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Spraino: A novel low-friction device for prevention of lateral ankle sprain injuries in indoor sports

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ABSTRACT

A heightened risk for lateral ankle sprain injuries has been associated with excessive shoe-surface friction. 'Spraino' is a novel product specifically designed towards preventing friction-related lateral ankle sprains. In a recent 510-athlete randomized controlled trial, allocation to this "low-friction" shoe-patch resulted in a 53% reduction of severe ankle sprain injuries. Until now, however, a theoretical explanation linking shoe-surface friction and lateral ankle sprain injury mechanism is missing, and the extent to which Spraino reduces shoe-surface friction remains unknown. Therefore, the purpose of this study was to present a theoretical link between lateral edge shoe-surface friction and the mechanism of lateral ankle sprain injuries, and ultimately establish the ability of Spraino to reduce lateral edge shoe-surface friction. In this paper, we present a theory on how ankle sprain mechanics are directly affected by the friction between shoe and surface, and why friction modifications might be a viable preventive strategy. When testing slip resistance in a modified mechanical test-setup, we detected a 63% reduction (0.83–0.31) in friction coefficient between the lateral edge of the outsole and the indoor sports floor when adding Spraino to the side of the shoe. Justified in our theory, and the previously established clinical effectiveness, this reduction in friction can mitigate both the risk and severity of lateral ankle sprain injuries. This suggests that reducing friction on the lateral edge of footwear can be an effective ankle sprain injury prevention strategy.

1. Introduction

A lateral ankle sprain has been identified as the most common injury in sports [1], where it is the typical traumatic result from an excessive rearfoot inversion and adduction of the foot, often combined with plantar flexion [2]. The risk of injury is highest in indoor and court sports where it predominantly occurs without contact between opponents [3,34].

It has long been hypothesized that the interaction between shoe and surface plays a vital role on the incidence of lateral ankle sprains in sports [4], and that high shoe-surface friction could be a direct risk factor for non-contact lower extremity injuries [5,6], in particular for lateral ankle sprains [6,7]. The interaction between shoe (equipment) and surface (sports setting) naturally lies outside of the body, and thus, shoe-surface friction would be considered an extrinsic risk factor [8]. Since shoe-surface friction is traditionally higher in indoor sports, compared to e.g. outdoor and field sports, it has been speculated that the higher friction between shoe and floor is an explanatory factor behind the higher incidence rate of lateral ankle sprains in these sports [1,3].

This speculation has since been particularly fueled by the way in which the simple application of a low-friction patch, i.e., Spraino, on the lateral side of indoor sports shoes was documented in a recent clinical trial to effectively reduce both injury incidence rate and injury severity of lateral ankle sprains [9].

To this date, the mechanical and biomechanical rationale behind why reducing shoe-surface might be a viable way for ankle injury prevention is sparse, and an elaborated theory hereof is lacking. Moreover, while Spraino is designed to minimize friction between the lateral edge of the shoe and the playing surface [10], its mechanical capacity to actually

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reduce this friction remains to be quantified. Documentation hereof would support the notion that this mechanical factor is linked to injury occurrence and potential prevention.

Therefore, the purpose of this study was to present a theoretical explanation of a potential link between lateral edge shoe-surface friction and lateral ankle sprain injury mechanism, and to quantify to what extent Spraino can reduce lateral edge shoe-surface friction.

2. Material and methods

2.1. Spraino

Spraino (*"no"* + *"sprain"*) is the novel injury preventive device that comprises of two low-friction (PTFE Teflon®) shoe patches that are attached along the lateral edge of indoor sports shoes. The patches are specifically designed to minimize shoe-surface friction whenever the foot is placed in an inappropriate position against the floor ultimately leading to a preventive effect. The front patch is attached along the lateral border of the outsole border at the forefoot, wrapping approximately 2–4 mm around the edge of the outsole. The rear patch is attached along the edge of the lateral rearfoot but does not wrap around the edge of the sole (Fig. 1). Spraino is only intended for use in indoor sports and has a reported durability of 20–40 h of sports activity [11].

2.2. Mechanical testing

To quantify the extent to which Spraino (Spraino ApS, Copenhagen, Denmark) reduces lateral shoe-surface friction in indoor sports, we designed and conducted a modified version of the *Personal protective equipment – Test method for slip resistance* (ISO: 13287:2019) [12]. Here, lateral edge shoe-surface friction was tested with and without Spraino attached to the lateral side of a Yonex badminton shoe (SHB-65 Z2 M, Yonex Co., Ltd., Tokyo, Japan).

