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Brief Report

Biosignals by In-Shoe Plantar Pressure Sensors on Different Hardness Mats during Running: A Cross-Over Study

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Featured Application: Running on soft polyurethane foam mats presented reduced maximum plantar forces. Soft mats reduced the peak pressures of the anterior part of the foot plantar region. Air chamber mats increased calcaneus and first metatarsal head peak pressures. The mechanical behavior of hardness mats impacts running plantar pressures. Future studies should replicate this study in patients with different conditions.

Abstract: Although the effects of running on plantar pressures have been detailed on several surfaces with different hardness, there is a lack of studies assessing the mechanical behavior analysis by in-shoe plantar pressure sensors on different hardness mats during running. The aim of the present study was to determine in-shoe maximum forces and peak plantar pressures on mats with different hardness, such as hard, soft and air chamber mats, during running. A cross-over study was carried out including 36 amateur runners from a sport center. The maximum force and peak pressures of the foot plantar region were analyzed on three different mat hardnesses —soft and hard polyurethane foam mats and air chamber mats—by in-shoe instrumented insoles. Running on soft polyurethane foam mats presented reduced maximum forces in the whole plantar region and mainly peak pressures in the anterior part of the foot plantar region, such as the toes and first to fourth metatarsal heads, compared to hard polyurethane foam and air chamber mats. The peak pressure in the fifth metatarsal head was specifically reduced during running on soft compared to hard polyurethane foam mats, and running on these soft mats decreased calcaneus peak pressures compared to running on air chamber mats. Running on air chamber mats increased peak plantar pressures in the first metatarsal head compared to running on hard polyurethane foam mats. The mechanical behavior of mats of different hardness could be used to adjust the degree of impact on plantar pressures to determine the most appropriate materials and hardness for running.

Keywords: biomechanical phenomena; running; sports

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1. Introduction

Running may be reported as a trending recreational activity presented in most sport modalities, its biomechanical analysis considered a key factor in minimizing injury risk [1]. Indeed, a prior systematic review linked the measurement of plantar pressures to running-related injuries, reporting possible associations between maximum forces and peak pressures in injured runners. Nevertheless, biomechanical risk patterns were inconsistent and additional studies may be necessary in the future [2].

Thus, running biomechanics may vary depending on the mechanical behavior exhibited by different surface hardnesses [3,4] and shoe materials [5]. In addition, plantar pressure and force parameters presented adequate within- and between-day repeatability during running for analyzing gait patterns and changes on different surfaces [6]. Concretely, peak plantar pressures and maximum forces in runners presented a clear relationship between different surface hardnesses and their impact on the lower limbs [3,4].

More than 30 years ago, the on-target use of plantar pressure distribution on flexible mats was claimed as a key evaluation in traumatology, sports orthopedics and adjacent overlapping fields. Dynamic measurements for pressure distribution on a flexible mat as a capacitor may provide valuable findings on human locomotor system stress, injury prevention and sport performance optimization [7].

Nowadays, in-shoe plantar pressure sensors have been used as the preferred measurement method for determining maximum forces and peak pressures to study the effects of running on several surfaces with different hardness [3,4]. The relationship between jumping modality performance and sprint parameters in sprinters was determined using in-shoe sensors [8]. In addition, footfall dynamics was evaluated in racewalkers and barefoot runners on different surfaces [9]. Although the effects of running on plantar pressures have been detailed on several surfaces with different hardness [3,4], there is a lack of studies assessing the mechanical behavior analysis by in-shoe plantar pressure sensors on mats with different hardness during running. We hypothesized that mats with greater hardness could present higher maximum forces and peak pressures during running. Thus, the aim of the present study was to assess and compare in-shoe maximum forces and peak plantar pressures on mats of three different hardnesses—hard, soft and air chamber mats—during running.

2. Materials and Methods

2.1. Study Design

This study was an observational descriptive cross-over study according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) criteria [10]. This study was carried out in a sport center from July 2018 to September 2018.

2.2. Ethical Considerations

All participants signed the informed consent form. The ethics committee approval had been obtained previously from the local Ethics Committee (registration number: 0304201707817). The present study complied with the ethical principles for medical research involving human subjects according to the Declaration of Helsinki [11].

