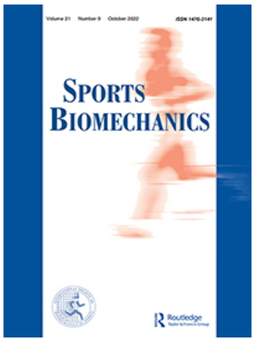

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Jumping on sand surfaces redistributes loading of the plantar surface to midfoot areas and reduces peak loading

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ABSTRACT

The purpose was to assess plantar mechanical loading on different surface conditions when performing jumps. Twenty subjects performed standardized drop jumps and countermovement jumps both in shoes and barefoot on a rigid surface and barefoot on a sand surface. Flexible insoles of the Pedar Mobile system (PedarX, Novel GmbH) were used for data collection. The foot was subdivided into eight regions where peak pressures and relative loads were derived. Significant differences were found for several foot areas for both, countermovement and drop jumps. For the sand surface, as compared to the rigid surface, peak pressures were significantly reduced in the hallux&2nd toe, medial/lateral forefoot, and heel but were increased in the medial/lateral midfoot. The relative load shifted significantly from the forefoot to the midfoot area. Substantially different plantar pressure distribution patterns between conditions were observed in jumping. The switch from a rigid to a sand surface is associated with a lower mechanical loading, whereas switching back from sand to an indoor surface potentially increases this loading. Our results show that the observed pressure distribution patterns for different surfaces align with other tasks like playing soccer/running, are in a typical range for these sports and entail a comparable mechanical loading.

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Playing surface; beach; handball; volleyball; pressure distribution

Introduction

Changing playing surfaces may have an enormous impact on athletes body's mechanical loading (Eils et al., 2004; Girard et al., 2007; Reeser et al., 2006; Tilp & Rindler, 2013) and may also contribute to the development of typical overuse injuries of bones, muscles, tendons and ligaments (Edwards, 2018). Popular indoor ball sports, such as volleyball and handball, are primarily played on rigid surfaces but are also played on sand, which has become more popular in recent years; beach volleyball is now part of the Olympic games, and beach handball is being considered for the Olympics (International Handball Federation, 2020). For professionals who play these sports, some only play on one surface, but many switch between surfaces when the indoor and beach seasons overlap (in late spring and autumn).

For coaches and athletes, both transition phases (rigid to sand and sand to rigid) are important to consider, as mechanical loading may be affected and training should be

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modified accordingly with respect to training volume and intensity. Jumping is a characteristic movement of all these beach sports where athletes may be exposed to high mechanical loadings (Orendurff et al., 2008); thus, analysing the load acting on the human body during jumps is of special interest.

Pressure distribution analysis using flexible insoles at the interaction of the body and the playing surface (i.e., the sole of the foot in jumping) can be used to investigate specific (anatomical) areas of the foot sole that are exposed to high pressures under different conditions. This method was successfully used when investigating pressure distribution analyses, e.g., during soccer-specific movements (Eils et al., 2004; Orendurff et al., 2008), long-distance running (Weist et al., 2004), walking and jogging (Nandikolla et al., 2017; Sterzing et al., 2016) or landing on different types of mattresses in gymnastics (Paulino et al., 2021). It has also been used in a beach volleyball setting to identify and describe the take-off phase during jumping (Vetter et al., 2004).

In this context, however, to the best of our knowledge, the plantar pressure distribution in a barefoot situation on sand has been insufficiently studied. Doing so would help researchers describe the amount of plantar mechanical loadings on sand surfaces during jumps in beach sports and compare this to jumps in indoor sports on rigid surfaces. This information would help coaches and athletes to better plan for transitioning between sand and rigid surfaces when indoor and beach seasons overlap or when sand surfaces are used as a exercise option during the summer (Hammami et al., 2020).

Thus, the aim of the present study is to characterise the mechanical loading of the foot by means of plantar pressure distribution during barefoot jumps on sand and to compare this with jumps on rigid surfaces both in shoes and barefoot. In all three conditions, we distinguish between the take-off and landing phases, allowing us to identify the predominantly loaded anatomical structures during these phases. Predominantly loaded areas of the foot are the heel, the medial or central forefoot and the hallux when the foot is interacting with a rigid surface in standing, walking or running (Cavanagh et al., 1987; Eils et al., 2002; Hennig et al., 1994; Orendurff et al., 2008; Sterzing et al., 2016; Weist et al., 2004). It can be assumed that a deformable surface like the sand will lead the feet to sink in with these predominantly loaded areas and other areas like the midfoot will be in more contact with the sand. We therefore hypothesise that the sand surface provides a more even distribution of the plantar forces during jumps than the rigid surface, i.e., the anatomical areas of the foot that are heavily loaded during jumps on a rigid surface will be less loaded during jumps in the sand, and the load distribution will be shifted towards the less heavily loaded regions due to the deformability of the sand.

Material and methods

Twenty physically active subjects participated in the study (23 ± 2 years, 181 ± 5 cm, 77 ± 9 kg, 18 m/2f). Subjects were either physical education students or regularly participated in different amateur sports at least 2–3 x sports per week. All of them were trained but mainly unexperienced acting on a sand surface. Prior to participation, all athletes gave their written consent to participate in the study. All tests were approved by the human ethics committee of the department of Psychology and Sport Sciences of the University of Münster (ID: 2018-03-EE), and all procedures were performed in accordance with the Declaration of Helsinki. At the time of the study, none of the participants had a known injury to the lower extremities. All subjects had a European shoe size between 40 (6 ½) and 46 (12 ½) and used their own sports shoes for the study.

The Pedar Mobile system (PedarX, Novel GmbH, Munich, Germany) was used to record the plantar pressure distribution. It includes flexible insoles with 99 sensors each, which are arranged in a matrix and work with a maximum sampling frequency of 50 Hz when both insoles are used. Thin neoprene socks (AET GmbH, Au i.d. Hallertau, Germany) were used to simulate a barefoot situation where the pressure insole was attached to the foot. Within the neoprene socks, the insole was prevented from moving around, and the socks also prevented sand from entering and potentially damaging the insoles. The use of neoprene socks was the most suitable solution for imitating a barefoot condition and has been successfully used in previous studies (Vetter et al., 2004).

