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Effects of Minimalist Footwear and Foot Strike Pattern on Plantar Pressure during a Prolonged Running

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Abstract: The use of minimalist shoes (MS) in running involves changes in running mechanics compared to conventional shoes (CS), but there is still little research analysing the effects of this footwear on plantar pressure, which could help to understand some risk injury factors. Moreover, there are no studies examining the effects of a prolonged running and foot strike patterns on baropodometric variables in MS. Therefore, the aim of this study was to analyse the changes produced using MS on plantar pressure during a prolonged running, as well as its interaction with the time and foot strike pattern. Twenty-one experienced minimalist runners (age 38 ± 10 years, MS running experience 2 ± 1 years) ran with MS and CS for 30 min at 80% of their maximal aerobic speed, and mean pressure, peak pressure, contact time, centre of pressure velocity, relative force and contact area were analysed using a pressure platform. Foot strike pattern and time were also considered as factors. The multivariable linear regression mixed models showed that the use of MS induced, at the end of a prolonged running, higher peak pressure ($p = 0.008$), lower contact time ($p = 0.004$) and lower contact area ($p < 0.001$) than using CS. Also, runners with forefoot strike pattern using MS, compared to midfoot and rearfoot patterns, showed higher mean and peak pressure ($p < 0.001$) and lower contact time and area ($p < 0.05$). These results should be considered when planning training for runners using MS, as higher peak pressure values when using this type of footwear could be a risk factor for the development of some foot injuries.

Keywords: minimalist shoes; conventional shoes; baropodometry; foot; sports biomechanics

1. Introduction

Barefoot running (BR) or minimalist running (MR) has been a recurring topic of study in the sports biomechanics field over the last decade [1–3]. Both modalities involve, in comparison with running with conventional shoes (CS), modifications in certain biomechanical and physiological parameters. In relation to the kinematic aspects, it has been suggested that BR and MR result in a more anteriorised initial contact (forefoot, FF; or midfoot, MF) [4–6], shorter stride length and higher cadence [7–11], and reduced joint range of motion in the lower limbs (reduced knee flexion and adduction, and reduced hip external rotation) [6,8,12–15]. With regard to physiological aspects, although a lower oxygen consumption and an improvement in running economy were observed during BR and MR [5,8,16–19], increased gastrocnemius muscle activity and decreased tibialis anterior activation during BR have also been observed [5,20].

Minimalist shoes (MS) are characterised by being very flexible, with a very thin sole, devoid of any element of stability [21], increasing the muscular demand on the athlete's foot, and in most cases forcing the runner to change his or her running pattern [22]. Despite the observed changes in muscle demand, the use of MS does not affect dynamic stability [23]. There exists some controversy as to whether the use of MS can reduce the risk of injury in running [24,25]. In this sense, the most frequent injuries reported in the literature during MR are located in the posterior leg musculature, such as Achilles tendonitis [25], and in the foot, such as plantar fascia rupture, bone marrow oedema or metatarsal stress fracture due to repetitive microtrauma and increased plantar loading and pressures [26–28].

In relation to plantar pressure, although the literature is scarce in the analysis of MR, some studies have reported an increase in pressure in the forefoot area [9,29–32]. Another factor to consider with an impact on plantar pressure is the influence of prolonged running, which can lead to pressure redistribution under CS conditions [33,34]. Other significant effects of prolonged running include increased contact time, reduced running economy [35], increased frequency and decreased stride length [36].

There are few studies that analyse the effect of plantar pressure combining both factors: minimalist shoes and prolonged running [36,37]. In addition, most research with MS does not consider other important factors such as the type and/or pattern of foot strike (forefoot, rearfoot, midfoot), or the runners' previous experience with this type of shoe [8,9,29–32,36–39]. Therefore, the aim of this study was to analyse the changes produced using MS on plantar pressure during a prolonged running, as well as its interaction with the time and foot strike pattern. The hypotheses posed were: (I) the use of MS will induce higher pressure values (mean and peak) compared to CS, regardless of the foot strike pattern; (II) the use of MS will lead to increased pressure during forefoot support; (III) at the end of the run, pressure values will be higher with MS compared to CS.

