (Lake & Lafortune, 1998), thus footwear may be an important factor that determines the amount of kinematic variability. It can be speculated based on these observations that reduced midsole cushioning associated with the military boot may be the mechanism by which variability in this condition was reduced, although further work is required to confirm this. This is nonetheless an interesting avenue for further investigation in footwear biomechanics literature, particularly as movement variability is considered to have a role in the aetiology of chronic injury initiation (Hamill, Palmer, & Van Emmerik, 2012).

A potential limitation to this work is that a predictive technique was used to measure patellofemoral loading. This was necessary, however, because of the impracticality in obtaining invasive measurements of patellofemoral kinetics. This technique has been used in other work to effectively resolve differences in knee kinetics between different footwear (Bonacci et al., 2013; Sinclair, 2014). Nonetheless this procedure may lead to underestimation of patellofemoral loads as the KEM was used as the key input measurement and thus antagonist forces that act in the opposing direction of the joint are not accounted for (Kulmala, Avela, Pasanen, & Parkkari, 2013). In addition, that participants were from a civilian population may also serve as a limitation. Although the extent to which military recruits differ in terms of their running mechanics from civilian runners is not known, future research may wish to further investigate the potential benefits of footwear interventions in military recruits.

In conclusion, the observations of the current investigation show that running in military boots significantly increased PTFC and PTCP compared to running in the running shoe and cross-trainer. Given the proposed relationship between joint loading and patellofemoral pathology, the risk of the developing running related knee injuries may be attenuated through utilization of the running shoe and cross-trainer conditions. However, taking into account the small yet statistically significant increases in peak knee abduction moment in the running shoe condition, this in turn may increase the probability of chronic injury development in relation to coronal plane knee mechanics. On the basis of the findings from this study, it is recommended that recruits who are susceptible to or have previously presented with knee pain select the cross-trainer for their running activities. Future work should focus on prospective analyses regarding the effects of different footwear on the development of chronic pathologies in military recruits and also the effects of different knee loading mechanics on the aetiology of running injuries.

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