In indoor sports, athletes wear shoes and play on a rigid surface, and in beach sports athletes are barefoot and play on sand. Therefore, a comparison of solely these two loading conditions using pressure distribution analysis is not useful; for meaningful comparisons with only one determinant at a time, a third measurement condition (barefoot on a rigid surface) was needed. This third condition allowed us to quantify differences in loading patterns by comparing the *shoe* (shoe on a rigid surface) and *sand* (barefoot on sand) conditions to the *rigid* (barefoot on a rigid surface) condition.

The subjects performed standardised (no arm swing, hands touching the hip) countermovement jumps (CMJ) and drop jumps (DJ) from a height of 40 cm under three different conditions: (i) with shoes on a rigid surface (*shoe*), (ii) in neoprene socks on a rigid surface (*rigid*) and (iii) in neoprene socks on a sand surface (*sand*) within a custom-built sand box (1 m x 1 m × 0.35 m) that was placed on the floor. The sandbox was built of plywood (panel thickness of 0.027 m) and strengthened by metal square pipes (0.04 m × 0.04 m). The sand fulfilled the specifications of the German beach volleyball federation for indoor sand (grain size: 0.1–1.0 mm; grain shape: from round edges to rounded; grain distribution: even; $CaCO_3$ ≤2–3%; SiO_2 ≥95–98%) (Borrmann et al., 2009). The test sequence was carried out in a pseudo-randomised order for organisational reasons: either the test was started with the condition *shoe* followed by *rigid* and *sand*, or it was started with the condition *rigid*, followed by *shoe* and *sand* (sand condition was always measured at the end to not transfer sand to the force plates to avoid damage of the surface). Furthermore, 50% of subjects started each condition with the DJ, 50% with the CMJ but both jumps (DJ, CMJ) were carried out for all subjects under all conditions (*rigid*, *shoe*, *sand*).

To begin the experiment, the pressure distribution insoles were first inserted into the shoes/neoprene socks and participants had time (3–5 minutes) to get used to the sole and shoe condition. After the jumping movement was introduced, each subject had at least 2 trials to become familiarised with the condition and jumping technique. Any incorrect execution of the technique (e.g., releasing hands from the hips in both jumps, non-permitted pause in the countermovement phase in CMJ) was corrected immediately. For DJ, subjects were also instructed to perform maximum vertical jumps with minimal ground contact time. Before starting the measurements, the pressure inside the shoe or neoprene sock was set to zero in an unloaded situation. In each condition, three valid trials were recorded, and sufficient recovery times (minimum of 30 sec.) were instituted between trials to avoid fatigue. In the sand condition, sand surface was raked between trials to ensure similar surface quality. The pressure distribution was measured under

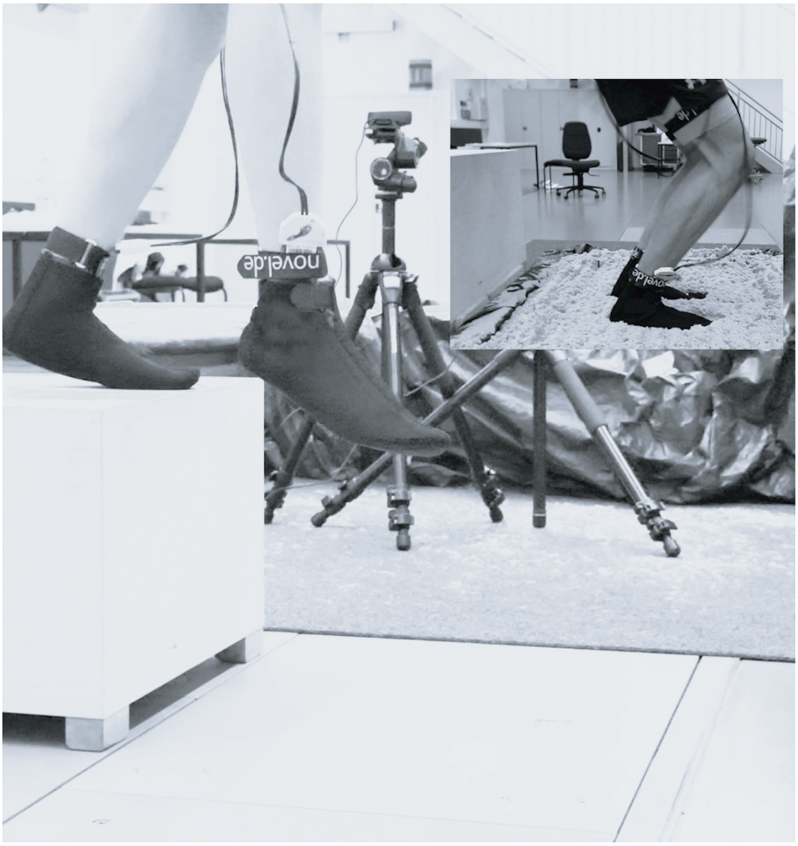

Figure 1. Experimental setup for pressure distribution analyses in *rigid*, *shoe* and *sand* conditions. The subject is performing a DJ in neoprene socks on the rigid surface (*rigid* condition). The small inset picture shows a subject performing a DJ in neoprene socks into the sand box (*sand* condition). In addition to these two conditions, subjects performed a DJ in shoes on the rigid surface (*shoe* condition). Along with the DJ, a CMJ was also performed for the *rigid*, *shoe* and *sand* conditions.

both feet, but data analysis was only performed on the right foot. The experimental setup of the tests for the DJ is shown in Figure 1.