For this purpose, we used the mechanical test setup previously presented by Jakobsen et al. [13,39], which comprises of a steel frame bolted to the floor above an actuated force plate (AMTI-OPT464508HF-1000, Advanced Mechanical Technology, Watertown MA, USA; Serman & Tipsmark, Brønderslev, Denmark) [13,14,39].

Force plate data were recorded with a sample frequency of 1000 Hz and the movement of the force plate was captured via a single retro-reflective marker fixed on the hydraulic platform using eight infrared cameras sampling at 500 Hz (Oqus 300+, Qualisys AB, Gothenburg, Sweden). The hydraulic platform was controlled using Mr. Kick software (Mr. Kick version 3.0, Knud Larsen, Aalborg, Denmark).

Standard weight plates summing up to a mass of 50 kg were added atop the test shoe and the floor surface attached to the top of the force plate was accelerated to a sliding speed of 0.3 m/s, as per ISO: 13287:2019 [12]. We modified the ISO test standard by covering the force plate with a standard vinyl sports floor (7.5 mm Taraflex – Evolution, Gerflor, Lyon, France) that is commonly used for badminton, handball, and various other indoor sports – to make the test indoor sport-specific. Additionally, we turned the shoe last 90-degrees to facilitate lateral translation, as well as orienting the shoe in a 15-degree pitch and 30-degree roll angle, to mimic a likely shoe-floor contact in a typical ankle sprain situation (Fig. 2).

The floor surface and outsoles were prepared and cleaned according to ISO: 13287:2019. We recorded five trials with and without Spraino, respectively, and the floor was cleaned using isopropyl alcohol in-between conditions [12]. For a more in-depth description of the mechanical testing procedure, please refer to Bagehorn et al. [15].

Fig. 1. Spraino low-friction shoe patches on an indoor sports shoe.

2.3. Data processing and statistics

Ground reaction forces were imported into MATLAB (R2018a, The MathWorks, Massachusetts, USA) and low-pass filtered with a cut-off frequency of 30 Hz, using a 2nd order dual-pass Butterworth filter. Ten unloaded force plate movements were initially recorded for later subtraction of the inertial contribution from the hydraulics accelerating the force plate [13,15,39]. All measurements were synchronized in MATLAB using the kinematics of the single retro-reflective marker [16]. The friction coefficient (μ) was then subsequently calculated from the adjusted force plate-measured reaction forces (Equation (1)), where F_x and F_y represent the horizontal reaction forces and F_z the reaction force in the vertical direction (normal force).

$$\mu = \frac{\sqrt{F_x^2 + F_y^2}}{|F_z|} \quad \text{(Eq 1)}$$

The friction coefficients were computed over 0.50 s (500 frames), with the start of the measurement being defined as exceeding a threshold value of 50 N in frictional force. The mean available dynamic coefficient of friction was calculated from the plateau that followed the peak in static friction, as per the ISO test standard [12].

Descriptive statistics were conducted in Microsoft Excel and used to summarize the friction coefficient of the two conditions. Means and standard deviations (SD) were used to describe the measures of central tendency and variability within testing [17], and differences between conditions were reported in both absolute and relative terms.

3. Theory on friction and ankle sprain mechanics

It is widely acknowledged that lateral ankle sprain injuries are predominantly caused by an excessive inversion moment around the subtalar joint [18–20], and that the risk of injury is considered especially high when the foot touches the surface in an inverted position [21]. In biomechanics we consider this inversion moment as the direct result of the position, magnitude and orientation of the ground reaction force vector - in relation to the ankle joint center [18,20,21].

Here, it is important to concede that the orientation of the ground reaction force vector is directly affected by the friction between the shoe and surface [22]. The friction coefficient is not just a unitless descriptor of the exact relationship between the horizontal (braking) forces and normal force (from the gravity and mass), but is directly affecting the moment around the ankle joint [23].