2.3. Participants and Recruitment

Recruitment was performed in a sport center by a convenience sampling method.

Inclusion criteria were male amateur runners, aged from 25 to 55 years, who performed physical exercise for at least 3 h per week. Exclusion criteria comprised participants with flat feet, nervous system disorders, orthopedic insoles, ankle dorsal flexion lower than 25° or lower limb injuries suffered during the six months prior to the study [4].

2.4. Descriptive Data

Physical activity was measured using the International Physical Activity Questionnaire (IPAQ) [12,13]. The absence of flat feet was checked through the Navicular drop test [14]. Ankle dorsal flexion was assessed using the ankle dorsiflexion test [15] with the digital inclinometer smartphone app Goniometer Pro (5FUF5 CO®; Wyndham Vale, VIC, Australia) [16,17]. Previously, demographic data such as weight, height, age and dominant lower limb had been collected from each participant using the step forward test [18].

2.5. Procedure and Materials

Participants were instructed to run on site on three mats with different hardnesses: soft, hard and air chamber. The Gymnova® soft mat (size 200 × 100 × 50 cm; weight 21 kg), with a density described by the manufacturer as 20 kg/m^3, was composed of one piece of polyurethane foam and seemed to be commonly used to train jumping receptions (Figure 1A). The Gymnova® hard mat (size 400 × 200 × 50 cm; weight 78 kg), with a density described by the manufacturer as 25 kg/m^3, was also composed of one piece of polyurethane foam and was commonly used to train exits from gymnastic tools (Figure 1B). The Airgym® (AG Industries BV Beek-Ubbergen, The Netherlands) Airtrack inflatable air chamber mat (size 600 × 150 × 20 cm; pressure 70 mbar) was used after checking the initial pressure with a manometer as recommended by the manufacturer (Figure 1C). Pressure measurements were registered in six different zones (Figure 1D) during the procedure.

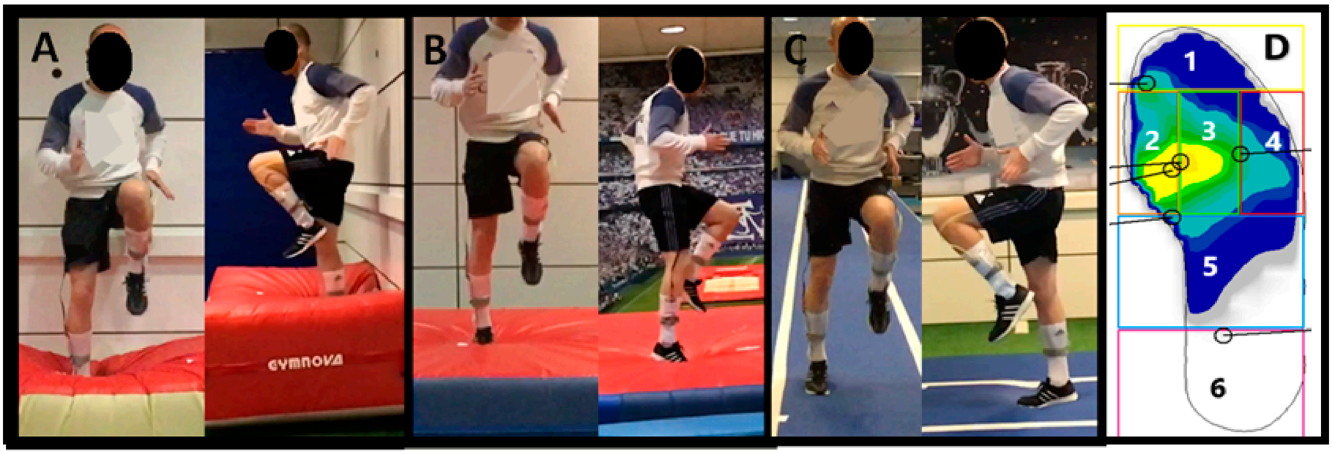

Figure 1. Procedure to run on three mats with different hardness: soft (**A**), hard (**B**) and air chamber (**C**). Layout of pressure measurement zones (**D**) for the toes (1), the first metatarsal (2), the second, third and fourth metatarsals (3), the head of the fifth metatarsal (4), the longitudinal arch of the foot (5) and the calcaneus (6).

