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EFFECT OF INVERTOR/EVERTOR AND PLANTAR-/DORSIFLEXOR FATIGUE ON PLANTAR PRESSURE DISTRIBUTION

Pierre E. OLIVIER
Department of Sport Science, Stellenbosch University, Stellenbosch, Republic of South Africa

ABSTRACT

Running induced lower limb muscle fatigue does not identify which loading alterations relate to fatigue of specific muscles. The purpose of the present study was to compare the effect of selectively induced fatigue of the lower limb muscles on plantar pressure distribution. Twelve male participants were assessed. A quasi-experimental pre-test post-test design was applied. The RS Scan system prior to and following dominant leg concentric isokinetic ankle invertor/evertor (InEv-F) and plantar-/dorsiflexor (PD-F) fatiguing was used. Maximum pressure (kPa) and impulse for 10 plantar regions of the dominant leg was measured. Differences between the dependant variables were evaluated with repeated-measures ANOVA with Tukey HSD tests for post hoc analysis ($p<0.05$). InEv-F and PD-F resulted in increased forefoot and decreased toe pressure and impulse. InEv-F attributed to significantly decreased heel pressure. Fatigue of tibialis anterior and posterior, achieved during both InEv-F and PD-F, resulted in loading similarities during fatigue. Independently InEv-F and PD-F contributed to increased injury risk through altered loading. To mitigate the injury risks of running associated with lower limb fatigue, targeted ankle inversion/eversion and plantar-/dorsiflexion resistance training is recommended.

Key words: Plantar pressure; Foot loading; Fatigue; Running; Biomechanics.

INTRODUCTION

The foot is the final link in the kinetic chain of the lower limb and as such, plays an important role during static and dynamic activities. Statically the foot assists, through delicate muscular activity, to maintain balance (Gurney *et al*., 2008). Of equal importance is dynamic foot function during locomotion because, as Katoh *et al*. (1983) elaborate, the foot is critical to an understanding of the mechanics of gait, as it often affects the normal motion pattern of the entire lower limb. Therefore, alterations in normal foot mechanics can adversely affect the functioning of the ankle (Harradine *et al*., 2006), knee (Ghani Zadeh Hesar *et al*., 2009), hip (Khamis & Yizhar, 2007), and possibly the back (Rothbart *et al*., 1995).

An important dynamic function of the foot is to transfer the internal forces generated by the muscles to the ground so that the body can be accelerated during push-off (Saltzman & Nawoczenski, 1995). Effective measurement of dynamic foot function can be conducted through the analysis of plantar pressure distribution patterns as this provides direct information about the quality of the interaction between different structures of the foot and the ground (Orlin & McPoil, 2000). However, many factors influence plantar pressure distribution patterns. Some of these factors include, but are not limited to, ethnicity (Gurney *et al*., 2009), age (Roislien *et al*., 2009), gender (Razeghi & Batt, 2002), speed of movement (Burnfield *et al*., 2004), weight (Birtane & Tuna, 2004), physical activity (Rai *et al*., 2006), shoe wear (Razeghi & Batt, 2002; Rai *et al*., 2006; Queen *et al*., 2010) and fatigue (Bisiaux & Moretto, 2008; Nagel *et al*., 2008). Muscular fatigue brings about unattenuated and altered impact loading patterns of the foot, and this has been identified as an aetiological factor in various running injuries (Christina *et al*., 2001; Nagel *et al*., 2008). Furthermore, excessive impact forces, abnormal ankle joint motion and/or loading rate (Chuter & Janse de Jonge, 2012), all generally associated with muscular fatigue, are proposed to also play a major role in running injuries (Nigg *et al*., 1995).

