Changes in foot measurements, plantar pressure and postural position during a mountain ultra-marathon race

S. Vermand, Sebastien Duc, F.J. Ferrari, O. Garsin, M. Vermand, P. Joly

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Modifications des mesures des pieds, de la pression plantaire et de la posture pendant un ultra-trail en montagne

S. Vermand[a,c,d]*, S. Duc[b], FJ. Ferrari[d], O. Garsin[d], M. Vermand[e] and P. Joly[a]

[a] *Laboratory of Engineering and Materials Science (LISM EA4695), University of Reims Champagne Ardenne, France ;*

[b] *Research Group in Engineering Sciences (GRESPI EA 4694), University of Reims Champagne Ardenne, France ;*

[c] *Podiatrist office and postural study, Amiens, France ;*

[d] *Association of sport's podiatrist Podo'xygène, Tourcoing, France ;*

[e] *Mines School– Campus ARTEM, Nancy, France*

Short title : Changes in foot measurements, during a Mountain Ultra-Marathon race

Corresponding author: VERMAND Stéphane, stephane.vermand@gmail.com

Abstract

Objectives

The aim of this study was to compare the plantar pressure distribution and foot measurements during standing posture before, during and after a mountain ultra-trail race.

Methods

Thirty-eight runners were tested before (km-0) and after (km-171) of the Ultra-Trail Mont Blanc 2016. Ten runners among of them were also tested at three checks points (km-49, km-79 and km-124). Standing erected posture was recorded on a stabilometric platform and was analyzed by the mean position of the center of pressure (CoP) on the antero-posterior (Y_{CoP}) and medio-lateral (X_{CoP}) axis. The relative body weight under the forefoot (FPP), the foot length (LF) and the front foot width (WFF) were also measured. The rating of perceived overall fatigue (RPF) was evaluated by Borg scale.

Results

Y_{CoP} moved forward ($p < 0.05$) after the UTMB while FFP and WFF were increased ($p < 0.05$). Changes in Y_{CoP} and changes in FFP were positively correlated ($r = 0.47$, $p < 0.05$). Y_{CoP}, FFP and RPF increased significantly ($p < 0.05$) from the start to km-79 but were unchanged between km-79 to km-171. WFF increased at km-79 then remain unchanged until the end. X_{CoP} and LF were unaltered throughout the UTMB.

Conclusions

The increase of the forefoot plantar pressure is related to the forward displacement of CoP. These results explain probably why many runners have injuries in this area during a MUM. The increase of the front foot width should be taken into account for the choice of the running shoes, as much as the foot length.

Keys word: running; fatigue; center of pressure; foot width; foot length, pressure

Résumé

Objectif

Le but de cette étude était de d'évaluer les modifications des pressions plantaires, des mesures du pied et de la posture, en position debout avant, pendant et après une course d'ultra-trail en montagne.

Méthodes

Trente-huit coureurs ont été testés avant (km-0) et après (km-171) de l'Ultra-Trail Mont Blanc 2016. Dix coureurs parmi eux ont également été testés à trois points de contrôle (km-49, km-79 et km -124). La posture debout a été enregistrée sur une plate-forme stabilométrique permettant d'établir la position moyenne du centre de pression (CoP) sur l'axe antéro-postérieur (YCoP) et médio-latéral (XCoP). Le poids corporel relatif sous l'avant-pied (FPP), la longueur du pied (LF) et la largeur du pied avant (WFF) ont également été mesurés. L'évaluation de la fatigue globale perçue (RPF) a été évaluée par échelle de Borg.

Résultat

YCoP a avancé (p <0,05) après l'UTMB tandis que FFP et WFF ont augmentés (p <0,05). Les changements de YCoP et les changements de FFP étaient positivement corrélés (r = 0,47, p <0,05). YCoP, FFP et RPF ont augmenté significativement (p <0,05) du début au km-79, mais sont demeurés inchangés entre le km-79 et le km-171. Le WFF a augmenté au km 79 puis reste inchangé jusqu'à la fin. XCoP et LF étaient inchangés tout au long de l'UTMB.