Participants performed a warm-up based on the following sequence. First, gentle rolling was performed on a WattBike® cycloergometer (Nottingham, UK) at 80 rpm and with a power of 90–100 W without exceeding 100 W during 4 min. Second, light jogging and hip, knee and ankle mobility exercises (hurdle step, openers, flexion and extension stretching and lunge) were carried out on an artificial turf surface for 2 min. In addition, participants were allowed to perform a short 30 s trial to familiarize themselves with the test on each mat type. Between each trial, a rest period of 1 min duration was established. Furthermore, the order of test execution on the different mats was randomized (Graphpad® software; San Diego, CA, USA). The dynamic process of running was similar for each kind of mat. When analyzing the lower limb during running on the spot, it was observed that there was no linear forward movement and the running technique was slightly different. In addition, the center of gravity was always kept within the base of support. The support period was made up of three additional phases: the landing phase, the support phase and the takeoff phase. The propulsion or takeoff generated a flight phase. All tests were carried out indoors, scheduled from 5:00 to 7:00 pm and under the same environmental conditions of temperature 22–23 °C and 55–60% humidity. A tuning fork was used to determine the running speed [19]. In this study, a mobile application named Real Metronome Pro® (Gismart Limited; London, UK) was used. A cadence of 180 rpm was established providing 90 impacts per minute for each leg [4].

2.6. Outcome Measurements

In-shoe plantar pressures were measured by Gebiomized® instrumented insoles (Munster, Germany). These tools registered a maximum frequency of 200 Hz and presented a resolution of 12 bits [4]. The insole size ranged from 245 mm (European size 39) to 295 mm (European size 44.5). These insoles were placed in training shoes (Adidas®; Herzogenaurach, Germany; model Supernova Glide 6, with a drop of 11 mm and a weight of 295 g for size 42) and connected via cable to the transmitter equipment worn on the participants' backs [20].

Outcome measurements were determined through the instrumented insole commercial software (Gebiomized®; GP MobilData; Munster, Germany). This software recorded data from 50 points and calculated the virtual pressure values between these points showing a measurement uniform distribution [4]. Once appropriate speed was reached in each test, we proceeded to record 10 steps with each foot. Using a graphic visual distribution, the most correct and symmetrical six consecutive steps were selected [21]. Collected outcome measurements were maximum force (Fmax) and peak pressures (PPs). Fmax comprised the maximum force (N) in the whole foot plantar region defined as a vector magnitude measured by applying an acceleration of 1 m/s^2 to a body weight of 1 kg. The total force value corresponded to the force received in the foot area of each sensor during the stimulus duration. PPs comprised forces' pressures in a perpendicular direction per unit area. Indeed, six foot plantar areas were studied: toes (PP1), head of the first metatarsal (PP2), region of the second, third and fourth metatarsals (PP3), head of the fifth metatarsal (PP4), longitudinal arch of the foot (PP5), and calcaneus (PP6) [4], according to Figure 2.