2. Materials and Methods

2.1. Participants

Twenty-one runners with experience in minimalist footwear voluntarily participated in this study (age 38 ± 10 years, height 1.76 ± 0.07 m, body mass 72.7 ± 8.6 kg, body mass index 23.4 ± 2.3 kg/m^2, previous running experience with MS 2 ± 1 years). Runners were recruited from a recreational club of minimalist runners. Participants were informed of the study characteristics, and all provided written informed consent prior to participation. All experimental procedures followed the Declaration of Helsinki principles and were approved by the University of Valencia ethics Committee (no. H1412433550236). For the sample selection, the following inclusion criteria were established: runner with habitual use of MS with at least one year of experience in this type of running, weekly training of at least 20 km/week, not having suffered any type of muscular injury due to overload in the last 6 months, not presenting painful keratopathy or skin lesion in the forefoot area, nor osteoarticular intervention in the lower limbs and/or spine that could interfere with the performance of the tests. Eighteen participants were right-handed and 3 were left-handed. Leg dominance was determined through the question "If you were to kick a ball at a target, which leg would you use?" [40].

2.2. Exercise Protocol

For the study (crossover design), each runner performed three tests, with a 7-day gap between each test. The first consisted of a 5-min run test with MS in which each participant had to run at their maximum constant speed in order to determine their maximal aerobic speed (MAS) [41,42]. The other two tests were performed on two different days, 7 days apart, and consisted of running for 30 min at 80% of MAS, one day with MS and the other with CS (randomized order using a Python routine). All participants used their own footwear (minimalist and conventional) and the only inclusion-criteria characteristic for the footwear was that the MS had a 0 mm drop and a sole of less than 4 mm and the CS (the last conventional running shoe that the participant had used for training before transitioning to MS) were neutral and had a drop of at least 8 mm. The footwear used each day was randomised. The tests were performed on a 400 m track. In order to determine each participant's 80% of the MAS, the running pace was adjusted by distributing 10 cones on the circuit and, using an audio file created with the free software Audacity v.2.0.6 (MuseCY Holdings Ltd., Limassol, Cyprus), the times of passing through each cone were determined.

2.3. Plantar Pressure Assessment Procedure

The instrumentation used for plantar pressure analysis was a pressure platform (S-Plate®, Medicapteurs, France) [43]. All steps performed with the dominant leg were analysed, excluding all steps from the non-dominant leg and/or those in which the foot did not rest entirely on the platform surface.

2.4. Statistical Analysis

Statistical analyses were carried out using the software RStudio (v.1.2.5033, RStudio Inc., Boston, MA, USA). All the registered complete steps were considered for analysis and were classified according to the initial foot strike pattern (Rearfoot (RF), MidFoot (MF), or Forefoot (FF)) [44]. For each participant, the predominant foot strike pattern was determined based on the one that occurred in more than half of the total recorded steps. The independent variables (factors) were: footwear type or condition (MS vs. CS), minute in which the step was registered, initial foot strike pattern (RF, MF and FF), and if the step was from the dominant leg (Yes vs. No). The dependent variables were: mean pressure, peak pressure, contact time, center of pressure (CoP) velocity, relative force, and contact area. Firstly, outliers from the database were identified by the intersection of different outlier detection methods defined by the package "OutlierDetection" (v.0.1.1) and removed from the database. Descriptive data were then provided using the mean, standard deviation and 95% confidence intervals (CI) of the mean. Multivariable linear regression mixed models were carried out for each factor using the package "nlme" (v. 3.1-142), being the participant a random factor fitted by the intercept, and analysing the main effect of each independent variable, as well as the interaction of these variables with the condition variable. The assumptions of the mixed models were evaluated by checking the standardised residuals in relation to the fitted values, observing a normal distribution and similar variance within and between groups. Standardised effect sizes (ES) of the model factors were obtained using the "emmeans" package (v.1.4.8), and were interpreted as $\geq$0.2, small; $\geq$0.5, moderate; $\geq$0.8, large. The level of significance was set at $p < 0.05$.

3. Results

Descriptive plantar pressure data for all registered steps are shown in Table 1. A total of 194 and 207 steps were registered for the CS and MS conditions, respectively. For both conditions, the foot contact of most of the steps was the midfoot. However, the proportion of forefoot contacts with MS was higher than for CS (21 vs. 9%).