The sole of the foot was divided into 8 different regions with a standardised mask, which automatically adapted to the differently sized insoles. The 8 foot regions were the hallux and 2nd toe, the lateral toes (3rd – 5th toes), the medial forefoot, the lateral forefoot, the medial midfoot, the lateral midfoot, the medial heel, and the lateral heel. The same mask was used for all subjects and conditions to ensure intra- and interindividual comparability. The relative impulses and the peak pressures were calculated for all areas and jumps. Figure 2 shows an example of the maximum peak pressures during a countermovement jump and a drop jump for the *rigid*, *shoe* and *sand* conditions.

One can gain a better understanding of the load-bearing function of the individual anatomical structures of the foot by calculating relative loads (force-time integral of an area in relation to the total force-time integral of the foot). In addition to making these calculations, we also measured the peak pressures, which describe the maximum load to which one sensor of an area was exposed at a given time during the movement.

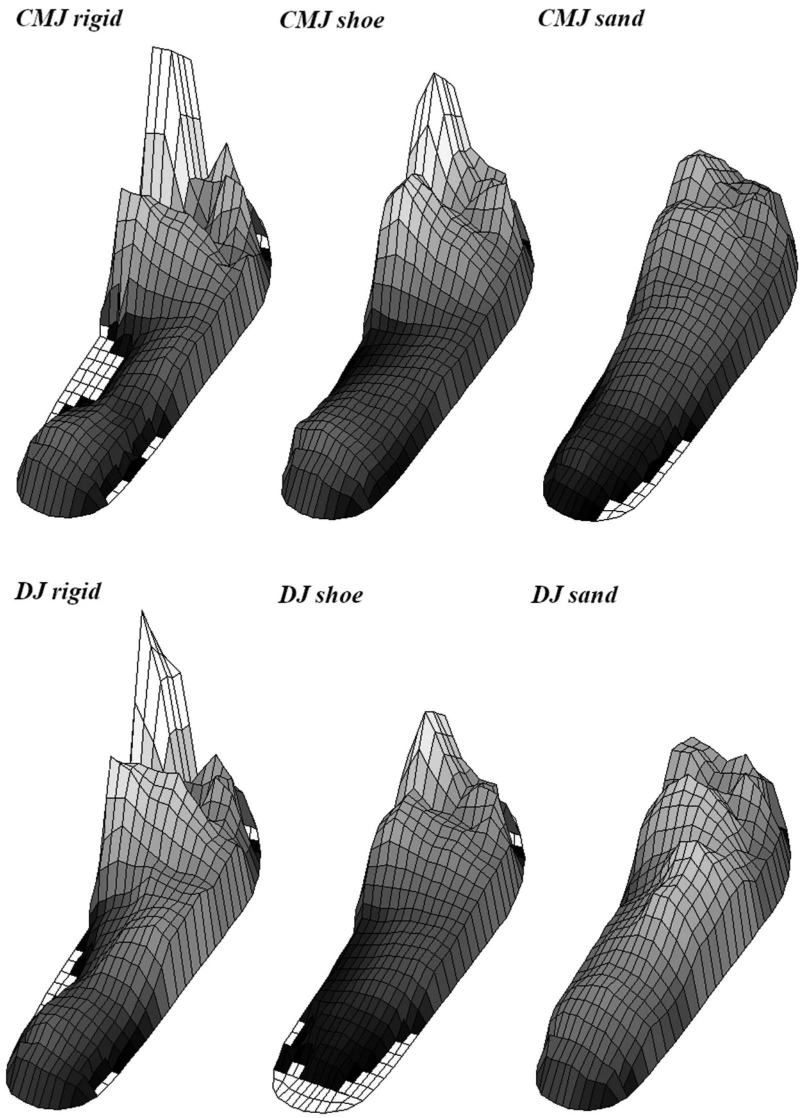

Figure 2. Example of one subject's peak pressure pictures of CMJ (first row) and DJ (second row) for conditions *rigid*, *shoe* and *sand*. Please note the reduction of peak loading between the conditions from left to right and the more even pressure distribution for the entire foot under the *sand* condition.

Furthermore, we divided each jump into take-off and landing phases. The take-off phase was defined from the beginning of the measurement until the middle of the flight time (when no pressure occurs on the insoles), whereas the landing phase was defined as the middle of the flight time until the end of the measurement (participants standing still for 2 seconds after the jump).

An a-priori sample size calculation was performed using G*Power (Version 3.1.9.6) and resulted in a required sample size of n = 20 (medium effect size $f = 0.25$ was modified for repeated trials $f' = \sqrt{3} \cdot f$, power = 0.8, correlations among repeated measurements = 0.4, number of groups = 1, number of measurements = 3, and $\propto = 0.05$) (Faul et al., 2007). For statistical evaluation (SPSS version 25, IBM Corporation), mean values of all three trials were used. The data of the three different conditions (*rigid*, *shoe*, *sand*) were tested for normal distribution with the Shapiro-Wilk test. After assuring normal distribution ($p > .05$), a repeated measures ANOVA (rmANOVA) (within-factor underground: *rigid*, *shoe, sand*) was performed. If applicable, a Bonferroni-corrected post-hoc test was used to evaluate paired comparisons. The alpha level was set to 5%. Effect sizes were presented as generalised eta squared (η^2_G). The magnitude of effect sizes was interpreted on the following criteria: η^2_G <0.02 (small), $\eta^2_G = 0.02–0.13$ (medium), $\eta^2_G = 0.13–0.26$ (large; Bakeman, 2005). For non-normally distributed data, we used the non-parametric Friedmann test in combination with the Wilcoxon test. The alpha level was adjusted for multiple testing accordingly to $\alpha = .05/3$. Effect sizes for paired comparisons for Wilcoxon tests were obtained by calculating the correlation through $r = \left|\frac{z}{\sqrt{N}}\right|$ where z is the test-statistic and N is the sample size. The magnitude of effect sizes was interpreted according on the following criteria: $|r| >= 0.1$ and $|r| < 0.3$ (small), $|r| >= 0.3$ and $|r| < 0.5$ (medium), $|r| >= 0.5$ (large; Cohen, 1988).