Conclusions

L'augmentation de la pression plantaire sous l'avant-pied est liée au déplacement vers l'avant de la CoP. Ces résultats expliquent probablement pourquoi de nombreux coureurs ont des blessures dans cette zone au cours d'une MUM. L'augmentation de la largeur du pied avant doit être prise en compte pour le choix des chaussures de course, autant que la longueur du pied.

Mots Clés : course à pied; fatigue; centre de pression; largeur de pied; longueur du pied, pression

1. Introduction

Foot injuries, including stress fractures of the metatarsal heads, represent a large part (15%) of the all injuries observed after a long distance running race, i.e. a marathon [1–3]. The appearance of these injuries is seems to be related to the increase of the ground reaction force under the front feet. Previous studies showed that the plantar pressure under the forefoot increased after a running race [1,4] or after an exhaustive laboratory running exercise [3,5,6]. Changes in foot architecture, such as a decrease of navicular height [7] or a widening of forefoot [8] or joint movement [9], and increase of muscular fatigue can also explain foot injuries [10,11]. Finally, the use of an orthopedic insole can be used to prevent most of these changes, and thus, would decrease the injury risk in this area. However, the measure of plantar pressure of a runner by a podiatrist is generally performed in rest without previous long distance running exercise and in a non-fatigued state. In addition, the evolution of the forefoot plantar pressure and foot measurements during a long distance running race in natural terrain (i.e. trail) remain unknown in spite of several recent scientific studies in ultra-trail runners [12–17].

Mountain ultra-marathons (MUMs; e.g., Western States 100, Ultra-trail du Mont-Blanc, Tor des Géants) represent an opportunity to investigate the physiological responses of the human body when pushed to its limits because they comprise running/walking usually in high altitude on mountain trails with positive and negative slopes over a distance longer than the traditional marathon [18]. In addition, MUMs longer than 100 hours involve sleep deprivation [19], which is not an issue in shorter events. Several previous studies have already assessed the acute consequences of MUM on muscle damage and inflammation[13], muscular fatigue and neuromuscular function [12,13,16,20], running mechanics [15–17,21,22], energy cost [22] and postural control [14] but none of them have assessed the consequences of such an extreme event on foot measurements and plantar pressure.

Interestingly, each of the characteristics (e.g., unstable ground, muscle fatigue/ damage, sleep deprivation, high altitude) of MUM is likely to impair plantar pressure and foot characteristics to a large extent. In this study, we aimed to compare the foot pressure, the length and the width of the foot by using data recorded prior to, during and after the world's popular single-stage MUM in the world, i.e. Ultra-Trail Mont Blanc (UTMB). We tested the hypothesis that CoP of move forward due to muscle fatigue, and thus involve an increase of the pressure under the forefoot. In addition, we supposed that both foot length and width of the front foot increase throughout the MUM race.

2. Methods

2.1. Experimental design

The race supporting this study was the Ultra-Trail Mont-Blanc (UTMB®) 2016 (171km, 10 000 m positive elevation). The race included sixteen check points with five with tolerated assistance, and thus where testing is allowed without stopping is mandatory.

The runners were tested five times: before the run (Chamonix, France, altitude 1035 m, km 0, PRE-); during the run five minutes after their arrival (les Chapieux, France, altitude 1554 m, km 49, MID49-; Courmayeur, Italy, altitude 1195 m, km 79, MID79-; Champex, Switzerland, altitude 1465 m, km 124, MID124-); and approximately 5 minutes after the run (Chamonix, France, altitude 1035 m, km 0, POST-).

2.2. Ethic statement

All subjects were fully informed of the procedure and the risks involved. They were allowed to stop the study at all times and to refuse to perform the tests. The study was approved by the institutional ethics committee of the University of Reims Champagne Ardennes. All subjects provided written, voluntary, informed consent prior to participation. The experiment was conducted according to the Declaration of Helsinki.