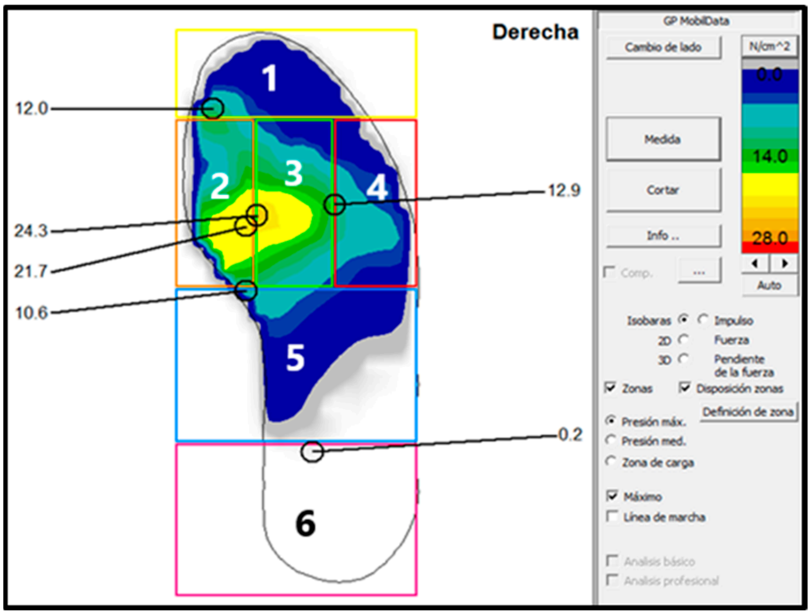

Figure 2. Presentation of the detailed overall system setup and an example of the acquired and processed data of the pressure measurement zones (D) for the toes (1), the first metatarsal (2), the second, third and fourth metatarsals (3), the head of the fifth metatarsal (4), the longitudinal arch of the foot (5), and the calcaneus (6).

2.7. Sample Size Calculation

A sample size calculation was carried out and based on F family tests for statistical tests of within factors analysis of variance (ANOVA) of repeated measures by G*Power 3.1.9.2 using a general moderate effect size of f = 0.25 according to Salkind [22]. Furthermore, a power (1-β error probability) of 0.80, an α error probability of 0.05, a total of 3 measurements (on 3 mats with different hardness) for one group, a correlation for repeated measurements of 0.5, as well as an ε non-sphericity correction of 1 were applied for the sample size calculation. According to these parameters, a total sample size of 28 participants was necessary to get an actual power of 0.812. Regarding a possible 30% loss during follow-up, a final sample of 40 participants was recruited.

2.8. Statistical Analysis

Statistical analysis was performed using IBM SPSS statistics® (version 22.0) considering a p-value < 0.05 statistically significant. Data were expressed as the median and interquartile range. The Shapiro–Wilk test was used to determine normality distribution. Since the data did not follow a normal distribution, the Friedman test for repeated measures was used. For outcome measurements which showed statistically significant differences, the Wilcoxon signed-rank test was subsequently performed in order to allow a comparison between two related measurements. Because three comparisons were performed in the study (measurements on soft versus hard mats; measurements on soft versus air chamber mats; and measurements on hard versus air chamber mats), a p-value < 0.016 was considered statistically significant according to Bonferroni's correction. This correction was calculated and based on a significant p-value < 0.05 divided by three study conditions (soft, hard and air chamber mats), obtaining significant findings if the p-value < 0.016.

3. Results

3.1. Descriptive Data

From the 40 participants initially recruited for eligibility, 36 male participants completed the study with age 33.9 ± 7.2 years, weight 75.3 ± 7.8 kg and height 179.0 ± 7.5 cm. A total of 33 participants presented right dominance for lower limb. All participants presented moderate physical activity according to the IPAQ.

3.2. Outcome Measurements

Statistically significant differences (p < 0.05) were shown for Pmax and all peak plantar pressure regions of the foot among the different mat hardnesses during running, with the exception of PP5, showing that the peak pressure of the longitudinal arch of the foot did not differ significantly among these mats (Table 1).

Table 1. Comparison of in-shoe maximum forces and peak plantar pressures for different foot regions (Figure 1D) in mats with different hardness (hard, soft and air chamber) during running.

Outcome Measurement	Soft Mat		Hard Mat		Air Chamber Mat		Friedman		Wilcoxon	
	Median	IR	Median	IR	Median	IR	Chi	p-Value *	Z	p-Value †
Pmax (N)	174.50	148.25	272.50	184.25	310.50	250.25	46.58	<0.01	(a) −5.185	(a) <0.01
									(b) −5.216	(b) <0.01
									(c) −1.483	(c) 0.138
PP1 (N/cm^2)	5.30	3.38	7.05	5.88	6.80	6.70	19.98	<0.01	(a) −4.243	(a) <0.01
									(b) −3.355	(b) 0.001
									(c) −1.202	(c) 0.229
PP2 (N/cm^2)	3.05	3.28	5.65	7.25	6.45	9.30	40.62	<0.01	(a) −4.814	(a) <0.01
									(b) −5.131	(b) <0.01
									(c) −3.009	(c) 0.003
PP3 (N/cm^2)	2.90	1.63	5.15	3.13	5.15	2.57	29.67	<0.01	(a) −4.587	(a) <0.01
									(b) −4.808	(b) <0.01
									(c) −1.434	(c) 0.151
PP4 (N/cm^2)	3.00	1.90	4.00	1.93	3.80	2.05	8.13	0.017	(a) −2.628	(a) 0.009
									(b) −1.591	(b) 0.112
									(c) −1.317	(c) 0.188