The friction coefficient (μ) is calculated by dividing the sum of friction forces with the normal force (Equation (1)) [22]. Thus, the illustrated ground reaction force vectors in Fig. 3 represent friction coefficients ranging from 0.0 (top) to 2.0 (bottom), with the angle of these vectors given by Equation (2).

$$\theta = \tan^{-1} \cdot \mu \quad (2)$$

A friction coefficient between 0.8 and 1.3 has been described as the typical range for shoes with a rubber outsole against a traditional indoor sports floor material [15], and in certain experimental situations

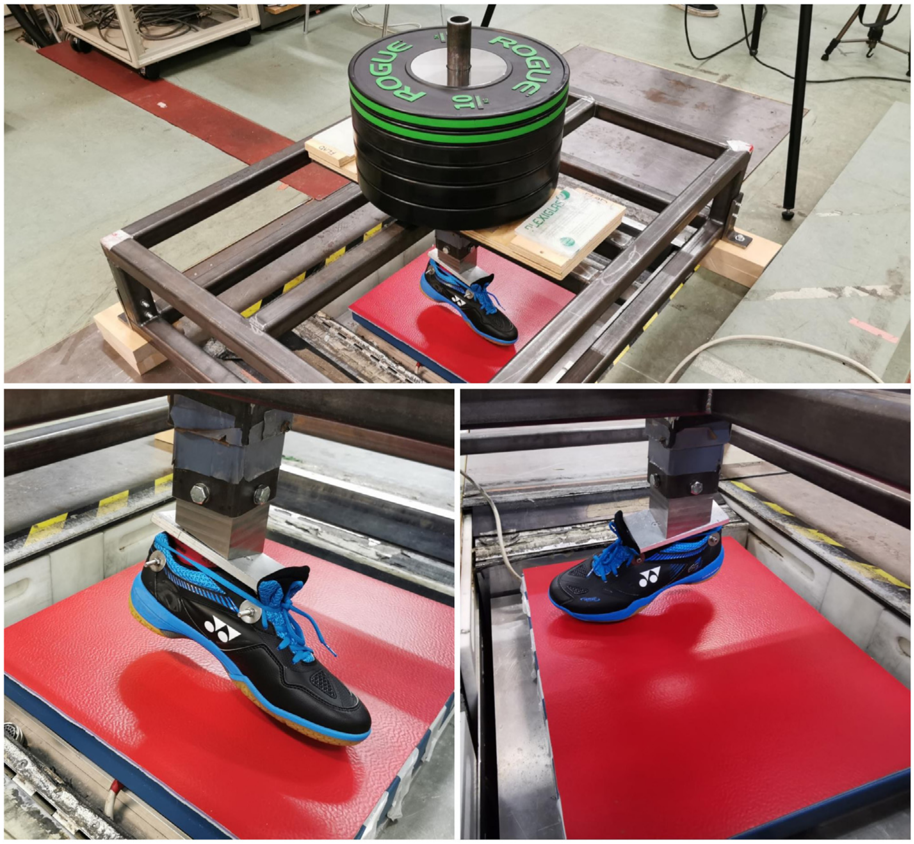

Fig. 2. Mechanical setup of the modified ISO: 13287:2019 slip resistance test. Shoe is fixed in 15° pitch and 30° roll angle in relation to the floor surface and loaded with 50 kg.

adequate for athletic performance [24–27]. However, it might be far from ideal to have this level of traction in a situation where the foot is placed in a vulnerable position, immediately prior to, or during the course of an injury, such as the one depicted (Fig. 3).

Covering the lateral edge of the outsole with a low friction material could in this case reduce the immediate adhesive friction [28]. If this initial adhesion between shoe and floor becomes sufficiently low (i.e., less than 0.4), then the shoe will not stick and can slide “freely” against the floor surface. This would therefore also affect the subsequent hysteresis friction that builds up when the viscoelastic rubber outsole deforms following initial contact with the surface [29].

This would naturally result in an initially more vertical ground reaction force vector, which in turn would bring the resulting ground reaction force vector closer to the joint center (Fig. 3), whereby the torque around the subtalar joint axis would be lowered [19]. This could mitigate both the risk and severity of lateral ankle sprain injuries [21].