Table 2 shows the results of the mixed models obtained. Although condition did not show a significant main effect for any of the variables ($p > 0.05$), its interaction with time was significant for peak pressure (ES = 0.7), contact time (ES = 0.2) and contact area (ES = 0.5). In this sense, in this interaction, the differences between conditions were greater at the end of the run, with the minimalist shoe presenting a higher peak pressure (CI: 0.79, 5.35; $p = 0.008$), a shorter contact time (CI: −7.48, −1.42; $p = 0.004$), and a smaller contact area (CI: −2.26, −0.86; $p < 0.001$). The interaction of the condition with the foot strike pattern was also significant for mean pressure, peak pressure, contact time, relative force and contact area, with the forefoot showing the greatest differences between the two conditions (mean pressure CI: −46.39, −19.49; $p < 0.001$ ES = 1.3, peak pressure CI: −52.33, −17.63; $p < 0.001$ ES = 1.4, contact time CI: 18.26, 64.79; $p = 0.001$ ES = 0.8, contact area CI: 7.27, 17.86; $p < 0.001$ ES = 0.9), except in the case of relative force which occurred in the rearfoot (CI: −15.01, −2.21; $p = 0.009$ ES = 0.7). Regarding the rest of the independent variables, a main effect of the foot strike pattern was observed, with a forefoot pattern resulting in a lower mean pressure (CI: 4.87, 30.00; $p = 0.007$ ES = 0.0 for midfoot, and CI: 7.42, 41.84; $p = 0.005$ ES = 0.1 for rearfoot), a lower peak pressure (CI: 4.26, 36.82; $p = 0.014$ ES = 0.1

for midfoot, and CI: 13.87, 58.52; $p = 0.02$ ES = 0.3 for rearfoot), a higher contact time with respect to midfoot pattern (CI: −55.28, −12.29; $p = 0.002$ ES = 03), and a higher contact area with respect to rearfoot pattern (CI: −13.85, −0.09; $p = 0.047$ ES = 0.2). A main effect of time was also observed, showing that the longer the time, the lower the peak pressure and the larger the contact area. Figure 1 shows the predictions of the condition effect and its interaction with time and foot strike pattern for each of the variables.

Table 1. Descriptive data all registered steps in pressure platform variables for both conditions assessed: running with conventional shoes (CS) and running with minimalist shoes (MS).

Characteristic	CS, *n* = 194 [1]	95% CI [2]	MS, *n* = 207 [1]	95% CI [2]
Foot contact				
Forefoot	18 (9.3%)	5.7%, 14%	43 (21%)	16%, 27%
Midfoot	151 (78%)	71%, 83%	140 (68%)	61%, 74%
Rearfoot	25 (13%)	8.7%, 19%	24 (12%)	7.7%, 17%
Predominant pattern	153 (79%)	72%, 84%	167 (81%)	74%, 86%
Mean pressure (Kpa)	79 (26)	75, 83	84 (34)	79, 88
Peak pressure (Kpa)	156 (37)	150, 161	173 (46)	166, 179
Contact time (ms)	195 (46)	188, 201	195 (48)	188, 201
[3] CoP velocity (m/s)	0.20 (0.10)	0.19, 0.22	0.18 (0.09)	0.17, 0.19
Relative force (%)	58 (9)	57, 59	56 (9)	54, 57
Contact area (cm^2)	60 (14)	58, 62	56 (18)	53, 58

[1] *n* (%); mean (SD); [2] CI = confidence interval; [3] CoP = center of pressure.