Table 1. *Cont.*

Outcome Measurement	Soft Mat		Hard Mat		Air Chamber Mat		Friedman		Wilcoxon	
	Median	IR	Median	IR	Median	IR	Chi	*p*-Value *	Z	*p*-Value †
PP5 (N/cm^2)	1.70	1.57	1.70	1.98	2.05	2.43	8.71	0.138	(a) −1.139	(a) 0.255
									(b) −2.320	(b) 0.020
									(c) −1.747	(c) 0.081
PP6 (N/cm^2)	2.70	1.88	2.40	1.73	2.05	1.70	11.61	0.003	(a) −1.497	(a) 0.134
									(b) −2.805	(b) 0.005
									(c) −2.349	(c) 0.019

Abbreviations: Fmax, maximum force; PP1, peak pressure of the toes (Figure 1D); PP2, peak pressure of the head of the first metatarsal (Figure 1D); PP3, peak pressure of the region of the second, third and fourth metatarsals (Figure 1D); PP4, peak pressure of the head of the fifth metatarsal (Figure 1D); PP5, peak pressure of the longitudinal arch of the foot (Figure 1D); PP6, peak pressure of the calcaneus (Figure 1D). * *p*-value was statistically significant at $p < 0.05$ for a 95% confidence interval. † *p*-value was statistically significant at $p < 0.016$ according to Bonferroni's corrections for post-hoc comparisons: (a) Soft versus hard mats; (b) Soft versus air chamber mats; (c) Hard versus air chamber mats.

Post-hoc comparisons showed that the Pmax median of the whole foot plantar region was lower ($p < 0.01$) during running on soft mats with 174.50 N than hard and air chamber mats with 272 and 310 N, respectively. In line with these findings and the Figure 1D regions, the median peak plantar pressure values of the toes (PP1), head of the first metatarsal (PP2) and region of the second, third and fourth metatarsals (PP3) were also lower ($p < 0.01$) during running on soft mats (varying from 2.90 to 5.30 N/cm^2) than hard and air chamber mats (varying from 5.15 to 7.05 N/cm^2 and from 5.15 to 6.80 N/cm^2, respectively). In addition, running on air chamber mats increased the median peak pressure value of the first metatarsal head (PP2) up to 6.45 N/cm^2. Only the median peak pressure of the fifth metatarsal head (PP4) was lower ($p = 0.009$) on soft mats (with 3.00 N/cm^2) than hard mats (with 4.00 N/cm^2), while only the median peak pressure of the calcaneus (PP5) was lower ($p = 0.005$) on soft mats (with 1.70 N/cm^2) than air chamber mats (with 2.05 N/cm^2). The rest of the comparisons did not show statistically significant differences ($p > 0.05$).

4. Discussion

The present study highlighted that running on soft polyurethane foam mats presented reduced maximum forces for the whole plantar region as well as mainly peak pressures for the anterior part of the foot plantar region compared to running on hard polyurethane foam and air chamber mats. In addition, the peak pressures of the fifth metatarsal head were specifically reduced during running on soft compared to hard polyurethane foam mats, and running on these soft mats decreased calcaneus peak pressures compared to running on air chamber mats. Nevertheless, running on air chamber mats increased the peak plantar pressure of the first metatarsal head compared to running on hard polyurethane foam mats.

