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original research

Changes in Plantar Loading Based on Shoe Type and Sex During a Jump-Landing Task

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Context: Metatarsal stress fractures are common in cleated-sport athletes. Previous authors have shown that plantar loading varies with footwear, sex, and the athletic task.

Objective: To examine the effects of shoe type and sex on plantar loading in the medial midfoot (MMF), lateral midfoot (LMF), medial forefoot (MFF), middle forefoot (MidFF), and lateral forefoot (LFF) during a jump-landing task.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: Twenty-seven recreational athletes (14 men, 13 women) with no history of lower extremity injury in the last 6 months and no history of foot or ankle surgery.

Main Outcome Measure(s): The athletes completed 7 jumping trials while wearing bladed-cleat, turf-cleat, and running shoes. Maximum force, contact area, contact time, and the force-time integral were analyzed in each foot region. We calculated 2×3 analyses of variance ($\alpha = .05$) to identify shoe-condition and sex differences.

Results: We found no shoe $\times$ sex interactions, but the MMF, LMF, MFF, and LFF force-time integrals were greater in men ($P < .03$). The MMF maximum force was less with the bladed-cleat shoes ($P = .02$). Total foot and MidFF maximum force was less with the running shoes ($P < .01$). The MFF and LFF maximum forces were different among all shoe conditions ($P < .01$). Total foot contact area was less in the bladed-cleat shoes ($P = .01$). The MMF contact area was greatest in the running shoes ($P < .01$). The LFF contact area was less in the running shoes ($P = .03$). The MFF and LFF force-time integrals were greater with the bladed-cleat shoes ($P < .01$). The MidFF force-time integral was less in the running shoes ($P < .01$).

Conclusions: Independent of shoe, men and women loaded the foot differently during a jump landing. The bladed cleat increased forefoot loading, which may increase the risk for forefoot injury. The type of shoe should be considered when choosing footwear for athletes returning to activity after metatarsal stress fractures.

Key Words: athletic injuries, sex differences, lower extremity

Key Points

- During a jump-landing task, the bladed-cleat increased forefoot loading and, potentially, injury risk compared with the turf-cleat and running shoes.
- For contact time (medial and lateral forefoot) and force-time integral (medial and lateral midfoot, medial and lateral forefoot), men demonstrated greater foot loading than women when performing the jump landing.
- When an athlete is returning to sport after a metatarsal stress fracture, selection of appropriate footwear is important.

With 265 million players worldwide,[1] soccer is the most popular sport in the world, but players are subject to a risk of injury about 1000 times greater than that for high-risk industrial occupations.[2] Approximately 5% of soccer injuries affect the foot,[3] representing millions of injuries. Thus, it is important to investigate the factors that may lead to foot injuries and methods that can be implemented to decrease reinjury rates and more safely return athletes to practice and competition.

Among the most common injuries in sport are stress fractures, which result from repeated loads that are individually insufficient to cause a fracture. Stress fractures account for as many as 20% of all injuries seen in sport medicine clinics.[4] In elite soccer players, most stress fractures affect the fifth metatarsal; they can result in several months of lost playing time[5] and significantly affect an athlete's ability to train and compete during a season. Furthermore, unlike tibial and femoral stress fractures, metatarsal stress fractures do not decrease in incidence after adaptation to physical training.[6] This suggests that primary prevention is necessary to reduce the risk of metatarsal stress fractures in soccer players.

Athletic task, footwear, and sex are factors that have been examined to assess their effects on in-shoe plantar loading.[7–12] Certain tasks place particularly high stress on specific areas of the foot. For example, performing side cuts, 45° cuts, and jump landings increases the load on the medial forefoot (MFF) and hallux,[7,8] crosscuts increase the load on the lateral forefoot (LFF),[7] and running and accelerating increase the load on the middle forefoot (MidFF).[7,8] Side cuts and crosscuts are sport-specific tasks that usually consist of an approach of a few steps, followed

Table 1. Participants' Demographic Information, Mean ± SD

	Men	Women
Age, y	23.9 ± 3.5	20.2 ± 0.9
Height, m	1.784 ± 0.056	1.635 ± 0.052
Mass, kg	75.8 ± 6.3	57.8 ± 4.3

by a single-foot plant and then a 45° cut, either away from the plant foot (side cut) or across the plant foot (crosscut). Sex differences in plantar loading have been observed during side cuts,[9] crosscuts,[9] and running,[10] with men demonstrating increased load beneath the lateral column of the foot during each task. Importantly, differences among bladed, firm-ground, hard-ground, and turf cleats alter plantar loading during both side cuts and crosscuts, with the turf cleat demonstrating less loading than the other cleats.[11] These findings highlight some of the factors that should be considered when designing soccer cleats and underscore the importance of the risks and the need to avoid certain tasks when returning from foot injuries.

Although the effects of footwear and sex on plantar loading have been examined for several athletic tasks, their effects on plantar loading during jump landings have not yet been investigated. The fifth most common noncontact mechanism of injury in soccer is landing from a jump.[3] Previous authors[13] have demonstrated that women have greater hip flexion and less knee flexion than men during landing, and both of these differences increase with fatigue. These sex differences in kinematics will likely be reflected in plantar loading during landing. Data on the effects of footwear on plantar loading during landing are lacking, but the fact that footwear does result in differences in loading during cutting raises the possibility that footwear will also alter plantar loading during landing.