Treadmill or long distance running has featured most prominently as a method to induce lower limb muscle fatigue. This method enables the investigation of the influence of lower limb muscle fatigue on the impact loading of the foot. Treadmill running close to anaerobic threshold speeds induces sufficient muscular fatigue to alter associated impact loading patterns, such that an increase in forefoot pressure is observed (Weist *et al*., 2004). Plantar pressure data collected, through participants walking over a capacitive surface following the completion of a marathon race, also showed an increase in forefoot pressure and reduced pressure under the toes (Nagel *et al*., 2008). Based on these and other studies, Willems *et al*. (2012), assert that consensus exists concerning the increased forefoot loading that is induced by fatigue. This demonstrated load transfer to the forefoot, particularly to the metatarsal heads, reflects a diminished capacity of the fatigued muscles to stabilise and control the foot (Mizrahi *et al*., 2000; Weist *et al*., 2004). The increased pressure on the metatarsal heads is associated with an increased bending load and may lead to stress fractures (Bennell *et al*., 1999; Jacob, 2001). This is because a cumulative fatiguing effect results from repeated force applications below the acute injury threshold of a structure, which over time surpasses the capacity of the specific structure and leads to the development of an overuse injury (Willems *et al*., 2012).

PURPOSE OF THE STUDY

Treadmill and marathon runs to induce fatigue do not enable the identification of which fatigued muscle group, particularly of the lower limb, is predominantly responsible for the altered impact loading pattern, as well as increased risk of injury. If the responsible muscle group could be identified, specific attention through targeted exercises could be allocated to it in an attempt to prevent injuries or facilitate secondary prevention.

The purpose of the present study was to determine and compare the effects of selectively induced fatigue of the invertor/evertor and plantar-/dorsiflexor muscle groups upon the impact loading characteristics of the foot as represented by plantar pressure distribution, impulse and the forefoot to toe loading ratio. In contrast to other studies that use treadmill and marathon runs to induce lower limb muscular fatigue, an isokinetic protocol separately targeting the invertor/evertor and plantar-/dorsiflexor muscle groups was employed in the present study to selectively and independently induce fatigue. In addition, the use of an isokinetic fatiguing protocol allowed for an accurate determination of when muscular fatigue occurred.

METHOD

Subjects

Twelve male participants (mean±SD; age, 23.58±2.68 years; body mass, 76.62±11.68kg; height, 175.07±7.76cm), who were enrolled postgraduate students, volunteered to participate in this study. The participants conformed to the inclusion criteria of this study, which included no current or previous foot injury, or current lower limb injury. The Nelson Mandela Metropolitan University Research Ethics Committee (Human) approved the study, and informed consent was obtained from all participants.

Anthropometric measurements

Subsequent to obtaining informed consent, each participant was assessed anthropometrically. Measurements of body mass and stature were conducted. The measurement of body mass was made with the participant clothed as minimally as possible (Norton *et al.*, 1996) and accurately recorded to the nearest 0.01kg as measured by an electronic scale (ScaleMaster). The measurement of stature involved the participant standing with his feet together at the heels, and with buttocks and scapulae touching the vertical board of the stadiometer (Holtain). Stature was taken with the participant wearing no footwear (socks were allowed) and as little clothing as possible, so that the body position could be clearly visible. The participant's weight was evenly distributed over both feet and the head placed in the Frankfort plane. The headboard of the stadiometer was pushed down firmly onto the vertex of the skull, depressing the hair as much as possible. The measurement, according to the procedure as described by Norton *et al.* (1996), was then taken at the end of a deep inhalation and accurately logged to the nearest 0.1cm.

Isokinetic fatiguing protocol

Prior to the measurement of plantar pressure distribution, isokinetic fatiguing protocols were performed on a Cybex Norm. Isokinetic fatigue of the invertors/evertors and plantar-/dorsiflexors was achieved by participants performing continuous concentric contractions at 60°.sec^{-1}. The method, as described by Yaggie and McGregor (2002), was used to determining fatigue. This entailed the performance of three consecutive maximal concentric repetitions against the isokinetic dynamometer to determine a peak torque value. After 5 minutes of rest, maximal concentric repetitions were performed against the dynamometer until fatigue occurred. The point at which invertor/evertor and plantar-/dorsiflexor torques, respectively, decreases below 50% of the applicable peak torque value (determined previously), was regarded as being representative of fatigue.