Results

The statistical analysis showed significant differences between conditions for several specific foot areas for both the take-off and landing phases, for both CMJ and DJ, and for both peak pressures and relative loads (Table 1). The foot areas that were predominantly affected by these significant differences were the medial/lateral forefoot, the medial midfoot and the medial/lateral heel.

Take-off and landing phases were divided to be able to obtain loading characteristics for each phase separately. Results of both phases revealed similar pressure and loading ranges between conditions; therefore, no additional differentiation is hereafter made between the two jumping phases. Results for the relative loads were presented first followed by peak pressure analysis.

Relative loads

The statistical analysis of the *relative loads* showed that the medial and lateral forefoot, the lateral heel, and, to a lesser extent, the medial heel bore most of the load in CMJ and DJ under the rigid condition (e.g., CMJ landing in %: med. forefoot 24.8 ± 5.1, lat. forefoot 22.0 ± 5.0, lat. heel 26.9 ± 9.7, med. heel 11.1 ± 8.4); the toes and the medial and lateral midfoot were barely loaded (e.g., CMJ Landing in %: Hallux & 2nd toe 4.5 ± 3.0, lat. toes 2.6 ± 1.8, med. midfoot 1.1 ± 1.1, lat. midfoot 6.9 ± 4.2). When performing jumps in shoes on a rigid surface and when performing jumps barefoot on sand the load was more evenly distributed. Thus, from the rigid condition to the shoe condition to the sand condition, the relative load on the medial and partly the lateral forefoot was reduced.

Comparing only the shoe and sand conditions, the relative loads in the mentioned areas were similar but tended to be lower for the sand, e.g., lateral heel during take-off

Table 1. Peak pressures and relative loads for CMJ and DJ.

DJ Take-Off	Condition: rigid	shoe	sand	Statistics and post-hoc Test
Relative loads (%)				
Hallux & second toe	4.4 ± 3.4	5.2 ± 2.7	4.3 ± 1.8	F(2, 38) = 1.131; p = 0.333; η^2_G = 0.02; n.s.
Lateral toes	2.8 ± 2.2	2.7 ± 1.7	3.3 ± 1.8	p = 0.005[α], sa>sh (r = .60); sa=ri; sh=ri
Medial forefoot	25.2 ± 6.2	21.2 ± 6.0	20.8 ± 3.2	F(2, 38) = 6.405; p = 0.004; η^2_G = 0.13; sa<ri; sa=sh; ri=sh
Lateral forefoot	21.9 ± 5.3	17.0 ± 4.1	22.2 ± 6.6	p = 0.002[α], sa>sh(r = .77), ri>sh (r = .76); sa=ri
Medial midfoot	1.1 ± 1.1	3.7 ± 2.1	7.2 ± 3.8	p <0.001[α], sa>sh (r = .75); sh>ri (r = .79); sa>ri (r = .87)
Lateral midfoot	6.2 ± 4.5	14.4 ± 5.5	17.3 ± 3.5	F(2, 38) = 62.121; p <0.001; η^2_G = 0.53; sa>ri; sh>ri; sa=sh
Medial heel	12.4 ± 7.4	15.1 ± 4.8	8.5 ± 4.6	F(1.43, 27.25) = 12.505; p <0.001; η^2_G = 0.19; sa<ri; sa<sh; ri=sh
Lateral heel	26.0 ± 11.0	20.8 ± 6.9	16.5 ± 6.0	F(2, 38) = 13.321; p <0.001; η^2_G = 0.19; sa<ri; sa<sh; ri=sh
Peak pressure (kPa)				
Hallux & second toe	238 ± 148	233 ± 121	119 ± 27	p <0.001[α], sa<ri (r = .71); sa<sh (r = .88); ri=sh
Lateral toes	142 ± 69	147 ± 67	120 ± 34	F(1.55, 29.35) = 2.28; p = 0.13; η^2_G = 0.04; n.s.
Medial forefoot	409 ± 129	293 ± 86	164 ± 19	F(2, 38) = 42.18; p <0.001; η^2_G = 0.56; sa<sh<ri
Lateral forefoot	204 ± 56	169 ± 32	149 ± 24	F(1.52, 28.88) = 14.62; p <0.001; η^2_G = 0.25; sa<sh<ri
Medial midfoot	37 ± 26	55 ± 17	71 ± 18	F(1.32, 25.03) = 22.04; p <0.001; η^2_G = 0.33; sa>sh>ri
Lateral midfoot	63 ± 30	72 ± 20	79 ± 21	F(2, 38) = 5.43; p = 0.008; η^2_G = 0.08; sa>ri; sa=sh; sh=ri
Medial heel	157 ± 87	103 ± 34	62 ± 17	F(1.20, 22.85) = 19.87; p <0.001; $\eta^2 G_p$ = 0.34; sa<sh<ri
Lateral heel	182 ± 93	96 ± 32	67 ± 18	p <0.001[α], sa<sh (r = .73); sh<ri (r = .88); sa<ri (r = .88)