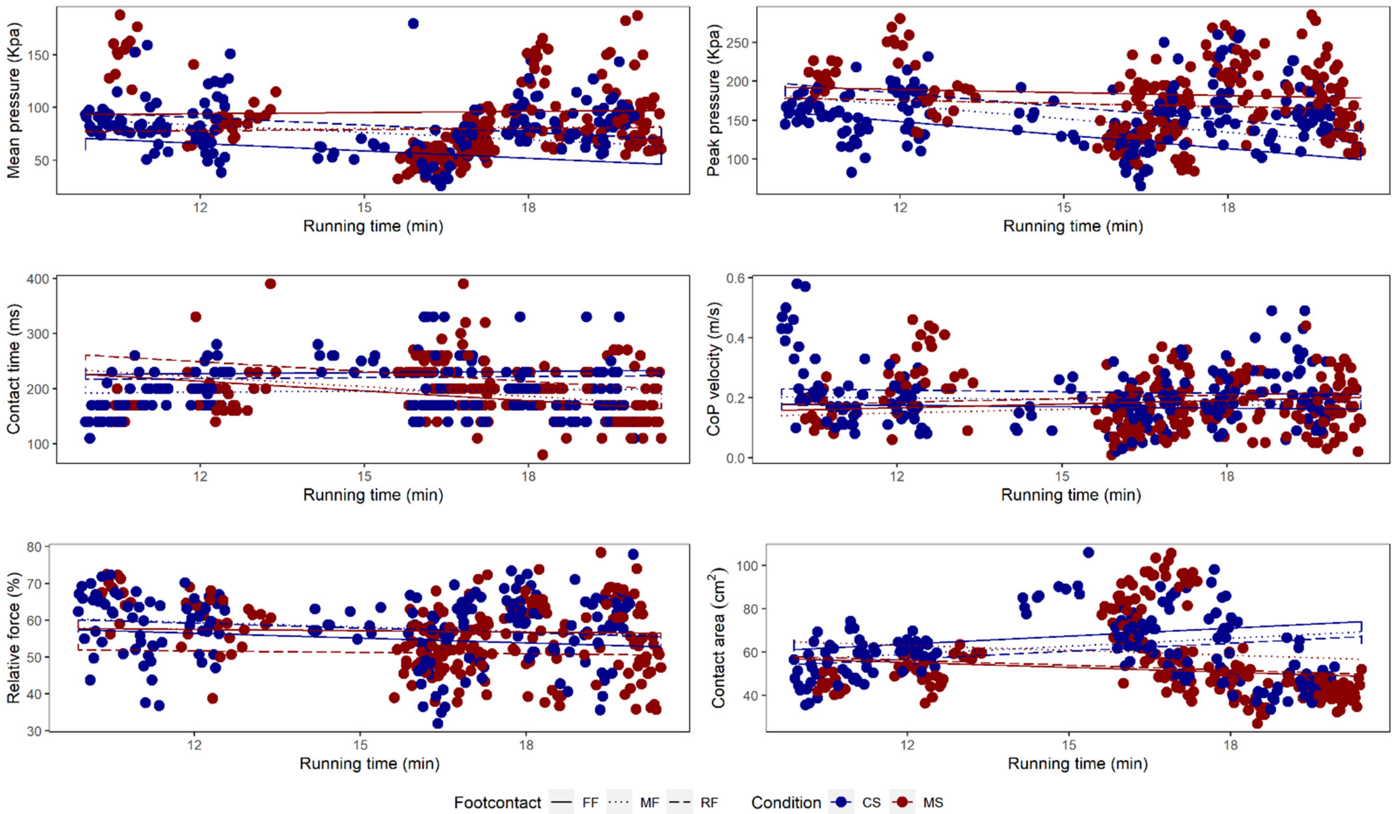

Figure 1. Predictions (lines), on the data obtained (points), of the condition effect and its interaction with time and foot strike pattern for each of the plantar pressure variables. CoP = center of pressure.

Table 2. Results from multivariable linear regression mixed models to predict plantar pressure variables.

	Mean Pressure			Peak Pressure			Contact Time			CoP Velocity			Relative Force			Contact Area		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	71.18	43.19 99.16	<0.001	187.51	150.22 224.80	<0.001	242.31	196.83 287.79	<0.001	0.15	0.06 0.25	0.002	60.30	51.53 69.08	<0.001	57.89	45.28 70.49	<0.001
Condition [MS]	20.80	−6.57 48.18	0.136	15.91	−19.46 51.28	0.377	22.04	−25.12 69.21	0.359	−0.03	−0.13 0.07	0.542	1.97	−7.54 11.49	0.684	6.60	−4.21 17.42	0.231
Time	−1.23	−2.74 0.28	0.110	−4.30	−6.27 −2.33	<0.001	−0.47	−3.00 2.07	0.719	0.00	−0.00 0.01	0.849	−0.37	−0.87 0.13	0.151	0.79	0.18 1.40	0.012
Foot contact [MF]	17.44	4.87 30.00	0.007	20.54	4.26 36.82	0.014	−33.78	−55.28 −12.29	0.002	0.02	−0.02 0.07	0.294	2.97	−1.34 7.28	0.176	−4.77	−9.78 0.23	0.062
Foot contact [RF]	24.63	7.42 41.84	0.005	36.20	13.87 58.52	0.002	−9.35	−38.69 19.99	0.531	0.05	−0.01 0.11	0.109	2.74	−3.12 8.60	0.359	−6.97	−13.85 −0.09	0.047
Predominant Pattern [Yes]	11.76	2.22 21.29	0.016	15.68	3.31 28.05	0.013	−11.67	−27.94 4.59	0.159	0.02	−0.01 0.06	0.190	0.67	−2.59 3.92	0.687	−4.56	−8.37 −0.75	0.019
Condition [MS]: Predominant pattern [Yes]	−13.07	−25.21 −0.92	0.035	−14.68	−30.39 1.03	0.067	21.52	0.66 42.38	0.043	−0.02	−0.07 0.02	0.269	−2.30	−6.50 1.90	0.282	4.41	−0.41 9.23	0.073
Condition [MS]:Time	1.49	−0.27 3.26	0.096	3.07	0.79 5.35	0.008	−4.45	−7.48 −1.42	0.004	0.00	−0.00 0.01	0.282	0.08	−0.53 0.69	0.793	−1.56	−2.26 −0.86	<0.001
Condition [MS]: Foot contact [MF]	−32.94	−46.39 −19.49	<0.001	−34.98	−52.33 −17.63	<0.001	41.52	18.26 64.79	0.001	−0.04	−0.09 0.01	0.088	−2.99	−7.70 1.73	0.213	12.57	7.27 17.86	<0.001
Condition [MS]: Foot contact [RF]	−41.06	−59.31 −22.80	<0.001	−50.15	−73.70 −26.60	<0.001	44.74	13.15 76.32	0.006	−0.03	−0.10 0.03	0.331	−8.61	−15.01 −2.21	0.009	8.06	0.87 15.24	0.028