Plantar pressure measurement

Measurement of maximum pressure (in kPa) and impulse per square centimetre (in Ns.cm^{-2}) for 10 identified regions (T1 - hallux; T2-5 - toes 2-5; M1 - metatarsal 1; M2 - metatarsal 2; M3 - metatarsal 3; M4 - metatarsal 4; M5 - metatarsal 5; MF - mid-foot; HM - medial heel & HL - lateral heel), of the plantar surface, as well as the forefoot to toe loading ratio [(Σimpulse under M1 to M5)/(Σimpulse under T1 and T2-5)], was conducted by having the participants walk over a 2m long capacitive surface (Footscan® RSScan International, Olen, Belgium). Participants were instructed to walk across the measurement surface in approximately 1.6s, which translated to a walking speed of approximately 1.25m.s^{-1}. To assist participants with obtaining the correct speed a digital timer, connected to photocells positioned at the edges of the capacitive surface, displayed the participant's time taken to cross the capacitive surface. Each participant completed 10 trials with each trial starting with an alternate foot. Similar measurements for each participant were made prior to and following each of the concentric isokinetic ankle InEv-F and PD-F protocols, which were performed on the dominant leg. The dominant leg was taken as the leg identified by the participant.

To negate the impact of DOMS (Delayed Onset of Muscle Soreness), a period of 5 days elapsed between the performance of the selectively induced muscular fatigue protocols of the invertor/evertor and plantar-/dorsiflexor muscles and subsequent measurement of plantar pressure distribution. Owing to practical considerations related to the fatiguing protocol, selected data analysis of plantar maximum force and impulse, as well as forefoot to toe loading ratio was conducted for the dominant leg only.

Statistical analyses

The collected data was labelled as pre-fatigue (Pre-F), invertor/evertor fatigue (InEv-F) and plantar-/dorsiflexion fatigue (PD-F). Averaging the data collected from the 10 trials performed prior to and following each of the fatiguing protocols generated a representative data set for each participant. This data was then used to perform descriptive (means and standard deviations) and inferential statistics. Significant differences between the data were evaluated with repeated-measures ANOVA with Tukey HSD tests for post hoc analysis ($p<0.05$). All statistical analyses were performed with the use of STATISTICA (v.10.0).

RESULTS

Tables 1 and 2 display descriptive (mean±SD) and inferential statistical results for maximum pressure and impulse per square centimetre data measured at the 10 plantar regions during the pre- and post-fatigued states.

Table 1, which displays maximum pressure data, demonstrates that a significant reduction in pressure was observed at T1, following both InEv-F and PD-F, when compared to the Pre-F. Following InEv-F, significantly decreased pressure was also observed at T2-5, Ml and M2 compared to pressure measured during Pre-F. It is of interest to note that following PD-F significantly more pressure was measured at Ml, M2, M3 and M4, compared to that measured following InEv-F. These pressure measurements were, however, not significantly different from those measured during Pre-F. A significant decrease in pressure was measured during InEv-F and PD-F at HM and HL compared to Pre-F. Furthermore, a significant decrease in pressure was measured at HM and HL during InEv-F, compared to similar measurements during PD-F.

TABLE 1: MAXIMUM PRESSURE (kPa) BEFORE AND AFTER INDUCED FATIGUE

Variables	Pre-F	InEv-F	PD-F
T1	91.84 ± 25.59	71.33 ± 27.63*	77.54 ± 22.28*
T2-5	17.61 ± 7.71	11.50 ± 5.73*	14.43 ± 7.87
Ml	108.74 ± 49.83	84.99 ± 37.48*	105.25 ± 43.33†
M2	179.80 ± 38.14	157.13 ± 34.57*	177.54 ± 43.64†
M3	192.48 ± 33.59	178.19 ± 29.26	203.76 ± 43.33†
M4	128.62 ± 27.77	117.63 ± 26.67	135.48 ± 32.14†
M5	58.15 ± 28.28	52.76 ± 28.66	55.53 ± 25.45
MF	21.35 ± 8.99	18.17 ± 7.85	22.29 ± 8.79†
HM	188.72 ± 33.28	159.96 ± 21.23*	175.61 ± 27.54*†
HL	165.04 ± 30.71	133.37 ± 22.74*	144.86 ± 32.97*†