4. Results

The friction coefficient increased steadily from the start of the measurement in the control condition, until around 0.2 s where a static maximum value was reached. This maximum value was reached after 0.1 s with Spraino attached on the shoe (Fig. 4). The respective maximum in both conditions were followed by a relatively smooth envelope from

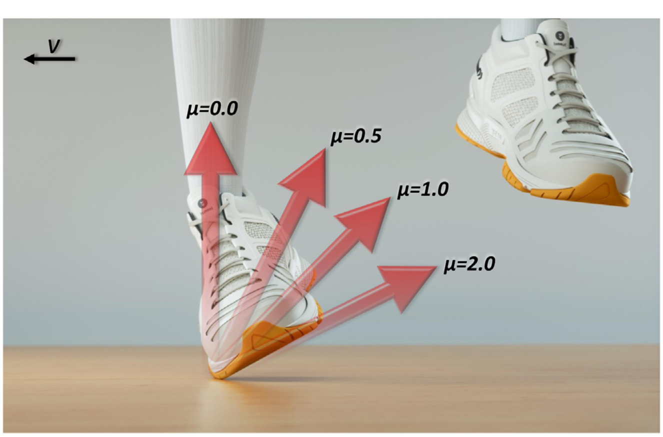

Fig. 3. Initial shoe-surface friction and ground reaction force orientation during a bad landing. Adapted with permission from Lysdal et al. [9].

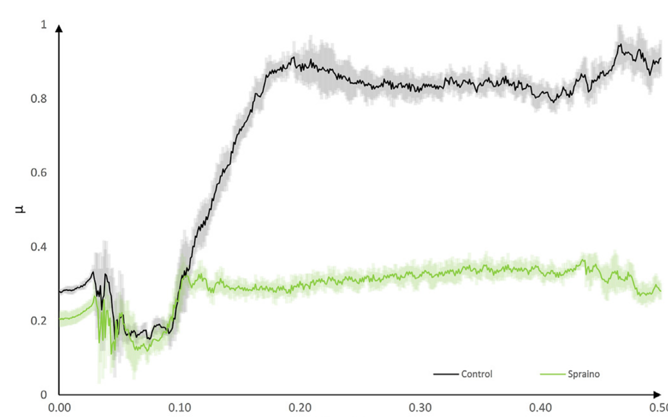

Fig. 4. Lateral edge friction coefficient of indoor sports shoe with and without Spraino attached in a modified ISO: 13287:2019 slip resistance test.

which the dynamic friction coefficient was derived. The mean dynamic coefficient of friction was 0.83 (±0.03) in the normal shoe condition, and 0.31 (±0.01) with Spraino covering the lateral edge of the shoe sole, effectively reducing the friction coefficient by 0.52 (63%).

5. Discussion

The purpose of this study was to present a theoretical explanation of the link between lateral edge shoe-surface friction and lateral ankle sprain injury biomechanics, and to quantify to what extent Spraino can reduce lateral edge shoe-surface friction through mechanical testing.

In our theory section on friction and ankle sprain mechanics, we presented how the injury promoting supination moment around the subtalar joint axis is directly affected by the friction coefficient between shoe and surface, as especially problematic if the foot is placed in an inverted position [21].

Contacting the floor surface on only the lateral edge of the forefoot is of course different to a normal gait or landing pattern, and no existing footwear friction test devices are designed to assess lateral edge shoe-surface friction. We therefore modified our mechanical test setup [13] to accommodate friction measurements in an injury-critical foot position [15].

The friction coefficient on the lateral edge of indoor sports shoes is on average 24% lower than when the same shoes are tested under standard flat forefoot conditions [15]. However, we still obtained a friction coefficient of 0.83 (in the control condition) between the lateral edge of rubber outsole and the indoor sports floor. A level of friction which is comparable to various other studies investigating dry friction between shoe and surface in indoor sports [7,25,27].

When adding Spraino onto the lateral side of the shoe, we observed a further 63% reduction in friction coefficient on the lateral edge of this specific indoor sports shoe (0.31 vs 0.83). This was likely driven by a lower adhesive friction between the surfaces [28].

We have previously speculated that using Spraino to minimize the initial adhesive friction between shoe and floor would allow for "free" horizontal sliding whenever in an injury situation [30]. We have since demonstrated that this allows for a re-alignment of the shoe against the surface [31], by this simple removal of the anchor between shoe and floor, around which the lateral ankle sprain injury expectedly takes place [2]. That adding a low-friction material could be a viable way for future injury prevention was exemplified in the recent clinical trial on Spraino effectiveness [9]. Here the intervention group allocated to Spraino had a 36% lower risk of sustaining a noncontact lateral ankle sprain, 57% lower risk for a severe noncontact lateral ankle sprain, as well as 37% less overall time-loss per injury (including contact injuries) [9].