CoP = center of pressure; CI = confidence interval; MS = running condition with minimalist shoes; MF = midfoot; RF = rearfoot.

4. Discussion

The aim of this study was to analyse the changes produced using MS on plantar pressure during a prolonged running, as well as their interaction with the time and foot strike patterns. In this sense, there are few studies that analyse the effect of MS on plantar pressure, and most of these studies do not consider the foot strike pattern (FF, MF, RF), not knowing whether the differences found are associated with the footwear type, foot strike pattern during running or the interaction of both [8,9,29–32,38,45].

The results of this study do not show a main effect of the footwear type on the variables analysed, contrary to the results obtained in previous studies, where higher plantar pressure values were obtained with MS vs. CS [9,29,36,46]. In this sense, although several studies relate the increase in pressure to a rapid or inadequate transition to this type of footwear [9,30,45], all participants in this study were runners with previous experience in MS, and the factor of previous experience/transition to MS may be the reason for the increased pressure in these studies.

However, the results did show significant differences in terms of the shoe*foot strike pattern interaction, specifically in the use of MS in relation to the forefoot vs. midfoot/rearfoot pattern. Thus, higher mean and peak pressure values were observed for forefoot pattern compared to midfoot and rearfoot (Figure 1). In this sense, Kasmer et al. [37] also obtained higher peak pressure values with MS as well as the study of Kernozek et al. [45] in non-heeler vs. heeler runners, which could be due to an increase in plantar flexion, a decrease in the contact area, as well as due to the lack of cushioning elements/materials in this type of footwear [5,8,13,31,39].

In terms of contact area and contact time, the shoe*foot strike pattern interaction reveals that in MS, forefoot runners show less contact time and contact area compared to midfoot/rearfoot runners (Figure 1). Thus, in relation to the contact area, and considering exclusively the footwear type, the results are in line with Mei et al. [38], who observed a decrease in the contact area in the forefoot and midfoot area when analysing barefoot running vs. CS. However, if the foot strike pattern is considered, our results are contrary to those obtained by these authors, as they observed a decrease in this in rearfoot runners in the barefoot condition, probably due to the absence of any type of sport shoes that suppose a small protection. Although it is true that no comparison was made between CS and MS, these results suggest that the decrease in the contact surface with the use of MS may be due to the smaller sole size [46,47]. Nevertheless, future research considering the sole dimension of the MS with respect to the CS will be necessary to know the effect of the change in the contact area.

Regarding the shorter contact times found with MS with a forefoot stride pattern, Lussiana et al. [36] explain how the reduction in contact time with MS may be an adaptive mechanism to try to attenuate the high loads and pressures that occur with this type of footwear. As discussed above, in our study an increase in mean and peak pressure was observed with a forefoot vs. midfoot/rearfoot running pattern, and it was in this same stride pattern that a reduction in contact time was also found, reinforcing the results of Lussiana et al. [36]. Another aspect to take into account, as other authors have considered [48–50], is that the midsole of CS needs time to deform during the step, causing an increase in contact time the thicker the shoe midsole is. Probably the adaptive mechanism to decrease loads in MS and the reduction in the thickness of the sole, together with the reduction in the contact area that occurs in forefoot runners, were the main factors that justifies this reduction in contact time.