Pre-F - Pre-fatigue; InEv-F - Invertor/evertor fatigue; PD-F - Plantar-/dorsiflexor fatigue

T1 - hallux; T2-5 - toes 2-5; MI - metatarsal I; M2 - metatarsal 2; M3 - metatarsal 3; M4 - metatarsal 4; M5 - metatarsal 5; MF - mid-foot; HM - heel medial; HL - heel lateral

* Statistically significant difference between pre-fatigue and invertor/evertor or plantar-/dorsiflexor fatigue ($p<0.05$)

† Statistically significant difference between invertor/evertor fatigue and plantar-/dorsiflexor fatigue ($p<0.05$)

TABLE 2: MAXIMUM IMPULSE PER SQUARE CENTIMETRE ($Ns.cm^{-2}$) BEFORE AND AFTER INDUCED FATIGUE

Variables	Pre-F	InEv-F	PD-F
T1	1.66 ± 0.52	1.24 ± 0.56*	1.38 ± 0.42
T2-5	0.22 ± 0.11	0.15 ± 0.09*	0.19 ± 0.14
Ml	2.61 ± 1.30	2.03 ± 1.00*	2.65 ± 1.22†
M2	4.28 ± 1.07	3.77 ± 1.04*	4.34 ± 1.15†
M3	4.85 ± 1.13	4.49 ± 1.08	5.20 ± 1.44†
M4	3.47 ± 0.98	3.17 ± 0.71	3.68 ± 1.03
M5	1.51 ± 0.83	1.41 ± 0.80	1.53 ± 0.85
MF	0.49 ± 0.18	0.42 ± 0.17	0.54 ± 0.22†
HM	3.98 ± 0.92	3.27 ± 0.75*	3.65 ± 0.89*†
HL	3.42 ± 0.91	2.72 ± 0.72*	3.04 ± 0.91*†

Pre-F - Pre-fatigue; InEv-F - Invertor/evertor fatigue; PD-F - Plantar-/dorsiflexor fatigue

T1 - hallux; T2-5 - toes 2-5; MI - metatarsal I; M2 - metatarsal 2; M3 - metatarsal 3; M4 - metatarsal 4; M5 - metatarsal 5; MF - mid-foot; HM - heel medial; HL - heel lateral

* Statistically significant difference between pre-fatigue and invertor/evertor or plantar-/dorsiflexor fatigue ($p<0.05$)

† Statistically significant difference between invertor/evertor fatigue and plantar-/dorsiflexor fatigue ($p<0.05$)

Table 2 displays impulse per square centimetre data and the pattern observed significant differences between the pre- and post-fatigued states are very similar to those observed in the maximum pressure data displayed in Table 1. This is due to the impulse per square centimetre variable (measured in $Ns.cm^{-2}$), being a representation of the maximum pressure (measured in kPa, where $1kPa=10N.cm^{-2}$), with the additional consideration of how long the particular plantar region was in contact with the capacitive surface. As speed of movement over the capacitive surface was controlled the above-mentioned result was expected.

In Table 3 the forefoot to toe loading ratio, calculated with the impulse per square centimetre data is presented. It displays the forefoot to toe loading ratio as calculated for the pre- and post-fatigued states. A significantly larger ratio was calculated subsequent to InEv-F compared to Pre-F.

***TABLE 3*: FOREFOOT TO TOE LOADING RATIO BEFORE AND AFTER INDUCED FATIGUE**

Variable	Pre-F	InEv-F	PD-F
Ratio	1.66 ± 0.52	1.24 ± 0.56*	1.38 ± 0.42*

Pre-F - Pre-fatigue; InEv-F - Invertor/evertor fatigue; PD-F - Plantar-/dorsiflexor fatigue

* Statistically significant difference between pre-fatigue and invertor/evertor or plantar-/dorsiflexor fatigue ($p<0.05$)

DISCUSSION

The repeated stretch-shortening cycles of a muscle affects its force production by reducing neural input and lowering the efficiency of the contractile mechanism (Nicol *et al*., 1991). The resultant muscular fatigue of the lower limb causes diminished stability and control of the ankle (Mizhari *et al*., 2000; Weist *et al*., 2004). Bisiaux and Moretto (2008), suggest that these fatigue induced movement pattern changes and their consequential mechanical repercussions, are responsible for plantar pressure differences and increased injury risk.