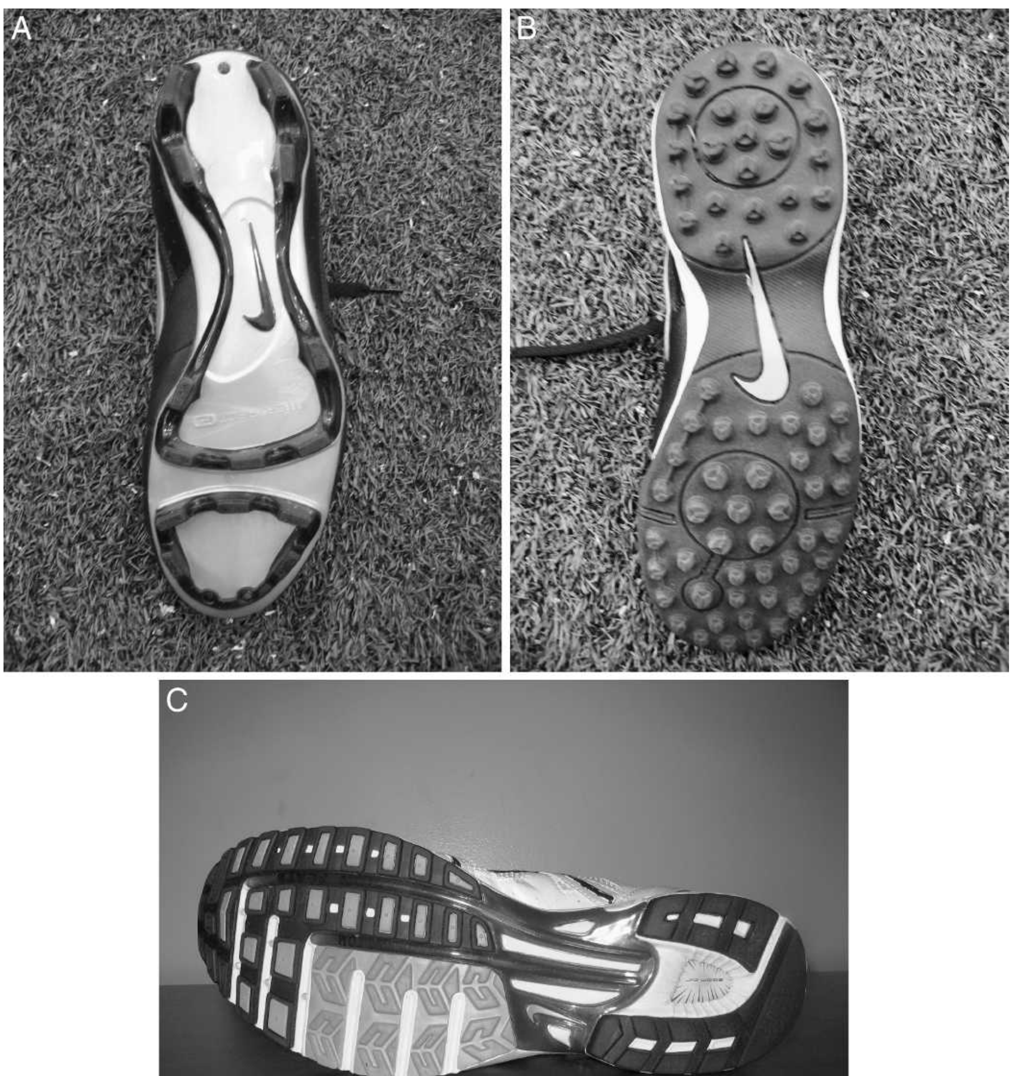

Figure 1. A, Bladed-cleat shoes. B, Turf-cleat shoes. C, Running shoes.

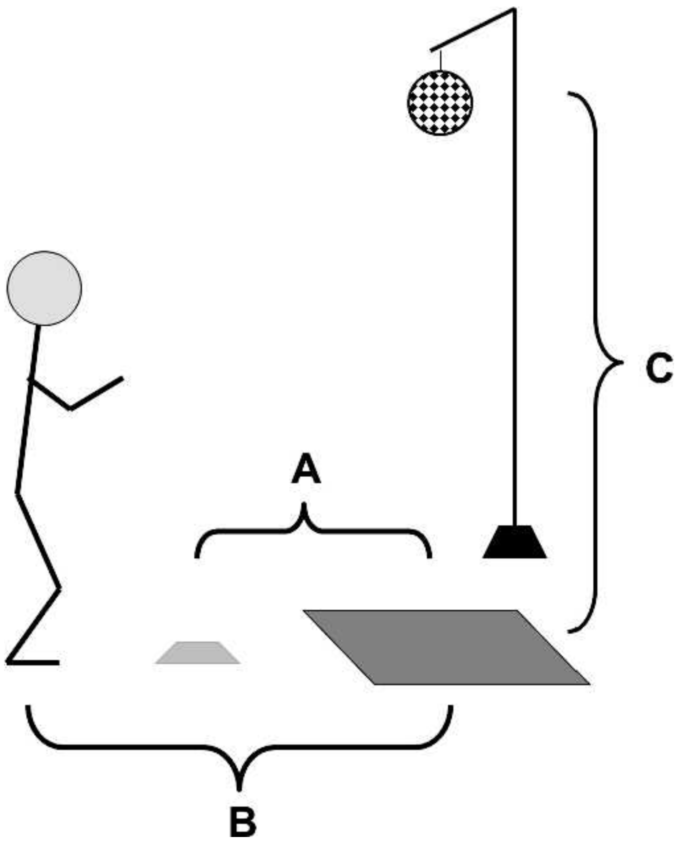

Figure 2. Diagram of the jumping task that was used during testing. A, From center of force plate to starting position is 25% of participant's height. B, From center of force plate to starting position is 50% of participant's height. C, Center of soccer ball is 50% of maximum vertical jump height.