2.3. Population

Thirty-eight runners (35 men and 3 women) took part in the present study at the beginning and the end, and 10 of them took part in the five testing sessions (i.e., PRE-, MID49-, MID79-, MID124- and POST-). All subjects were experienced in ultra-marathons/trails. Two subgroups of runners (PRE-MIDs-POST, n = 10; PRE-POST, n = 38) were considered in the present. There was no significant difference between the two groups for any characteristics.

2.4. Postural stability protocol

During the five test sessions, we used a platform coupling posturography and baropodometry (Fusyo-Medicapteur, Toulouse, France; Dekra certification) at a 40-Hz sampling rate. CoP data were recorded using Fusyo software (V1.2.1 - Medicapteur, Toulouse, France). The posturographic platform was equipped with three pressure gauges (hysteresis < 0.2%) and the baropodometric part was equipped with 2304 sensors pressures. Signal processing was accomplished using a 16-bit A/D converter. The duration of each test was 51.2 seconds, resulting in a 2048-point time series.

The subjects were placed barefoot and their feet formed a 30° angle relative to each other with an inter-heel distance of 4 cm via a shim provided by the manufacturer. Their legs were extended, and the subjects were first instructed to maintain their balance with open eyes. They were instructed to keep their arms parallel to the trunk in relaxed position and to look straight a head a fixed target placed at a distance of 90 cm on a wall at the level of their eyes. They were instructed to stand double-leg on the platform while trying to maintain postural stability during the trials in all sessions. Only one postural test was performed in each test session. To limit testing time, no familiarisation session was conducted.

2.5. Foot measurement protocol

Foot measurements were performed barefoot, by a podiatrist in the same subject's position. The length of each foot (LF) was measured using a rule graduated in mm (*Kapro®, Lake Mills, USA*) equipped with a cursor placed at the most anterior point of the foot [23]. The width of each forefoot (WFF) was determined between the first and the fifth metatarsal head [23] by an electronic caliper graduated in mm (Dexter, Lille, France).

2.6. Perceived overall fatigue

The rating of perceived fatigue (RPF) was measured at the end of each test session using a visual numeric scale graded from 6 to 20 like to RPE Borg's scale [24].

2.7. Data acquisition

CoP data were collected to extract postural stability parameters: average position of CoP in AP and ML axis; and distribution of plantar pressure in percentage of body weight under the forefoot (FFP). The average position of CoP in AP (Y_{CoP}) and ML axis (X_{CoP}) were measured in cm with respect to the platform reference point. The forefoot and rearfoot surfaces were identified by a median which was drawn from the half-distance between the most anterior and the most posterior points of each foot compared to the baropodometric footprint. FPP was averaged between the two feet.

2.8. **Statistical analyses**

All data presented in the text and tables are the mean value ± SD. Data were screened for normality of distribution and homogeneity of variance using Shapiro-Wilk normality tests, respectively. Since all data did not show a normal distribution, statistical analysis was performed with using non-parametric tests.

To compare means for each dependent variable (postural stability parameters, foot pressure distribution and foot measurement parameters) between the two independent experimental sessions (PRE, POST), we used a Wilcoxon signed-rank test for each dependent variable. To compare means for each dependent variable (postural stability, foot pressure distribution and foot measurement parameters) between the five independent experimental sessions (PRE, MID49, MID79, MID124, POST), we used a Friedman ANOVA test for each dependent variable followed by post-hoc Tukey tests. Spearman's rank correlation coefficient was calculated between PRE- to POST-MUM changes in postural stability, foot pressure distribution parameters and perceived overall fatigue. To compare the 2 groups, a Wilcoxon-Mann-Whitney test was used.

For all statistical analyses, a P value of 0.05 was accepted as the level of significance. Statistical analyses were computed using commercially available software (Statistica version 10; StatSoft Inc., USA).

3. Results

Thirty-eight subjects completed the UTMB race. Mean (± SD) race time was 41:34:23 ± 4:12:17 (Range: 37:14:00 - 46:08:15).