CMJ Landing	Condition: rigid	shoe	sand	Statistics and post-hoc Test
Relative loads (%)				
Hallux & second toe	4.5 ± 3.0	6.0 ± 3.3	4.4 ± 2.7	p = 0.247[α]; n.s.
Lateral toes	2.6 ± 1.8	2.9 ± 1.7	3.4 ± 2.4	p = 0.387[α]; n.s.
Medial forefoot	24.8 ± 5.1	20.9 ± 4.9	18.0 ± 4.2	F(2, 38) = 15.467; p <0.001; η^2_G = 0.27; sa<ri; sh<ri; sa=sh
Lateral forefoot	22.0 ± 5.0	16.6 ± 4.7	17.4 ± 5.3	F(2, 38) = 11.024; p <0.001; η^2_G = 0.20; sa<ri; sh<ri; sa=sh
Medial midfoot	1.1 ± 1.1	3.9 ± 2.8	8.7 ± 4.3	p <0.001[α], sa>sh (r = .86); sh>ri (r = .76); sa>ri (r = .88)
Lateral midfoot	6.9 ± 4.2	14.0 ± 5.8	18.0 ± 4.9	F(2, 38) = 29.004; p <0.001; η^2_G = 0.46; sa>sh>ri
Medial heel	11.1 ± 8.4	14.7 ± 5.2	10.2 ± 5.5	p = 0.035[α], sa<sh (r = .62); sa=ri; ri=sh
Lateral heel	26.9 ± 9.7	21.1 ± 8.2	19.9 ± 8.0	F(2, 38) = 6.983; p = 0.003; η^2_G = 0.12; sa<ri; sa=sh; ri=sh
Peak pressure (kPa)				
Hallux & second toe	266 ± 156	234 ± 106	105 ± 43	p <0.001[α], sa<ri (r = .82); sa<sh (r = .86); ri=sh
Lateral toes	114 ± 55	131 ± 54	90 ± 33	F(2, 38) = 6.35; p = 0.004; η^2_G = 0.12; sa<sh; sa=ri; ri=sh
Medial forefoot	442 ± 114	292 ± 94	170 ± 27	F(2,38) = 84.63; p <0.001; η^2_G = 0.63; sa<sh<ri
Lateral forefoot	282 ± 104	186 ± 51	139 ± 34	F(1.55, 29.44) = 36.23; p <0.001; η^2_G = 0.43; sa<sh<ri
Medial midfoot	64 ± 31	94 ± 33	141 ± 37	p <0.001[α], sa>sh (r = .86); sh>ri (r = .61); sa>ri (r = .87)
Lateral midfoot	119 ± 40	127 ± 39	152 ± 38	F(2, 38) = 6.84; p = 0.003; η^2_G = 0.12; sa>ri; sa>sh; ri=sh
Medial heel	283 ± 142	187 ± 126	138 ± 55	p <0.001[α], sa<ri (r = .46); sh<ri (r = .76); sa=sh
Lateral heel	219 ± 151	181 ± 127	154 ± 56	p = 0.212[α]; n.s.

DJ Take-Off	Condition: rigid	shoe	sand	Statistics and post-hoc test
Relative loads (%)				
Hallux & second toe	4.3 ± 2.5	5.6 ± 3.5	4.1 ± 1.7	p = 0.116[α]; *n.s.*
Lateral toes	3.0 ± 1.8	2.8 ± 1.6	3.3 ± 1.8	p = 0.091[α]; *n.s.*
Medial forefoot	26.7 ± 8.7	23.0 ± 8.7	21.5 ± 5.3	p = 0.002[α]; sa<ri (r = .87); sa=sh; ri = sh
Lateral forefoot	24.0 ± 5.5	18.4 ± 4.8	24.1 ± 6.1	p = 0.004[α]; sa>sh (r = .73); ri>sh (r = .73); sa=ri
Medial midfoot	0.9 ± 0.8	3.4 ± 2.1	3.2 ± 1.6	p <0.001[α]; sa>ri (r = .87); sh>ri (r = .75); sa=sh
Lateral midfoot	6.6 ± 4.0	14.8 ± 5.7	9.6 ± 4.2	F(1.35, 25.59) = 36.768; p <0.001; η^2_G = 0.35; *ri<sa<sh*
Medial heel	10.6 ± 8.5	13.3 ± 5.7	12.0 ± 8.8	p = 0.287[α]; *n.s.*
Lateral heel	23.9 ± 11.8	18.7 ± 8.6	22.3 ± 10.1	F(2, 38) = 4.34; p = 0.020; η^2_G = 0.05; *sh<ri; sa=ri; sa=sh*

(*Continued*)

Table 1. (Continued).

	Condition			
DJ Take-Off	rigid	shoe	sand	Statistics and post-hoc Test
Peak pressure (kPa)				
Hallux & second toe	379 ± 165	366 ± 137	188 ± 56	F(2, 38) = 23.35; p <0.001; η^2_G = 0.33; *sa<ri; sa<sh; ri=sh*
Lateral toes	168 ± 61	178 ± 62	168 ± 41	F(2, 38) = 0.528; p = 0.594; η^2_G = 0.01; *n.s.*
Medial forefoot	591 ± 92	478 ± 134	273 ± 57	p <0.001$^{\alpha}$; sa<sh (r = .87); sh<ri (r = .79); sa<ri (r = .88)
Lateral forefoot	333 ± 105	227 ± 60	242 ± 60	p <0.001$^{\alpha}$; sa<ri (r = .78); sh<ri (r = .87); sa=sh
Medial midfoot	85 ± 43	125 ± 43	165 ± 39	p <0.001$^{\alpha}$; sa>sh (r = .80); sh>ri (r = .62); sa>ri (r = .82)
Lateral midfoot	131 ± 43	134 ± 41	181 ± 37	F(2, 38) = 23.80; p <0.001; η^2_G = 0.25; *sa>ri; sa>sh; ri=sh*
Medial heel	155 ± 85	175 ± 130	159 ± 44	p = 0.449$^{\alpha}$; *n.s.*
Lateral heel	181 ± 81	165 ± 128	164 ± 32	p = 0.116$^{\alpha}$; *n.s.*
	Condition			
DJ Landing	rigid	shoe	sand	Statistics and post-hoc test
Relative loads (%)				
Hallux & second toe	3.5 ± 2.2	5.4 ± 2.9	5.5 ± 2.2	F(1.54, 29.22) = 5.341; p = 0.016; η^2_G = 0.12; *sa>ri; sa=sh; ri=sh*
Lateral toes	2.7 ± 1.5	2.6 ± 2.0	4.1 ± 2.1	F(2, 38) = 9.572; p <0.001; η^2_G = 0.11; *sa>ri; sa>sh; ri=sh*
Medial forefoot	22.6 ± 5.2	21.0 ± 5.4	16.7 ± 5.5	F(2, 38) = 9.038; p = 0.001; η^2_G = 0.18; *sa<ri; sa<sh; ri=sh*
Lateral forefoot	24.3 ± 5.6	17.3 ± 5.7	18.7 ± 6.2	F(2, 38) = 10.670; p <0.001; η^2_G = 0.22; *sa<ri; sh<ri; sa=sh*
Medial midfoot	1.2 ± 1.2	3.5 ± 2.5	6.9 ± 3.3	p <0.001$^{\alpha}$; sa>sh (r = .68); sh>ri (r = .69); sa>ri (r = .86)
Lateral midfoot	8.9 ± 5.2	14.6 ± 5.8	16.5 ± 4.6	F(1.56, 29.57) = 21.266; p <0.001; η^2_G = 0.29; *sa>ri; sh>ri; sa=sh*
Medial heel	10.9 ± 9.3	13.7 ± 4.9	11.6 ± 5.2	p = 0.074$^{\alpha}$; *n.s.*
Lateral heel	25.9 ± 11.4	21.9 ± 8.3	20.1 ± 9.0	F(2, 38) = 4.395; p = 0.019; η^2_G = 0.06; *sa<ri; sa=sh; ri=sh*
Peak pressure (kPa)				
Hallux & second toe	239 ± 119	225 ± 105	147 ± 53	p = 0.004$^{\alpha}$; sa<ri (r = .73); sa<sh (r = .66); ri=sh
Lateral toes	119 ± 48	131 ± 62	118 ± 46	F(2, 38) = 0.941; p = 0.399; η^2_G = 0.01; *n.s.*
Medial forefoot	411 ± 102	294 ± 82	175 ± 43	p <0.001$^{\alpha}$; sa<sh (r = .86); sh<ri (r = .84); sa<ri (r = .88)
Lateral forefoot	289 ± 95	192 ± 88	142 ± 33	p <0.001$^{\alpha}$; sa<sh (r = .62); sh<ri (r = .84); sa<ri (r = .88)
Medial midfoot	68 ± 27	98 ± 37	122 ± 43	F(2, 38) = 15.12; p <0.001; η^2_G = 0.28; *sa>sh>ri*
Lateral midfoot	136 ± 53	120 ± 34	142 ± 41	F(1.25, 23.70) = 2.58; p = 0.115; η^2_G = 0.05; *n.s.*
Medial heel	211 ± 157	188 ± 115	150 ± 58	p = 0.486$^{\alpha}$; *n.s.*
Lateral heel	271 ± 142	182 ± 112	166 ± 72	p = 0.019$^{\alpha}$; sa<ri (r = .68); sh<ri (r = .67); sa=sh