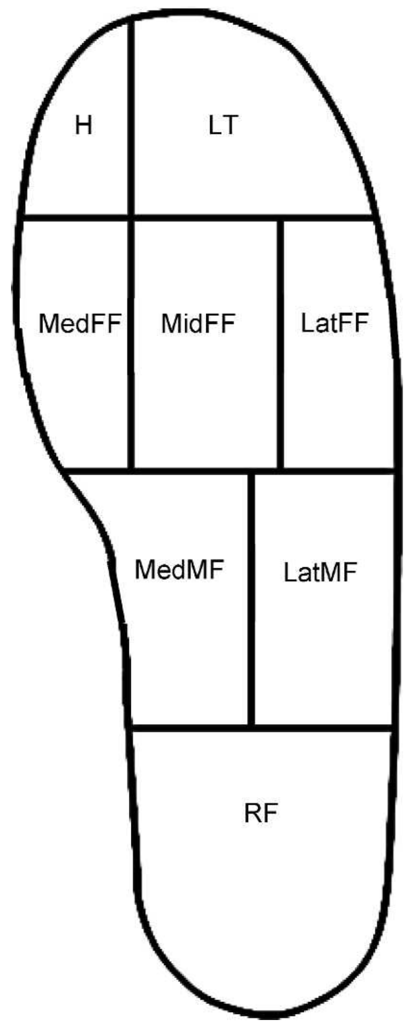

Figure 3. Diagram of how the regions of the foot were distributed for loading analysis. Definitions of the regions as percentage masks: H, hallux; LT, lesser toes; MFF, medial forefoot; MidFF, middle forefoot; LFF, lateral forefoot; MMF, medial midfoot; LMF, lateral midfoot; RF, rearfoot.

Because of the importance of metatarsal stress fractures as a major injury sustained in sport and because of the known sex differences in lower extremity mechanics, our goal was to measure plantar-pressure differences among 3 types of athletic shoes and between sexes. Identifying key differences could allow for more conscientious selection of the most appropriate footwear to use during training and competition to optimize both performance and injury prevention and the development of sex-specific injury-prevention strategies. We hypothesized that differences would exist among shoes in the midfoot and forefoot regions as well as beneath the hallux and that the bladed cleat would demonstrate increased loading in the lateral midfoot (LMF) and forefoot (LFF), based on previously published work that has demonstrated increased loading during cutting when wearing the bladed cleat. We also hypothesized that sex differences would exist.

METHODS

A total of 27 individuals (14 men, 13 women) volunteered to participate in this study. Their mean age was 22.1 ± 3.1 years, mean height was 1.71 ± 0.09 m, and mean mass was 67.1 ± 10.6 kg (Table 1). Inclusion criteria were age between 18 and 25 years, a history of playing soccer, being physically active (ie, participating in physical activity for at least 1 hour, 3 times per week), and no history of lower extremity stress fracture within the previous 2 years. All participants had played recreational soccer for at least 4 years. Each participant read and signed an informed consent form that was approved by the institutional review board.

The Pedar-X in-shoe plantar-pressure measurement system (Novel Electronics; St Paul, MN) was used to quantify plantar loading. Before testing, the Pedar insoles were calibrated to 9 bar using Novel's calibration device and according to manufacturer specifications. Pressure data were collected at 100 Hz via Bluetooth technology (Bluetooth SIG Inc, Kirkland, WA). Participants were fitted with properly sized bladed, turf, and running shoes (Figure 1) along with the corresponding Pedar insoles. The bladed and turf shoes were Nike Vitoria cleats; the running shoes were Nike Air Pegasus. All shoes were donated by Nike USA, Inc (Beaverton, OR). Insoles were placed in each shoe during testing, and participants wore a backpack containing the Pedar transmission device that was connected via cabling to the insoles. The cabling was secured to the leg distal to the knee to avoid potential injuries from the cabling. Participants walked around the laboratory for

Table 2. Foot Variables, Mean ± SD

Variable	Bladed Cleat: Men	Bladed Cleat: Women	Turf Cleat: Men	Turf Cleat: Women	Running: Men	Running: Women
Maximum force, N[a,b]	1.66 ± 0.44	1.76 ± 0.41	1.67 ± 0.42	1.70 ± 0.38	1.46 ± 0.40	1.47 ± 0.33
Contact area, units of normalized insole contact area[a,c]	0.79 ± 0.11	0.81 ± 0.10	0.86 ± 0.11	0.82 ± 0.09	0.84 ± 0.10	0.86 ± 0.08
Contact time, ms	404 ± 141	352 ± 94	382 ± 136	336 ± 91	379 ± 120	296 ± 54

[a] Difference between bladed-cleat and running shoes ($P < .05$).
[b] Difference between turf-cleat and running shoes ($P < .05$).
[c] Difference between bladed-cleat and turf-cleat shoes ($P < .05$).

approximately 5 minutes to become accustomed to the backpack and insoles before testing.

To make the testing conditions more similar to game conditions, we secured an artificial turf covering to the floor. A short cone was placed at a distance of 25% of the participant's height from the center of the ball, and a soccer ball was hung halfway between the participant's standing and vertical jump heights. The starting position for each participant was 50% of his or her height from the center of the soccer ball (Figure 2).