Data comparison before and after the UTMB (n=38)

The rating of perceived overall fatigue (RPF) was significantly ($p<0.01$) increased from 6.0 ± 0.0 at the start to 16.0 ± 3.2 at the end of UTMB. Table 1 shows the average position of CoP and the foot characteristics measured before and after the UTMB. The CoP moved significantly ($p<0.01$) ~17 mm forward after UTMB. The medio-lateral position of CoP (X_{CoP}) was unchanged. The forefoot plantar pressure (FPP) was significantly increase by ~8.1% after the UTMB. Although the length of the right and left foot (LF) was unaltered after the UTMB, the width of the left and right forefoot (WFF) was significantly ($p<0.01$) increase by 1.9% and 2.2% respectively.

We found a positive weak correlation between changes in Y_{CoP} and changes in FPP ($r = 0.47$, $p <0.05$) All the other variables were not significantly correlated.

Data comparison throughout the UTMB (n=10)

Table 2 reports the CoP of and foot characteristics data obtained in ten subjects before the start (km-0), at three check points (km-49, km-79, km-124) and after the arrival (km-171). RPF increased continuously during the UTMB race and it reached its maximum value at the finish line. Significant higher values of RPF were measured at km-79, km-124 and km-171 when compared to km-0 ($p<0.05$) and to km-49 ($p<0.05$). A significant difference in RPF was also found between km-0 ($p<0.05$) and km-49 ($p<0.05$). No significant differences in RPF were found between km-79, km-124 and km-171.

No significant changes in the length of the right and the left foot were observed throughout the UTMB race. In contrast, width of the right and the left forefoot were significantly higher at km-79, km-124 and km-171 when compared to km-0 ($p<0.05$) and km-49 ($p<0.05$). No significant differences in forefoot width were found between km-0 and km-49 nor between km-79, km-124 and km-171. The Y_{CoP} was significantly decreased between km-0 and km-49 ($p<0.05$) then between km-49 and km-79 ($p<0.05$) but remained constant between km-79 and the finish line. The X_{CoP}, was not significantly changed throughout the UTMB. These results indicate that the CoP moved toward on the antero-posterior axis but was unchanged on the medio-lateral axis. The FFP was significantly higher throughout the UTMB race when compared to km-0 ($p <0.05$). A significant difference in FFP was also found between km-0 and km-49 ($p<0.05$) and between km-49 and km-79. No significant differences in FFP were found between km-79, km-124 and km-171.

4. Discussion

The main result of the study was that the pressure under the forefoot increase during a 171 km MUM race due to the forward displacement of center of pressure. In addition, while the length of the foot was unchanged, the forefoot width increased apart the middle of a 171 km MUM race.

Alterations of standing postural control during a MUM race had ever been reported by Degache et al. [14]. Postural sway parameters of experienced runners were primarily affected at the end of the Tor des Géants (TdG) in the frontal plane (AP direction) with reduced effects in sagittal plane (ML direction). Tdg (330km) is carried out over several days (between 4 and 7) thus inducing a large magnitude of sleep deprivation compared to shorter MUMs such as UTMB. However, since none significant alteration in postural control have been observed in control group with similar sleep deprivation, these postural changes have been attributed to increase of general fatigue.

Our results are partly agree with those of Degache et al. [14] since we observed that CoP moved in forward direction from km-0 to km-79 but remained in the same position in AP axis until the end of the UTMB. While they focused to the range of CoP sway in AP and ML directions, we chosen to analyze the average position of COP on AP and ML axes to determine the equilibration strategy of each runner. Thus, even if the runner increases the length of his displacements in the AP and ML planes, the average position is only altered in the plane AP showing that the current changes its stabilization pattern forward. This change is largely explained by unidirectional running gesture in the sagittal plane and the modification of the efforts related to the race profile (climb, flat, descent) where the body alternates between the front and rear positions to stabilize. In addition, the changes in the ML plan found themselves on a much longer ordeal (Tor des Giants, 330 km) where the conditions of sleep and fatigue are much greater.