The lateral ankle sprain injury is often considered innocuous [32], and even in clinical studies, patients appear to stop doing rehabilitative and preventive exercises before they feel fully recovered [33]. Seeking new ways to prevent lateral ankle sprains is therefore of great importance [34,35] and is considered especially relevant for tertiary prevention due to the high risk of reinjury [32]. It has also been discussed how preventive devices requiring minimal effort for the athlete has a greater chance of being adopted into general use, than e.g. complex preventive training regimes [35–37].

5.1. Current limitations and future perspectives

This study is not without limitations. Firstly, our study is limited by using mechanical research methods to try to inform on biomechanical challenges. The mechanical test setup used in present study is, however, able to detect changes in friction coefficient with high precision [13,39], and its relevance to the field was sought improved by using both an indoor sports shoe and indoor sports surface in the testing. This test was constructed around ISO:13287 and used a rigid nylon shoe last as advised [13,15]. Future research should explore how an anatomical and deformable foot might affect the obtained reduction in friction coefficient.

It is naturally not ethically acceptable to purposefully injure human subjects. This limits our ability to determine biomechanical causal inference between level of friction and extent of structural ligament damage during an ankle sprain injury. However, using that same hydraulic force platform, we have previously demonstrated how adding Spraino allows the foot to realign against the surface during simulated bad landings, instead of further twisting [31]. A causal link between friction and ankle sprain injury risk is also strongly indicated by the significant reduction in both injury incidence rate and injury severity in the clinical trial. The positive outcomes were even observed despite less than perfect adherence to Spraino and treatment contamination in the form of observed use of Spraino in the control group [9].

Spraino in its current form is not a preventive strategy without limitations. Spraino is only intended for use on smooth indoor sports surfaces and therefore has a limited audience of relevance. Indoor sports are, however, associated with the highest risk of injury, and prevention among this target group is pertinent [3]. The reported durability of 20–40 h might also be viewed as a limitation for the individual considering using Spraino. While this duration might be longer than ankle taping, which is applied before every training and match, it is significantly less durable than rigid bracing which also boasts impressive preventive effectiveness [38].

Spraino was also associated with adherence concerns, with around 40% of the intervention group opting to stop using Spraino over the course of the trial, as well as adverse events and anecdotal reports of slipping due to Spraino. These adherence concerns might be an effect of usability since all athletes were responsible for applying and replacing the product throughout the trial [9]. All the mentioned factors could potentially be accommodated by a permanent integration of Spraino as part of the production process of new footwear.

Finally, the reported effectiveness of Spraino should as always be sought replicated in a confirmatory randomized controlled trial. Also, direct comparisons of ankle injury preventive measures, such as sports tape and rigid bracing are generally missing and testing Spraino and any future modifications should be added to the list of important studies that should be undertaken.

6. Conclusions

Spraino substantially reduces lateral edge shoe-surface friction in a mechanical test modified towards indoor sports. The theoretical rationale between friction and ankle sprain mechanics, coupled with the clinical effectiveness of Spraino, suggests that reducing friction on the lateral edge of footwear is an effective ankle sprain injury prevention strategy.

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Author contributions

Filip Gertz Lysdal: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation. Thor Buch Grønlykke: Supervision, Writing- Reviewing and Editing, Funding. Uwe G. Kersting: Conceptualization, Methodology, Writing- Reviewing and Editing, Funding, Validation.

Declaration of competing interest

TBG is the founder of Spraino ApS. Spraino ApS was responsible for provision of Spraino. FGL is no longer sponsored by Spraino ApS (since December 2020). The obvious conflicts were accommodated by restricting Spraino ApS and TBG from having any deciding role in the execution, analyses, interpretation of data, and decision to submit results. UGK have no conflicts of interest and had full authority of the study administration, and full authority in terms of submission for publication. Innovation Fund Denmark had no scientific role in this study.

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References

[1] Fong DTP, Hong Y, Chan LK, et al. A systematic review on ankle injury and ankle sprain in sports. Sports Med 2007;37:73–94. https://doi.org/10.2165/00007256-200737010-00006.

[2] Lysdal FG, Wang Y, Delahunt E, et al. What have we learnt from quantitative case reports of acute lateral ankle sprains injuries and episodes of 'giving-way' of the ankle joint, and what shall we further investigate? Sports BioMech 2022;21: 359–79. https://doi.org/10.1080/14763141.2022.2035801.