In a single continuous motion, the participant performed a standing jump over the cone to the center of the force plate and then jumped vertically with both feet in an attempt to head the suspended soccer ball and land. Plantar-pressure data were collected throughout the trial, but only the first landing event was used in data analysis. Participants completed 7 acceptable trials; an *acceptable*

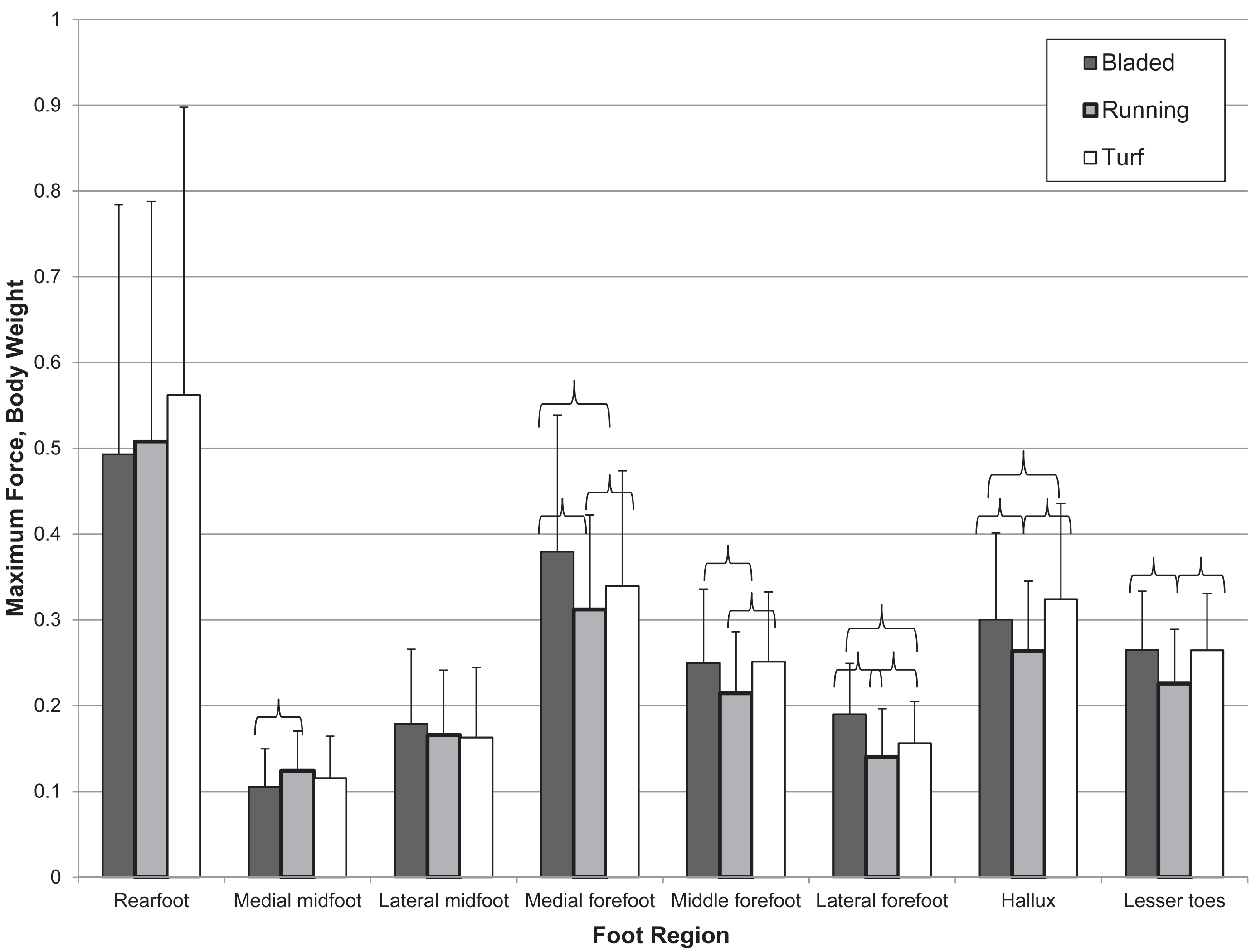

Figure 4. Jump-landing maximum force (% body weight) in the 8 foot regions. Brackets indicate differences ($P < .02$).