We found no significant correlation between changes in CoP in AP direction and changes in rating of perceived fatigue. However, RPF and Y_{cop} changed in same way throughout UTMB since they increased from km-0 to km -79 and remained constant until the end of the race. These concomitant evolutions confirm that the standing postural control is related in part to the occurrence of fatigue.

It has been suggested that alteration of standing postural control after a MUM race were related to the neuromuscular fatigue of lower limb [14]. It has been shown that maximal voluntary isometric force of knee extensors and foot plantar flexors decreased significantly in the middle and at the end of a Mountain Ultra Marathon (MUM), such as Ultra Trail Mont Blanc (UTMB) or Tor des Géants [12,13,16]. The increase in muscle fatigue of the plantar flexors is directly related to the increase of support under the feet [25] by increasing the foot-to-ground angle at impact [16]. In the present study, the decrease of force production ability combined with an increase in reaction time to an external stimulus [12,13,16] could explained the observed forward displacement of CoP. As the oscillatory movements became more important during standing [14], the central nervous system chosen to skip between the ankle strategy to the hip strategy for postural control in order to save energy. As the talo-crural joint was more locked, the CoP moved forward, and thus, the plantar pressure under the forefoot was increased. However, the higher forefoot plantar pressure could alos be a result of a lowering of the arch of the foot since it has been reported that navicular drop was decreased at the end of a road Half Marathon [7].

Our result is in accordance with several previous studies who shown that plantar pressure under the forefoot was increased during an exhausted laboratory running exercise [3,6] or after a race [1,4]. Moreover, as in the present study, Vie et al. [5] found a positive relationship between the forward displacement of the CoP and the increase of forefoot plantar pressure. Exercise modality for assessing plantar pressure after a prolonged running does not to be dependent factor since the increase in forefoot plantar pressure was observed during walking [1,4], running [3,6] or in a static standing position [5].

Our hypothesis that foot measurements are changed during a MUM race is partly validated since we observe that the forefoot width was significantly higher during the second part of the race while the foot length was unchanged. The increase of the forefoot width had ever been observed during a laboratory running exercise at 4 $m.s^{-1}$ in trained runners [8] without notion of fatigue of a race. In addition, it is known that the joints of the feet (in particular of the back foot) undergo movements during the race [9]. This fatigue and the repetition of the gesture causes a fall of the navicular bone at the end of a half-marathon [7]. These results are in line with ours and show changes in the architecture of the feet during races. However, our results occur only from the km-49 contrary to the navicular fall appearing from km-21. During a MUM, the repetition of stride (several thousand hundreds of cycles) combined with the instability of ground support and the increase of muscular fatigue [12,13,16] could explain the widening of the forefoot but especially that this modification persists starting from km-49.

4.1. Practical applications

These results show some practical applications for reducing the risk of low limb injuries during long distance running. The increase of plantar pressure under the forefoot can involve higher risk of metatarsalgia and stress fracture in this area. In the case of these injuries, the runner have to rest and therefore suspend his training. Treatment by individual orthopedic soles could be proposed in prevention to the forward displacement of Cop, and, thus, could potentially reduce the pressure under this forefoot [26,27].

The second practical application of this study is related to the modification of the forefoot width during a MUM without changing the length. Most of runners choose their shoes with an extra size without paying attention to the width. The increase of forefoot width can involve blisters and wounds due to the higher compression of the forefoot by the shoe. Therefore, runners that engaged in long distance MUM race should to use larger shoe in the forefoot area to prevent this phenomenon. However, starting with a wider shoe can cause a significant risk of friction. This change may occur around kilometer 79, when the width actually changes during the race. However, this strategy is only possible today with some brands offering different widths whereas for the majority of commercial shoes the increase of the width of the forefoot goes with an increase of the length.