Although there is a lack of studies assessing maximum forces and peak plantar pressures running on different mat hardnesses, these findings were in line with prior studies showing the influence of different surface hardnesses on plantar pressures while running [3,4,23,24]. Indeed, the maximum forces of the dominant foot were 657 N on artificial turf and 692.5 N on rubber floor, greater than the maximum force of 262 N presented on the trampoline during running. In accordance with our findings, plantar pressures exerted by the foot on hard surfaces, such as artificial turf and technical floor, were also greater in the metatarsal heads, while these plantar pressures were higher in the calcaneus than in the metatarsal heads while running on the trampoline [4]. In addition, running on different treadmill surfaces should be considered for plantar pressure interpretation with respect to overground running due to their different surface hardnesses [3]. In this sense, running on different surfaces such as concrete, synthetic rubber and grass surfaces affected plantar loads showing the influence of different surface hardnesses [24]. Furthermore, plantar pressures were analyzed during linear running on surfaces of different hardness such as cement, asphalt, rubber and natural grass, showing lower pressures while running on soft surfaces such as grass than running on hard surfaces such as cement and asphalt, especially for the forefoot and medial regions of the foot [23].

The study findings could play a key role in training, injury prevention and the return to sport after an injury, since the practice of running or skipping is an important part of both sport training and injury recovery [25]. The mechanical behavior of different mat hardnesses enabled us to know their degree of impact by plantar pressures in order to choose the most appropriate materials and hardness for running. This fact was based on the "spring mass" model, which claims that the lower limb tension is adjusted to the training surface [26].

According to our study findings, some considerations could be taken into account for guiding the rehabilitation training of runners and should be further analyzed in future studies. Foot-strike and the associated load rate are factors related to overuse injuries in the hindfoot during running [27], such as Achilles tendinopathies and plantar fasciopathy [28]. Interventions to reduce pain in hindfoot injuries consist of reducing load ratios during running, for example, by using floating-heel shoes or foot orthoses [27]. Therefore, training on soft mats for runners with hindfoot pain could be used for the recovery of these pathologies. In addition, our study findings may support the notion that training for runners on harder surfaces may not be the most appropriate option for athletes with frequent foot-related overuse pathologies such as plantar fasciitis and foot pain (e.g., metatarsalgia). One important aim is to reduce plantar pressure in prominent areas following these injuries [29]. Therefore, training on soft mats could be a better option of intervention for athletes with acute foot pain. Under these circumstances, further studies are needed to compare the effects of training on different surfaces on runners with foot injuries.

Limitations and Future Studies

The present study presented several limitations. First of all, participants were healthy subjects. Future studies should replicate this study in patients with different conditions due to the fact that running on soft surfaces may reduce the risk of injuries [30], including musculoskeletal conditions such as meniscal injuries, tibial stress and fractures and spine alterations [31] as well as forefoot injuries such as metatarsalgia and metatarsal stress fractures [32]. Second, participants were only men; female participants should be analyzed due to the fact that sex has been associated with running plantar pressure differences [33]. Third, participants presented moderate physical activity; sedentary participants should be studied in order to determine the best adaptation to surface hardnesses to establish or standardize a training protocol, which is especially important for patients with plantar skin disorders such as diabetes [34]. Finally, the thickness of all mats should be the same in control experiments. In this study, the thickness of the air chamber mat was 20 cm while both the soft and hard mats presented a thickness of 50 cm. Nevertheless, this thickness difference did not influence the hardness of the air chamber mats as their hardness was established by the air pressure at which it swelled, providing a fixed hardness because they were made of foam rubber [4]. Future studies should analyze spatiotemporal parameters in addition to plantar pressure distribution in superficies with different hardness, including older adults and people with neurological conditions [35,36].

5. Conclusions

In conclusion, running on soft polyurethane foam mats presented reduced maximum forces in the whole plantar region, as well as peak pressures mainly in the anterior part of the foot plantar region such as the toes and the 1st–4th metatarsal heads, compared to hard polyurethane foam and air chamber mats. In addition, the peak pressure of the fifth metatarsal head was specifically reduced during running on soft compared to hard polyurethane foam mats, and running on these soft mats decreased calcaneus peak pressures compared to running on air chamber mats. Nevertheless, running on air chamber mats increased the peak plantar pressure of the first metatarsal head compared to running on hard polyurethane foam mats. Thus, the mechanical behavior of different mat hardnesses could be used to adjust the degree of impact by plantar pressures in order to choose the most appropriate materials and hardness for running.

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