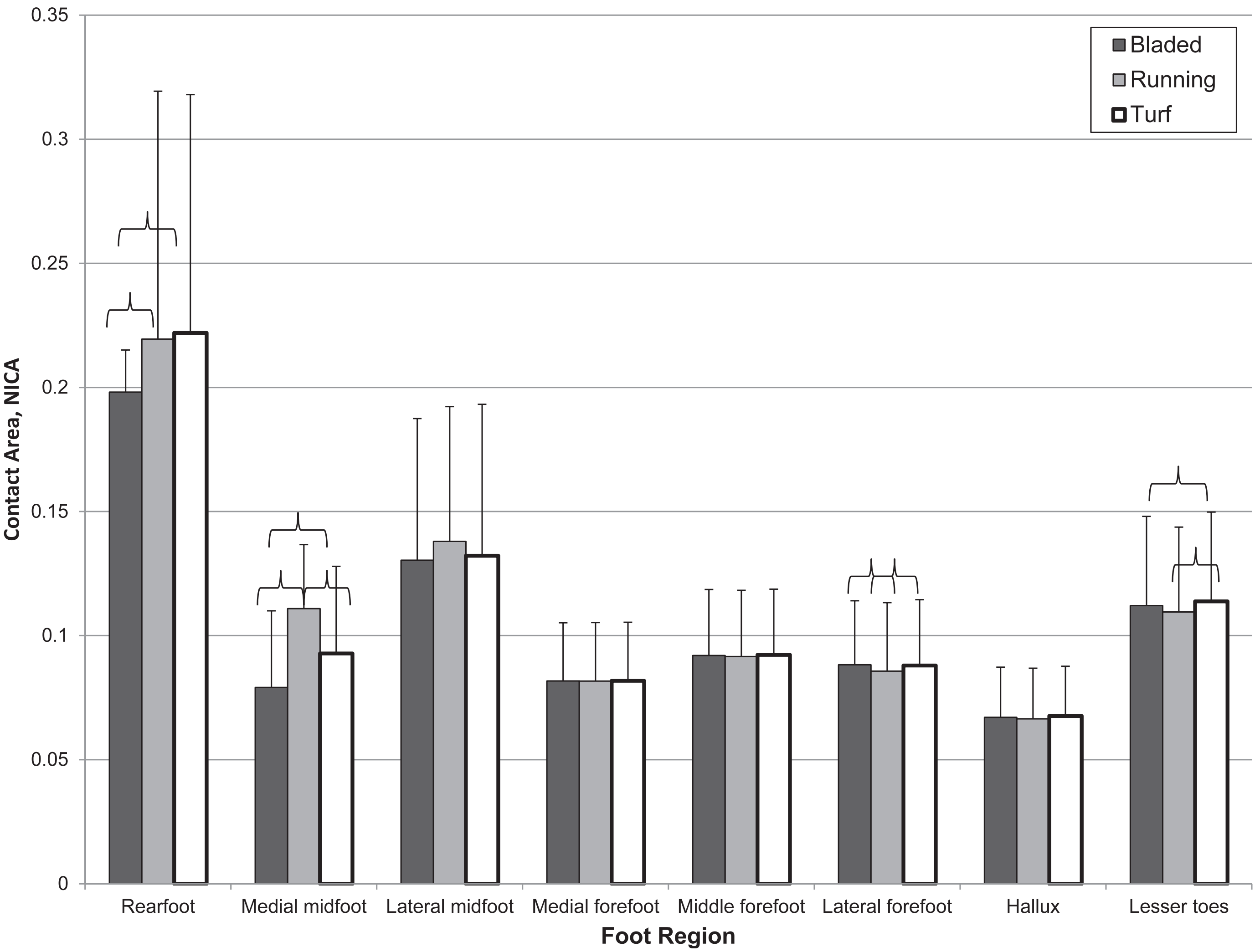

Figure 5. Jump-landing contact area (normalized insole contact area) in the 8 foot regions. Brackets indicate differences ($P < .04$).

trial was a trial in which bilateral pressure data were collected throughout the entire trial and the individual landed on the turf surface for both landing events.

Data were then analyzed using Pedar Multiproject-ip software (Novel Electronics). The software divided the foot into 8 anatomic regions (hallux, lesser toes [LT], MFF, MidFF, LFF, medial midfoot [MMF], LMF, and rearfoot) through the use of a percentage mask (Figure 3).[7,9,14–16] The results of the 7 trials were averaged and used for statistical analysis. The pressure variables were maximum force, contact area, peak pressure, contact time, and force-time integral. Maximum force was normalized to body weight (BW) to allow for statistical comparison between sexes and across study participants. The contact area of each region and the entire foot was normalized to the contact area of the entire insole in order to statistically compare participants. Results are reported in units of normalized insole contact area (NICA).[7,9] The *force-time integral* is a measure of the area beneath the force-time curve and therefore can indicate for how long an area is being loaded and how much force is being applied over that period of time. The foot regions of interest for this study were the MFF, MidFF, and LFF as well as the MMF and LMF. We calculated a 2 (sex) $\times$ 3 (shoe) analysis of variance for the plantar-loading data, followed by appropriate post hoc testing ($\alpha = .05$). Effect sizes (ESs) were calculated for the variables of interest. The *footwear ES* was defined as the difference between the bladed- or turf-cleat condition and the running-shoe condition divided by the standard deviation of the running-shoe condition.

RESULTS

No significant shoe $\times$ sex interactions existed for any of the study variables.

Shoe Effects

A main effect for total foot maximum force was found for shoe ($P < .001$, $ES_{bladed} = 0.64$, $ES_{turf} = 0.58$), where the bladed (1.70 $\pm$ 0.41 BW) and turf (1.68 $\pm$ 0.39 BW) conditions were greater than the running condition (1.47 $\pm$ 0.36 BW) (Table 2). We demonstrated shoe main effects for maximum force at the MMF ($P < .01$, $ES_{bladed} = 0.41$, $ES_{turf} = 0.20$), MFF ($P < .02$, $ES_{bladed} = 0.61$, $ES_{turf} = 0.25$), MidFF ($P < .002$, $ES_{bladed} = 0.49$, $ES_{turf} = 0.51$), LFF ($P < .004$, $ES_{bladed} = 0.88$, $ES_{turf} = 0.60$), hallux ($P < .01$, $ES_{bladed} = 0.44$, $ES_{turf} = 0.74$), and LT ($P < .001$,