4.2. Limits of the study and Perspectives

The first limit of this study is that only 10 subjects of the 38 completed the UTMB have been tested between the start and the finish line. The second limit is that these athletes did not performed all the tests at the same time of day which could affect the postural response [28].

Future studies should evaluate knee, hip, shoulder and head positions on anterior-posterior axis in order to explain why the CoP moved forward with the occurrence of the fatigue after a MUM race. Dynamic evaluation of the stride during long distance running, notably the pronation-supination degree, the navicular height and the position of calcaneus would be interested to understand the foot measurement changes.

5. Conclusion

This study showed that a 171-km running MUM involved a forward displacement of centre of pressure during a standing erected position which increased the forefoot pressure. These results could explain the higher risk of injury for trail long distance runners in this area. The increase of the forefoot width observed in the present study should be considered for the choice of running shoes by practisers.

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Conflict of interest : none.

7. References

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Table 1. Rating of perceived overall fatigue (RPF), length of foot (LF), width of forefoot (WFF), average position of Center of Pressure on the antero-posterior axis (XCoP) and on the medio-lateral axis (YCoP), forefoot plantar pressure (FFP) measured before the start and after the arrival of the UTMB race. Significant difference are indicated by * ($p<0.05$).

		Start	Finish
RPF		**6**	**16 (± 3)** *
LF (mm)	**Right**	**265,9 (±13,2)**	**267,2 (± 12,1)**
	Left	**267,8 (±13,8)**	**269,3 (± 12,7)**
WFF (mm)	**Right**	**103,8 (± 5,6)**	**105,8 (± 5,3)** *
	Left	**103,9 (± 5,3)**	**106,1 (±4,9)** *
Y_{CoP} (mm)		**-37,1 (± 15,1)**	**-20,3 (± 14,43)** *
X_{CoP} (mm)		**-2,1 (± 6,1)**	**-4,4 (± 7,4)**
FFP (% of body weight)		**46,8 (± 7,9)**	**50,6 (±7,9)** *

Table 2. Rating of perceived overall fatigue (RPF), length of foot (LF), width of forefoot (WFF), average position of Center of Pressure on the antero-posterior axis (XCoP) and on the medio-lateral axis (YCoP), forefoot plantar pressure (FFP) measured before the start, at the three check points and after at the arrival of the UTMB race. Significant differences ($p<0.05$) when compared to km 0 and to km 49 are indicated by 'a' and 'b', respectively.

		Chamonix PRE	Chapieux Km-49	Courmayeur Km-79	Champex Km-124)	Chamonix POST
RPF		6	12 (±2) [a]	15 (± 1) [a,b]	16 (± 1) [a,b]	17 (± 3) [a,b]
LF (mm)	Right	271,4 (± 0,8)	270,6 (± 0,9)	271,6 (± 0,9)	271,7 (± 0,8)	272,1 (± 0,8)
	Left	273,5 (± 0,9)	271,8 (± 1)	272,8 (± 0,9)	271,3 (± 1,1)	274,5 (± 1)
WFF (mm)	Right	105,8 (± 4,2)	105,2 (±3,7)	108,4 (± 3,5) [a,b]	108, 9 (± 3,2) [a,b]	108,5 (± 3,8) [a,b]
	Left	104,8 (± 4,4)	105,2 (± 4,2)	106,9 (± 3,2) [a,b]	107,7 (± 4,5) [a,b]	108 (± 3,6) [a,b]
Y_{CoP} (mm)		-31,8 (± 11,7)	-24,2 (± 11) [a]	-20,7 (± 10,8) [a,b]	-21,8 (± 9,4) [a,b]	-21,1 (± 13,7) [a,b]
X_{CoP} (mm)		-4,3 (± 9,2)	-0,6 (± 7,1)	-2,1 (± 5,2)	-1,2 (± 7,8)	-3,1 (± 5,2)
FPP (% of body weight)		47,5 (± 3,5)	52 (± 5,1) [a]	54,5 (± 3,3) [a,b]	54,2 (± 4,3) [a,b]	53 (± 3,9) [a,b]