Similar to the results of Bisiaux and Moretto (2008) and Nagel *et al*. (2008), a significantly decreased maximum pressure under the hallux (T1) and heel (HM & HL), following induced fatigue (InEv-F and PD-F), was observed. Associated with these pressure decreases there was a notable, but not significant, increase in pressure under the forefoot (M3 & M4), following PD-F compared to Pre-F. Similarly for the measures of impulse, non-significant decreases under the toes (T1 & T2-5), and increases under forefoot (M1–M5), were noted as a result of PD-F compared to Pre-F. Comparable to the results of Nagel *et al*. (2008) and Willems *et al*. (2012), a significant decrease in pressure was observed following PD-F, compared to Pre-F, under the lesser toes (T2-5). This was, however, not observed by Bisiaux and Moretto (2008).

Although some reported results of PD-F, compared to Pre-F, were non-significant, the general trend was in accordance with observations made by Weist *et al*. (2004), Bisiaux and Moretto (2008), Nagel *et al*. (2008) and Willems *et al*. (2012), that a transfer of load from the toes to the forefoot occurs with running induced fatigue. This can be ascribed to the obvious similarities between the ankle motion used to induce PD-F and running. The lack of definitive significant differences, as compared to studies mentioned previously, might be attributed to the non-involvement of the toes during isokinetic fatiguing. Willems *et al*. (2012) noted that decreases in toe loading especially are seen in studies in which fatigue was induced by aerobic gait tasks. Nagel *et al.* (2008) speculated that fatigue resulted in a reduced involvement of the toes during push-off, which was associated with increased dorsiflexion in the metatarsophalangeal joints and lead to increased maximum pressure and impulse under the metatarsal heads. Thijs *et al.* (2008) found that increased peak force observed under metatarsal two (M2) and three (M3) increased the risk of novice recreational runners experiencing the patellofemoral pain syndrome (PFPS).

With regard to increased forefoot loading, the effect of PD-F appeared to be more pronounced than that of InEv-F. Although significantly reduced pressure and impulse, as a result of InEv-F, were observed under the hallux (T1) and lesser toes (T2-5), a significant transfer of load to the forefoot did not follow. In fact a reduction in pressure and impulse, which was significant under Ml and M2, occurred following InEv-F compared to Pre-F. Christina *et al.* (2001) surmised that in particular dorsiflexor muscle fatigue is associated with increased impact loading, thus explaining the more pronounced results associated with PD-F.

Similar pressure and impulse distribution patterns in response to InEv-F and PD-F were not observed. However, the general trend regarding plantar pressure distribution was similar. The forefoot to toe loading ratio prominently displays this. Ratios calculated, following both InEv-F and PD-F, were significantly larger than the Pre-F ratio. This indicated a significant shift of loading toward the forefoot and subsequent increase in injury risk as a result of fatigue.

Each isokinetic fatiguing protocol focussed on specific agonist/antagonist muscle pairs responsible for the control of ankle motion. Fatiguing of the respective muscle pairs brought about specific movement pattern changes and their consequential mechanical repercussions. Hence, different plantar pressure distribution patterns were observed in response to InEv-F and PD-F. Similarities with respect to muscle recruitment exist between the movements performed to achieve InEv-F and PD-F. The tibialis anterior and posterior muscles, which are the primary dorsiflexor and invertor of the foot respectively, are both recruited during both isokinetic-fatiguing protocols. Fatigue of these muscles and the resulting decreased amount of dorsiflexion (Christina *et al.*, 2001), attributed to the significantly decreased heel (HM & HL) pressure and impulse observed between the fatigued states and Pre-F. Particularly fatigue of the tibialis posterior, responsible for controlling rear foot eversion (Pohl *et al*., 2010), may be responsible for the observed significant reduction in pressure and impulse under the heel.