[3] Doherty C, Delahunt E, Caulfield B, et al. The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. Sports Med 2014;44:123–40. https://doi.org/10.1007/s40279-013-0102-5.

[4] Fahlström M, Björnstig U, Lorentzon R. Acute badminton injuries. Scand J Med Sci Sports 1998;8:145–8.

[5] Pasanen K, Parkkari J, Rossi L, et al. Artificial playing surface increases the injury risk in pivoting indoor sports: a prospective one-season follow-up study in Finnish female floorball. Br J Sports Med 2008;42:194–7. https://doi.org/10.1136/bjsm.2007.038596.

[6] Dragoo JL, Braun HJ. The effect of playing surface on injury rate: a review of the current literature. Sports Med 2010;40:981–90. https://doi.org/10.2165/11535910-000000000-00000.

[7] Frias Bocanegra JM, Fong DTP. Playing surface traction influences movement strategies during a sidestep cutting task in futsal: implications for ankle performance and sprain injury risk. Published Online First; 2021. https://doi.org/10.1080/14763141.2021.1980606.

[8] Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. Br J Sports Med 2005;39:324–9. https://doi.org/10.1136/bjsm.2005.018341.

[9] Lysdal FG, Bandholm T, Tolstrup JS, et al. Does the Spraino low-friction shoe patch prevent lateral ankle sprain injury in indoor sports? A pilot randomised controlled trial with 510 participants with previous ankle injuries. Br J Sports Med 2021;55: 92–8. https://doi.org/10.1136/bjsports-2019-101767.

[10] Lysdal FG, Bandholm T, Tolstrup JS, et al. Infographic. Does the Spraino low-friction shoe patch prevent lateral ankle sprain injury in indoor sports? A 510-participant pilot RCT. Br J Sports Med 2020:1–2. https://doi.org/10.1136/bjsports-2020-103342. 0.

[11] Spraino ApS. Produktinformation. Copenhagen: Spraino ApS; 2017.

[12] Personal protective equipment - test method for slip resistance (ISO 13287:2019). CEN, Eur Comm Stand; 2019. p. 13287.

[13] Jakobsen L, Lysdal FG, Bagehorn T, et al. Evaluation of an actuated force plate-based robotic test setup to assess the slip resistance of footwear. Int J Ind Ergon 2022;88:103253. https://doi.org/10.1016/J.ERGON.2021.103253.

[14] Doornik J van, Sinkjaer T. Robotic platform for human gait analysis. IEEE Trans Biomed Eng 2007;54:1696–702. https://doi.org/10.1109/TBME.2007.894949.

[15] Bagehorn T., Lysdal F.G., Jakobsen L., et al. Medio-lateral and lateral edge friction in indoor sports shoes. Unpubl results.

[16] Oliveira AS, Silva P de B, Lund ME, et al. Balance training enhances motor coordination during a perturbed side-step cutting task. J Orthop Sports Phys Ther 2017:1–32. https://doi.org/10.2519/jospt.2017.6980.

[17] Barde MP, Barde PJ. What to use to express the variability of data: standard deviation or standard error of mean? Perspect Clin Res 2012;3:113–6. https://doi.org/10.4103/2229-3485.100662.

[18] Wright IC, Neptune RR, Van Den Bogert AJ, et al. The influence of foot positioning on ankle sprains. J Biomech 2000;33:513–9. https://doi.org/10.1016/S0021-9290(99)00218-3.

[19] Fong DT, Chan Y-Y, Mok K, et al. Understanding acute ankle ligamentous sprain injury in sports. BMC Sports Sci Med Rehabil 2009;1:1–14. https://doi.org/10.1186/1758-2555-1-14.

[20] Fuller EA. Center of pressure and its theoretical relationship to foot pathology. J Am Podiatr Med Assoc 1999;89:278–91. https://doi.org/10.7547/87507315-89-6-278.

[21] Mok KM, Ha SCW, Chan ZYS, et al. An inverted ankle joint orientation at foot strike could incite ankle inversion sprain: comparison between injury and non-injured cutting motions of a tennis player. Foot 2021;48:101853. https://doi.org/10.1016/J.FOOT.2021.101853.

[22] Frederick EC. Optimal frictional properties for sport shoes and sport surfaces. In: ISBS conference proceedings archive; 1993. p. 15–22.