The results obtained of greater relative strength in the forefoot vs. rearfoot stride pattern in MS (CI −15.01, −2.21; $p = 0.009$) could be due to the increase in pressure that occurs in this type of runner together with the decrease in the contact area observed. Kernozek et al. [45] observed this phenomenon in minimalist runners, and Wei et al. [51] observed it in non-minimalist runners, although they did not observe statistically significant differences between loading in forefoot and rearfoot runners, both agree that forefoot runners have increased strength in this segment of the foot, leading to a risk of injury such as metatarsal fractures. Other authors have found contrary situations, including Hamzavi and Esmaeili [34], who explained how contact time and the percentage of relative force applied were closely related, and a decrease in relative force in forefoot runners (and especially in MS) may be related to a possible reduction in stride length and increase in stride frequency [8]. The work of Lieberman et al. [4] shows that the load was decreased in barefoot forefoot runners compared to those who ran barefoot and rearfoot, allowing for a decrease in the discomfort and mechanical stress that this type of running produces. The use of MS associated with a training programme to change the rearfoot pattern to a forefoot pattern may be effective in reducing a high loading rate, as proposed by Yang et al. [52]. In this sense, the work of Warne et al. [53] also postulates that although the loading rate was higher in the MS vs. CS condition, the combination of this type of footwear (MS) with a specific training programme to change the running pattern over 6 weeks reduces this loading as a tactic to attenuate the high impacts that occur in this type of footwear compared to CS. Based in these authors, runners who want to start in minimalist running should associate the footwear change with specific exercises to avoid increasing the foot load and thus increasing running injuries.

Regarding the effect of time during prolonged running, without considering the foot strike pattern, a reduction in peak pressure and an increase in contact area were observed, similar to what has been previously reported by other studies [54,55]. Most studies that analyse plantar pressure under fatigue conditions observed a change in its distribution between different foot segments, increasing especially in the metatarsal area [54] and in forefoot runners [33,34,56], becoming a risk factor for injuries such as metatarsal fractures. If we consider the time*shoe interaction, the results show a higher magnitude of peak plantar pressure, shorter time, and lower contact area at the end of the run in MS vs. CS. Furthermore, if we take into account that MS also showed higher mean and peak pressure values with a forefoot pattern compared to midfoot/rearfoot, it seems that the conjunction of MS and forefoot pattern may justify the incidence of metatarsal injuries in this type of running. However, the literature studying the behaviour of plantar pressure under fatigue and MS conditions is practically non-existent. Lussiana et al. [36] obtained different results in relation to plantar pressure with MS, finding a reduction in plantar pressure with this shoe, although it seems that these results were due to the effect of the slope inclination on the running surface. More research is needed in minimalist running shoes to observe the behaviour of these shoes during running fatigue.

Among the limitations of this study, it could be considered that only runners adapted to running with MS were analysed, so a comparison with runners with no experience in MS could provide relevant information on the effect of adaptation to this footwear type. In relation to the footwear used, this was not standardised, as participants ran with their own (both CS and MS) in order to contribute to the ecological validity of the study and to interfere as little as possible with the running technique [57,58]. However, in order to minimise the possible effects of this factor, we checked, on the one hand, that all the CS were neutral and with a drop greater than 8 mm, and on the other hand, that the MS complied with all the parameters defined by Esculier et al. [21].

5. Conclusions

In conclusion, plantar pressure is higher with MS than CS during prolonged run. Without considering foot strike pattern and prolonged run, the use of MS or CS has no effect on plantar pressures in runners with previous experience with MS. Nevertheless, if it is considered foot strike pattern, the use of MS increases mean and peak pressures, as well as shorter contact times and contact areas in the forefoot pattern compared with midfoot/rearfoot patterns. Finally, at the end of the run, the use of MS increases peak pressure and reduces contact time and contact area compared with CS. Therefore, the increase on plantar pressure in MS with a forefoot pattern should be taken into account as a risk factor in some pathologies such as periostitis, bone oedema or stress fractures.

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Data Availability Statement: The dataset generated and analysed during the current study are available from the corresponding author on reasonable request.

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