For normally distributed data, a full description including mean value, standard deviation, F-value, *p*-value, generalised eta2 and results of post-hoc tests (Bonferroni) are listed. For non-normally distributed data (illustrated by an $^{\alpha}$), only the mean value, standard deviation and *p*-value of the non-parametric Friedmann test and results of post-hoc tests (Wilcoxon) with the effect size r in parentheses are presented.

< and > indicate a significant difference between two conditions (sa=sand, sh=shoe, ri=rigid). < means smaller than and > means larger than; = indicates no significant difference between the two conditions; n.s. indicates no significant difference between any conditions at all. Please also note that the standard deviation shown in Table 1 is the standard deviation across all different subjects and does not reflect the intraindividual variation between trials within subjects.

(CMJ: shoe 20.8%; sand 16.5%). Yet, compared to the rigid condition, the shoe and sand conditions led to significantly increased relative loads in the medial and lateral midfoot. For the sand condition in particular, both jumps led to significantly greater loading on the midfoot areas (e.g., CMJ take-off: medial midfoot, rigid 1.1 ± 1.1, shoe 3.7 ± 2.1, sand 7.2 ± 3.8, p < .001). Also, when comparing the shoe and sand conditions, the sand condition showed significantly higher relative loads. Figure 3 shows the significant load shifts to the midfoot areas when comparing rigid, shoe, and sand conditions for the landing phase.

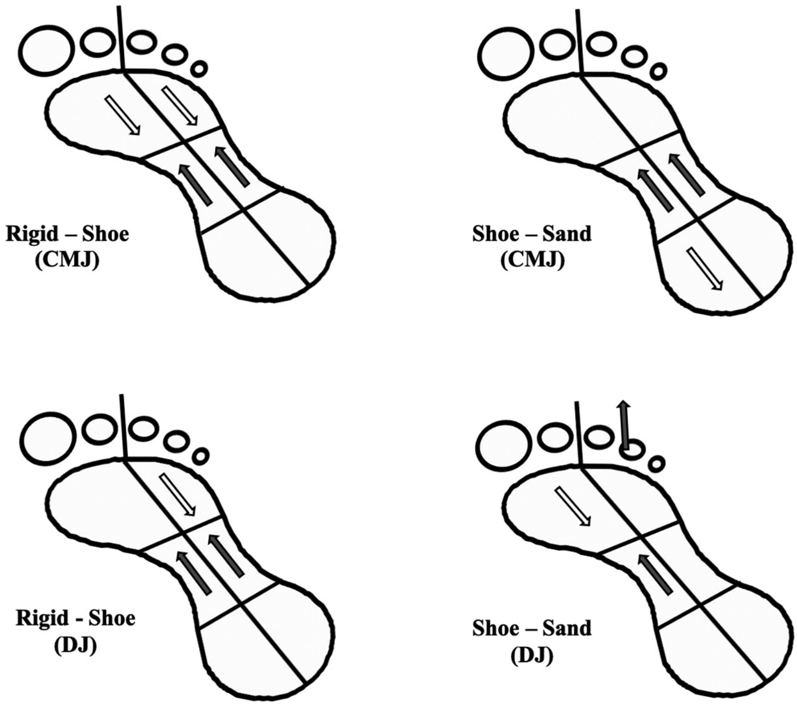

Figure 3. Shift of load between conditions *rigid*, *shoe* and *sand* for the landing. The arrows indicate a significant increase (filled) or decrease (unfilled) of load changing from the *rigid* to the *shoe* condition and from the *shoe* to the *sand* condition.