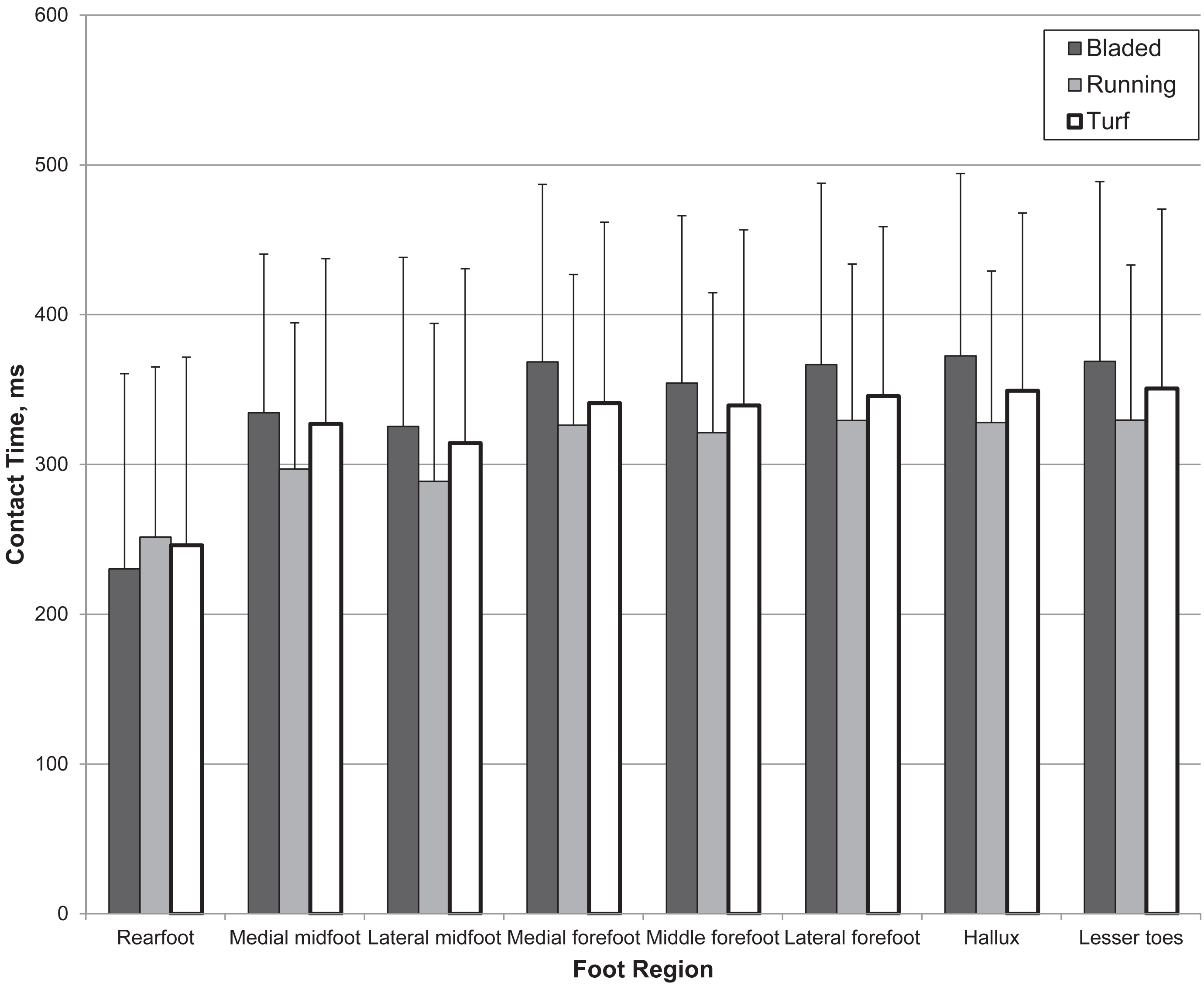

Figure 6. Jump-landing contact time (ms) in the 8 foot regions. No differences were noted.

$ES_{bladed} = 0.62$, $ES_{turf} = 0.61$) (Figure 4). A main effect was identified for shoe in the total-foot contact area ($P < .02$, $ES_{bladed} = 0.56$), where the bladed condition (0.80 ± 0.10 NICA) was less than the running (0.85 ± 0.09 NICA) or turf (0.84 ± 0.10 NICA) conditions. Shoe main effects also were noted for contact area in the MMF ($P < .01$, $ES_{bladed} = 1.22$, $ES_{turf} = 0.70$), LFF ($P < .04$, $ES_{bladed} = 0.07$, $ES_{turf} = 0.07$), and LT ($P < .04$, $ES_{bladed} = 0.07$, $ES_{turf} = 0.13$) (Figure 5). No main effects were observed for contact time (Figure 6). We found shoe main effects for force-time integral in the MFF ($P < .001$, $ES_{bladed} = 0.45$, $ES_{turf} = 0.11$), MidFF ($P < .01$, $ES_{bladed} = 0.58$, $ES_{turf} = 0.42$), and LFF ($P < .001$, $ES_{bladed} = 0.97$, $ES_{turf} = 0.28$) (Figure 7).

Sex Effects

Sex differences for contact time were identified beneath the MMF ($P < .02$, ES: 0.78) and LMF ($P < .01$, ES = 0.87) (Figure 8). We also found sex differences in the force-time integral beneath the MMF ($P < .01$, ES = 0.95), LMF ($P < .03$, ES = 0.82), MFF ($P < .02$, ES = 0.92), and LFF ($P < .01$, ES = 0.98), with the men demonstrating higher values than the women. No sex difference was observed for contact area.