[23] Wannop JW, Worobets JT, Stefanyshyn DJ. Footwear traction and lower extremity joint loading. doi:10.1177/0363546509359065.

[24] Dowling AV, Corazza S, Chaudhari AMW, et al. Shoe-surface friction influences movement strategies during a sidestep cutting task. Am J Sports Med 2010;38: 478–85. https://doi.org/10.1177/0363546509348374.

[25] Ismail SI, Nunome H, Tamura Y. Does visual representation of futsal shoes outsole tread groove design resemblance its mechanical traction, dynamic human traction performance, and perceived traction during change of direction and straight sprint tasks? Footwear Sci 2020:1–11. https://doi.org/10.1080/19424280.2020.1825534. 0.

[26] Luo G, Stefanyshyn D. Identification of critical traction values for maximum athletic performance. Footwear Sci 2011;3:127–38. https://doi.org/10.1080/19424280.2011.639807.

[27] Ismail SI, Nunome H, Lysdal GF, et al. Futsal playing surface characteristics significantly affects perceived traction and change of direction performance among experienced futsal players. Unpubl results.

[28] Jafari F, Razzaghi-Kashani M, Hosseini SM, et al. Effects of modified poly(tetrafluoroethylene) on the physico-mechanical and tribological properties of carbon-black filled nitrile-butadiene rubber. J Appl Polym Sci 2021;138:50061. https://doi.org/10.1002/APP.50061.

[29] Persson BNJ. Theory of rubber friction and contact mechanics. J Chem Phys 2001; 115:3840–61. https://doi.org/10.1063/1.1388626.

[30] Lysdal FG, Frank Á, Dziewiecki M, et al. Minimizing shoe-surface friction at initial contact: a novel approach to prevent lateral ankle sprains. ISBS Proc Arch 2017;35: 718–21. https://commons.nmu.edu/isbs/vol35/iss1/236.

[31] Lysdal FG, Jakobsen L, Grønlykke TB, et al. A kinematic analysis of the Spraino® realignment mechanism during simulated noncontact ankle sprain injuries. Footwear Sci 2019;11:S167–9. https://doi.org/10.1080/19424280.2019.1606309.

[32] Doherty C, Bleakley C, Hertel J, et al. Recovery from a first-time lateral ankle sprain and the predictors of chronic ankle instability. Am J Sports Med 2016;44:995–1003. https://doi.org/10.1177/0363546516628870.

[33] Bak J, Thorborg K, Clausen MB, et al. Using the app "Injurymap©" to provide exercise rehabilitation for people with acute lateral ankle sprains seen at the Hospital Emergency Department – a mixed-method pilot study. medRxiv; 2022. https://doi.org/10.1101/2022.01.31.22269313. 2022.01.31.22269313.

[34] Gribble PA, Bleakley CM, Caulfield BM, et al. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. Br J Sports Med 2016;50: 1496–505. https://doi.org/10.1136/bjsports-2016-096189.

[35] Verhagen E. If athletes will not adopt preventive measures, effective measures must adopt athletes. Curr Sports Med Rep 2012;11:7–8. https://doi.org/10.1249/JSR.0b013e318240dabd.

[36] Van Tiggelen D, Wickes S, Stevens V, et al. Effective prevention of sports injuries: a model integrating efficacy, efficiency, compliance and risk-taking behaviour. Br J Sports Med 2008;42:648–52. https://doi.org/10.1136/bjsm.2008.046441.

[37] Verhagen EALM, Bay K. Optimising ankle sprain prevention: a critical review and practical appraisal of the literature. Br J Sports Med 2010;44:1082–8. https://doi.org/10.1136/bjsm.2010.076406.

[38] Barelds I, van den Broek AG, Huisstede BMA. Ankle bracing is effective for primary and secondary prevention of acute ankle injuries in athletes: a systematic review and meta-analyses. Sports Med 2018;48. https://doi.org/10.1007/s40279-018-0993-2.

[39] Jakobsen L, Lysdal FG, Bagehorn T, et al. The effect of footwear outsole material on slip resistance on dry and contaminated surfaces with geometrically controlled outsoles. Ergonomics 2022. https://doi.org/10.1080/00140139.2022.2081364. https://www.tandfonline.com/doi/full/10.1080/00140139.2022.2081364.