Peak pressures

Statistical analysis of *peak pressures* revealed significant differences between the rigid condition and the shoe and sand conditions. Across all jump types and jump phases, the greatest peak pressures were found in the medial forefoot (e.g., DJ Take-off: rigid 591 ± 92 kPa, shoe 478 ± 134 kPa, sand 273 ± 57 kPa) followed by the hallux and lateral forefoot. In all areas, except for the lateral toes and the medial and lateral midfoot, significantly lower peak pressures were found in the shoe and sand conditions compared to the rigid condition.

When comparing the shoe and sand conditions, we found significantly lower peak pressures in the sand as compared to the shoe condition for most of the foot areas (e.g., CMJ Take-off: medial forefoot, rigid 409 ± 129, shoe 293 ± 86, sand 164 ± 19, $F(2, 38) = 42.18$; $p < .001$; η^2 p = .69). However, in the medial and lateral midfoot area, the sand condition was associated with higher peak pressures than the shoe and rigid conditions (see example of one subject in Figure 2 illustrating the results of the statistical analysis for the landing phase).

Discussion and implications

In the present study, a pressure distribution analysis during jumping (CMJ, DJ) was performed to evaluate the influence of the surface on plantar loading (relative loads, peak pressures) when switching between different playing surfaces. Three conditions, *rigid*, *shoe* and *sand* were analysed for the take-off and landing phases using peak pressures and relative impulses for 8 assigned areas of the foot.

The results clearly show that high local mechanical loadings (represented by peak pressures) of certain areas of the foot sole (heel, forefoot, hallux) on a rigid surface were reduced in the *shoe* and *sand* conditions, but the *shoe* and *sand* conditions showed increased loadings in the medial and lateral midfoot. Accordingly, the relative loads that occurred under the *rigid* condition were redistributed towards the medial and lateral midfoot in the *shoe* and *sand* conditions.

To our knowledge, limited information is available that compares the loading of the anatomical structures of the foot and describes the load shift within the foot areas when comparing different surface conditions during jumping. Thus, the present results help to build a foundation upon which coaches, physiotherapists and/or orthopaedists can consider decisions about setting up plans that can help athletes to ensure a smooth, healthy transition between different playing surfaces with respect to training volume and intensity. The particular emphasis of this work is on changing from rigid to sand surfaces and vice versa, especially during times of the year when athletes play on both types of surfaces (when indoor and beach seasons overlap) or when athletes use sand surfaces as part of a special training method (Hammami et al., 2020).

Comparing our results to the literature is difficult but necessary for putting our measured mechanical loadings into the context of other pressure distribution analyses in sports. However, some factors must be considered when performing these comparisons. It is known that due to different measuring principles, sensor sizes and sensor technologies, the measurement system influences the magnitude of the pressure distribution (Cavanagh et al., 1992; Hughes et al., 1993). In the existing literature, pressure distribution analyses are often described and evaluated using peak pressures and relative loads. The peak pressures depend on the size and number of sensors, whereas the relative loads are additionally dependent on the classification of the foot areas (Rosenbaum & Becker, 1997). Thus, unless the same mask is used for foot area classification, such comparisons are of limited use.

Under these circumstances (same measurement system), comparing our results and existing literature data shows that the peak pressures for jumps in *sand* are relatively low compared to movements in other sports. Orendurff et al. (2008) compared peak pressures on an artificial turf surface during different sport-related movements like jumping, running and cutting when wearing two different soccer boots (Orendurff et al., 2008). One of the shoes was more rigid (typical cleated soccer shoe) and the other more cushioned (multi-cleat design). The peak pressures in the rigid soccer shoe significantly exceeded the peak pressures of our jumps in the sand as well as most of the peak pressures of our rigid barefoot condition. The peak pressures in the more cushioned soccer shoe also significantly exceeded the peak pressures of our jumps in the sand and are comparable to our shoe condition. Sterzing et al. (2016) reported peak pressures between 276 ± 58 kPa/cm^2 (med. forefoot) and 156 ± 38 kPa/cm^2 (med. midfoot) when jogging on a treadmill. These values are comparable with our peak pressures in the shoe condition of the CMJ or during DJ in the sand condition (Sterzing et al., 2016). Furthermore, Weist et al. (2004) investigated a fatiguing run in experienced runners (average speed of 15 km/h) and reported peak pressure values of 409 kPa (first metatarsal head), 334 kPa (second

& third) and 263 kPa (fourth & fifth) (Weist et al., 2004). These are comparable to values of the CMJ in the rigid barefoot condition and the DJ in the shoe condition; the peak pressures in these areas for the sand condition were lower. Thus, for the mainly loaded areas, the measured peak pressures during the CMJ and DJ in a rigid barefoot situation were lower than loadings recorded in a rigid soccer shoe. Peak pressures obtained during jumps in the shoe situation are comparable to loadings recorded for normal jogging, but, of course, peak pressures increase when running velocity increases (Rosenbaum et al., 1994). Peak pressures during jumps on a sand surface were lower compared to those in normal jogging.

While we found that peak pressures for the predominantly loaded areas were lower on a sand surface, peak pressures in the midfoot area, especially in the medial part, increased; more specifically, they doubled as compared to the rigid condition, and they increased to 1.25–1.50× more than the shoe condition. These values can also be compared with peak pressures reported by Sterzing et al. (2016), Weist et al. (2004) and Orendurff et al. (2008). Thus, despite the sand condition having higher midfoot peak pressures than the other test conditions, the peak pressures in the medial midfoot in the sand condition can still be considered modest. Figure 2 shows an increase in contact area alongside the reduction of peak pressures. From a performance point of view, an increased contact area under the plantar sole of the foot may provide a better basis for a more effective push-off against the sand surface. However, while this is out of the scope of our study, it shows how pressure distribution analyses can offer insight into the complex interaction between the body and the playing surface in sports.