DISCUSSION

For plantar loading, our results are similar to those of previous authors,[11] who demonstrated increased loading in bladed cleats compared with turf cleats during a side-cut task. A previous investigation[9] of sex differences during side cuts and crosscuts showed increased plantar loading in men compared with women, which is similar to the current findings. Our results also suggest greater total foot maximum force for bladed and turf cleats, with a decrease in contact area for the former.

Sex differences in this study were not as apparent as the effects of the different shoes. For men, we found an increase in the force-time integral beneath the MFF, LFF, MMF, and LMF during the jump-landing task. This measure of both foot loading and the time over which the region is being loaded suggests an additional mechanism by

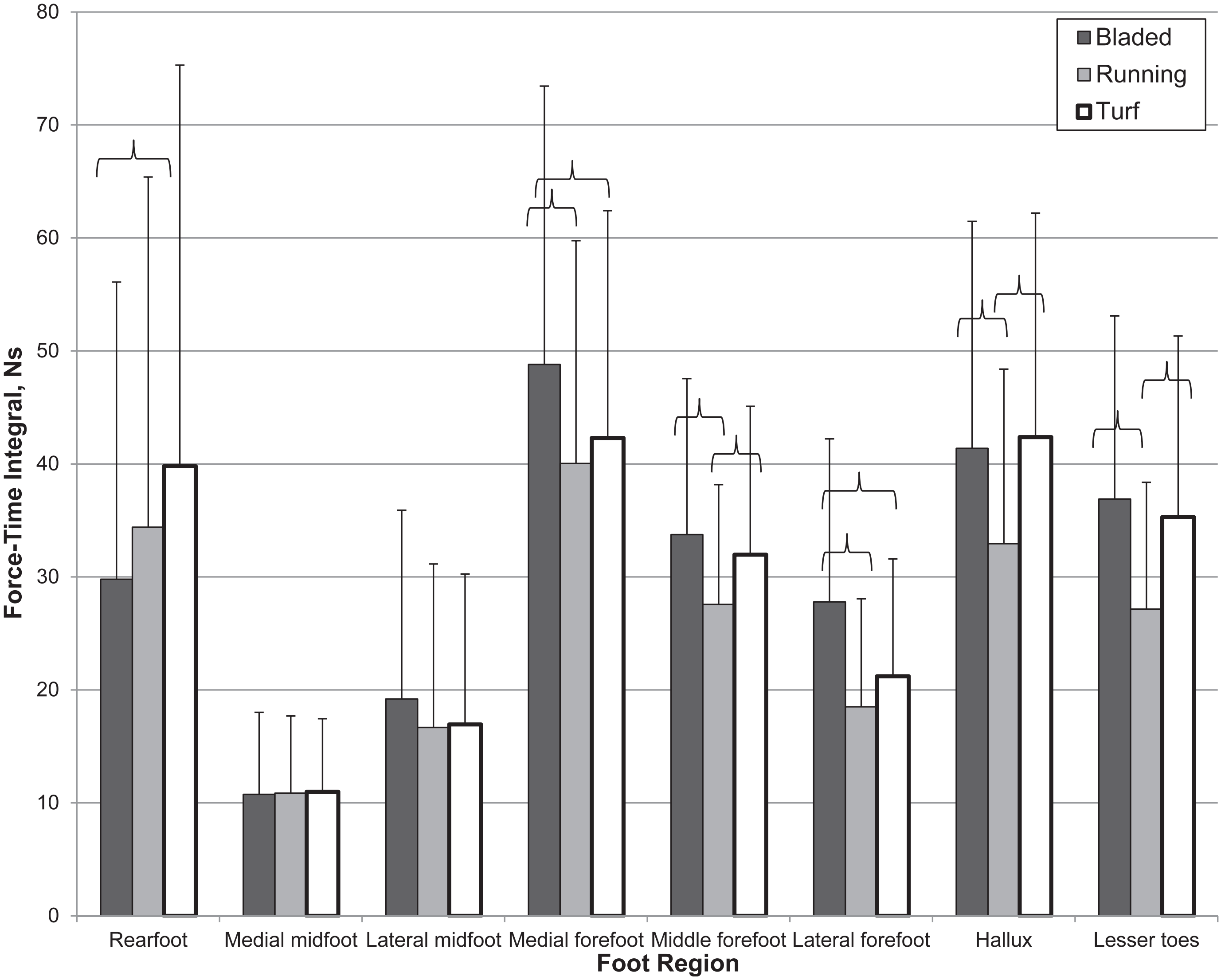

Figure 7. Jump-landing force-time integral (N·s) in the 8 foot regions. Brackets indicate differences ($P < .02$).

which male athletes may be at increased risk for metatarsal stress fractures. Sims et al[9] found similar increases in LFF loading in men performing side cuts, crosscuts, and acceleration tasks, which indicated an increased risk of fifth metatarsal stress fractures in men compared with women. The increased force-time integral beneath the lateral column in men suggests they were loading that region of the foot for a longer time during landing than were the women. These results are in agreement with the previous work showing that men were more likely to overload the lateral column of the foot during various athletic activities. Overall, our findings further support the concept that shoe design needs to be sex specific and able to account for these plantar-loading differences.

Focusing on the forefoot and midfoot regions, our results demonstrate the greatest loading in the bladed condition, followed by the turf-cleat condition. This is most evident in the maximum force and force-time integrals beneath the MFF and LFF: the bladed-cleat condition was greater than both the running shoes and the turf cleat. In the MidFF, the bladed and turf shoes showed similar values for all variables. Few differences, however, were observed in the midfoot among shoes other than greater maximum force in the running shoe when compared with the bladed cleat in the MMF.