Willems *et al*. (2012) state that fatigue of tibialis posterior may lead to imbalances about the ankle and foot, thus having significant repercussions for plantar pressure. Moreover, invertor/evertor fatigue has been found to have a significant effect on ankle joint motion and consequently loading rate (Christina *et al.,* 2001; Bisiaux & Moretto, 2008). Current results demonstrate that significantly less plantar pressure and impulse was measured under the heel (HM & HL), following InEv-F compared to Pre-F and even PD-F. Bisiaux and Moretto (2008) speculated that the decreased pressure under the heel specifically related to InEv-F, which resulted in impaired inversion-eversion foot control, shock-wave attenuation at heel strike and decreased muscular power during the loading phase. Significantly decreased pressure and impulse under the heel (HM & HL) was also observed during PD-F compared to Pre-F. Thus, both InEv-F and PD-F are associated with a decreased ability of the musculoskeletal system to attenuate shock waves at heel strike, and thus it increases the risk of injury (Voloshin *et al*., 1998; Mizrahi *et al*., 2000).

The use of selectively induced fatigue of the lower limb muscles to assess dynamic foot function alterations indicates that slight differences, dependant on which muscle pair was targeted, did exist. Results associated with PD-F were more pronounced, but did not always prove to be significantly different to Pre-F. Conversely, a significant shift of loading from the toes toward the forefoot did occur in response to InEv-F and PD-F, compared to Pre-F. This highlights the increased risk of injury, particularly metatarsal stress fractures, associated with lower limb muscle fatigue. In addition, significantly decreased pressure and impulse under the heel, particularly during InEv-F, highlighted the deleterious effects of fatigue on the ability of the musculoskeletal system to attenuate shock waves at impact and protect against injury. These observations, however, do not allow for a definitive identification of which fatigued muscle pair contributes more to injury risk. It thus seems prudent to advocate both targeted ankle inversion/eversion and plantar-/dorsiflexion resistance training, in addition to running, to mitigate injury risk. Following injury, the immediate return to normal running activity might not be indicated. Rather strengthening of the invertor/evertor and plantar-/dorsiflexor muscle to control rear and forefoot motion should be advocated, in conjunction with a gradual reintroduction to running activity.

It is acknowledged that walking is a less taxing activity than running. Highlighted plantar pressure and impulse differences between Pre-F, InEv-F and PD-F are believed to be indicative of the general effects of fatigue. The isokinetic fatiguing protocols employed did not achieve fatigue of the foot muscles, as is the case with other comparative research discussed above, which used running as a fatiguing activity. Hence the effect that fatigue of these muscles would have had on foot loading is not reflected in the present data. The use of the isokinetic fatiguing protocol was integral to achieving the purpose of this research. Lastly, the small sample recruited for this study restricts the generalisability of the results. This was due to the time consuming nature of the procedure and measurements made. In spite of this, the current study contributes to our understanding of the altered foot loading characteristics as a result of fatigue of different lower limb muscle pairs.

CONCLUSION

The risk of injury associated with lower limb muscular fatigue is well established. The contribution that specific fatigued muscle pairs make to injury risk is more difficult to determine. Despite specific foot loading alterations being associated with isokinetic fatigue of specific muscle pairs, both InEv-F and PD-F fatigue independently contribute to increased injury risk. To mitigate the injury risks of running associated with lower limb fatigue, targeted ankle inversion/eversion and plantar-/dorsiflexion resistance training should be done to improve the control of fore and rear foot motion.

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Dr. Pierre E OLIVIER: Department of Sport Science, Private Bag X1, Matieland 7602, Stellenbosch University, Stellenbosch, Republic of South Africa. Tel.: +27 (0)21 808 4718, Cell: +27 083 507 1275 Fax.: +27 (0) 21 808 4817, E-mail: polivier@sun.ac.za

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