The relative loads were also different between the test conditions (Figure 3). Comparing these findings with other studies is difficult because hardly any comparable data is available; so, we focus on the differences observed in the test conditions. Comparing the *rigid* and *shoe* conditions, the shoes seemed to decrease the loading on the forefoot and increase the load on the midfoot, likely because of the cushioning characteristics of the shoe's insole and its supportive properties in the midfoot area. Comparing the *shoe* and *sand* condition, the load on the midfoot was higher in the sand, and the load seemed to decrease on the forefoot and heel. Thus, while the sand and shoe conditions showed similar effects regarding cushioning and support for the foot, the sand tended to distribute the load more evenly than the shoe. This is due to the physical characteristics of the sand, which offer a more effective foot bedding under the medial midfoot (Vetter et al., 2004), and, in jumps on sand, some of the applied energy is used for compression/deformation (Vetter & Nicol, 2004; Vetter et al., 2004).

Various types of overuse injuries affecting bones, muscles, tendons and ligaments may arise when the musculoskeletal system is subjected to excessive mechanical loading, like repeated impacts of the lower extremities on a rigid surface (Edwards, 2018). When suffering from such injuries or when the current loading pattern must be changed or reduced for prevention purposes, our results show that a sand surface appears to be an adequate choice. This is also in accordance with results from Richardson et al. (2020), who showed that a sand surface efficiently reduces knee loading during single-leg jumps (Richardson et al., 2020). However, there might be some evidence that the sand itself may lead to specific symptoms where structures like muscles or ligaments are overloaded (Eerkes, 2012). In addition, the redistribution of load can also lead to unusual compensatory movements that may increase the risk of other injuries. Therefore, when focusing on mechanical loading and overuse symptoms in sports, one needs to analyse the properties of different surfaces as well as the specific requirements of the sports. Furthermore, these mechanisms need to be considered not only because excessive loading and insufficient recovery may increase injury risk, but also because some athletes might be "underprepared" for surface changes or spikes in loading (Gabbett et al., 2016), e.g., when changing playing surfaces from rigid to sand and vice versa. Our results show distinct load changes when switching from one surface to another, and the change from a rigid surface to sand is potentially associated with a lower risk of high-impact repeated overuse injuries; however, switching from sand back to an indoor surface might increase the risk of these injuries. However, our results and the literature comparison show that the observed pressure distribution patterns for different surfaces align with other tasks like running or playing soccer and are in a range that is typical for these sports and entail a comparable mechanical loading. Therefore, switching playing surfaces seems to entail only a moderate risk of developing mechanical overloading. Nonetheless, to improve athletes' pre-conditioning when switching to a new playing surface, a specific transition training for this switch should be developed. In this context, coaches and athletes often seem concerned that training on a sand surface may decrease their actual indoor performance on the rigid surface. Eils et al. (2022) showed that a transition training on sand can be considered effective for improving performance on both sand and rigid surfaces, indicating that there is no need for coaches to be concerned about performance impairments on a rigid surface when training on a sand surface (Eils et al., 2022).

It is important to note that it was not the aim of the study to evaluate performance differences in jumping between different surfaces. Indeed, the pressure distribution device offers the opportunity to perform and compare jumping performance on different surfaces and, thus, represents a special tool for analysing foot-to-ground contact in sand sports. The validity of the device compared to measurements on a force plate has been evaluated on rigid surfaces (Putti et al., 2007; Ramanathan et al., 2010) but not on sand surfaces. This is worth considering in future studies, since the popularity of beach sports is increasing, and valid performance diagnostics are necessary to further develop these sports.

Finally, we must discuss some limitations of this investigation. The pressure distribution insoles were calibrated to the standard maximum of 600 kPa, which turned out to be too low for the rigid barefoot condition in few subjects on the medial forefoot. This probably influenced the mean peak pressure values of that area, but it had no impact on the general discussion or findings. For future studies investigating jump movements using this system, a maximum calibration to 800 or 1000 kPa may be advisable.

In the present investigation, the use of participants' indoor footwear was not controlled, and subjects wore their own indoor shoes. Mainly running footwear and handball/football indoor footwear was used by the participants. The use of one uniform shoe available in all shoe sizes would have reduced the variance in the pressure data and probably would have made the results more consistent for the shoe condition. However, it is not expected that these differences would have affected the general conclusions, and non-uniform footwear represents a more realistic scenario than uniform footwear.

In addition, the foot type (flat, normal, high arched) of the subjects was not specifically inspected before the tests. However, in the actual investigation, we focused on changes between conditions within subjects (within-subject-design), irrespectively of the foot type or athletic status. From that point of view, within-statistics will remain stable although mean results may have slightly been influenced by foot type.

Finally, we used neoprene socks to fix the pressure insole to the plantar surface of the foot and, thus, to simulate the barefoot condition on a rigid and sand surface. Different sock sizes were used to ensure a tight fit and to minimise possible relocation of the insole; this is common practice when using pressure distribution devices in a barefoot situation (Natrup & Jeusfeld, 2016; Vetter et al., 2004). Yet, the thin neoprene material may have a minor cushioning function, such that actual pressure values may be slightly underestimated.

It also should be noted that the development of overuse injuries is a multifactorial problem (Gabbett et al., 2016) and the mechanical loading of anatomical structures of the sole of the foot is only one extrinsic risk factor in that context. However, a theoretical foundation and operational framework necessary to model overuse injury as a mechanical fatigue phenomenon that results from biomechanical events has recently been introduced (Edwards, 2018).

Conclusion

In conclusion, the results of the present investigation revealed the characteristic loading patterns of the plantar surface of the foot when performing CMJ and DJ under different surface conditions. Peak pressures of highly loaded areas (heel, forefoot, hallux) were significantly lower for the sand surface compared to the rigid and shoed conditions, and on the sand surface the relative loads were shifted towards the midfoot area. Peak pressure loading for all conditions was comparable to loading that has been reported in other sports. The switch from a rigid to a sand surface is associated with a lower mechanical load, whereas switching back from sand to an indoor surface potentially increases this load. Our results show that the observed pressure distribution patterns for different surfaces are in accordance/comparable with other tasks like running or playing soccer and are in a range that is typical for other sports and entail a comparable mechanical loading.

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Disclosure statement

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