Perhaps the differences in loading for bladed cleats result from the difference in design, which is intended to improve performance by increasing a player's energy transfer through a sturdy, stable sole along with a small number of relatively stiff studs optimized for firm ground conditions. Turf cleats have a more uniform layout, with a greater number of soft studs that are mounted on a somewhat softer sole, whereas running shoes have a heavily cushioned sole with a comparatively uniform outer sole. Because of the cushioning differences among the shoes, it is not surprising that the smallest amount of maximum force was observed with the running shoes. The distribution of studs for the bladed cleats increases contact area in the MFF and LFF regions relative to the MidFF, which may further increase regional loading differences between the bladed and turf cleats. The greater plantar loading in the forefoot regions for bladed and turf cleats compared with

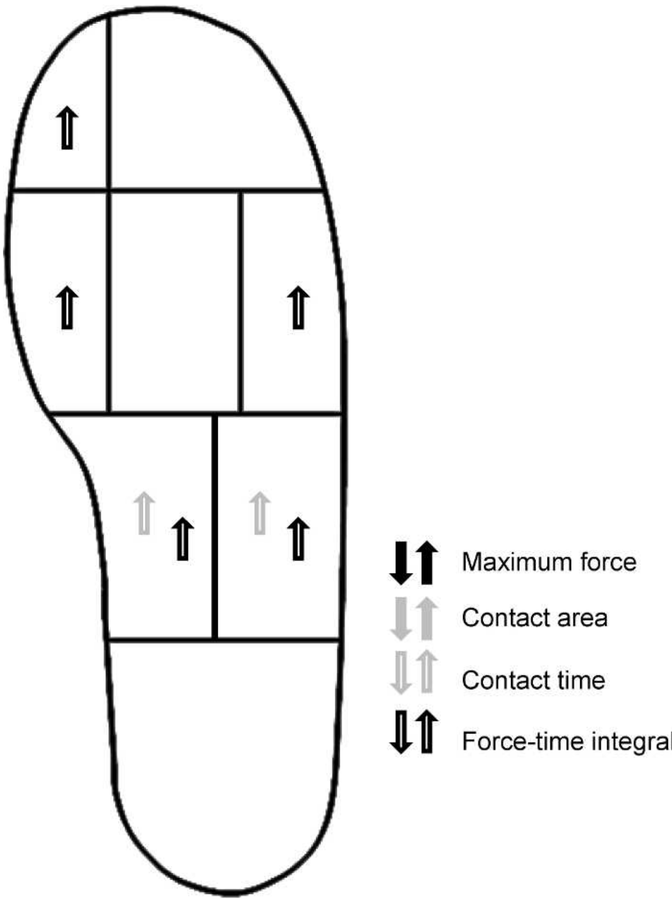

Figure 8. Sex differences (higher values in men than in women) during task by foot region ($P < .05$).

running shoes suggests that the former shoes may increase the risk of stress fractures during jumping and landing; however, further investigation is warranted. In particular, increased loading beneath the LFF reflects increased stress on the fifth metatarsal.[5] Given the differences in plantar loading between the cleats, for an athlete with a healing fifth metatarsal stress fracture, it is important to choose a shoe that effectively shifts the loading pattern away from the fracture. In addition, the results of this study indicate the importance of selecting appropriate shoes after an injury, when the player is initially returning to sports. A player might begin working out in a shoe with increased cushioning, such as a running shoe, and then transition to a turf cleat and finally to a traditional soccer cleat, such as the bladed cleat in this study, to gradually increase loading on the foot during recovery.

Apart from simple regional loading differences, Orendurff et al[17] suggested that the difference between loading of the metatarsal head and base is a potentially important bending moment that could lead to stress fractures. Their findings in 10 college-age men showed that jump landings did not produce a significant bending moment.[17]

Our study is limited because of the lack of understanding of the exact causes of stress fractures in the foot. Although plantar-loading data indicate normal stresses on the described foot regions, our results cannot describe the shear forces on the foot sustained during the jump-landing task, which have been suggested as a potential contributor to the development of stress fractures and other injuries.[18] In addition, no researchers have suggested a single-event stress threshold for force, pressure, force-time integral, or pressure-time integral that contributes to metatarsal stress fractures; thus, the absolute meaning of our data is difficult to interpret. Another limitation is that it is difficult to control for the exact height of the first jump during the task, which can add variability to the data. Furthermore, the task estimates actions that an athlete could perform in a competitive setting, but it is impossible to design a jump-landing procedure that is completely generalizable to all such tasks performed in any sport, including soccer training and competition.

Based on our results, we conclude that independent of shoe, men and women load the foot differently during jump landings. Specific differences attributed to the shoe condition reveal that the bladed cleat appeared to increase forefoot loading compared with the other shoes, especially when compared with the running shoe, thereby increasing injury risk. In the future, authors should investigate the effect of playing surface on plantar loading during jump landings and other athletic tasks. This information could assist in determining the safest training regimens and optimizing training shoes and training surfaces to minimize the risk of injury and decrease reinjury rates after metatarsal stress fractures. Other investigators could examine plantar loading in a basketball-specific jump-landing situation, where the loading is likely different because of the distinct jumping requirements of basketball, in addition to playing surface and shoe differences. Finally, we need to establish a relationship between plantar loading and stress injuries of the foot in order to develop footwear that minimizes the relevant risk factors.

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