biomechanics

MDPI

Article

Influence of Compliance and Aging of Artificial Turf Surfaces on Lower Extremity Joint Loading

Nicole Schrier, John William Wannop *, Jay T. Worobets and Darren J. Stefanyshyn

Human Performance Lab, Faculty of Kinesiology, University of Calgary, Calgary, AB T2N 1N4, Canada; nicole.schrier@adidas.com (N.S.); jay.worobets@nike.com (J.T.W.); darren.stefanyshyn@ucalgary.ca (D.J.S.)
* Correspondence: b.wannop@ucalgary.ca

Abstract: Background: Artificial turf (AT) has been related to increased injury rates when compared to natural grass (NG). One potential reason for the differences in injury rates is the difference in mechanical characteristics of the surfaces. Over the course of a season on artificial turf, due to heavy use and environmental factors, properties of the surface (such as compliance) may be altered. The purpose was to compare the effects of newly installed versus aged AT on injury risks at the metatarsophalangeal, ankle, and knee joint during soccer-specific movements. Methods: Eleven male soccer players performed three movements on newly installed and 'aged' AT. Kinematics and kinetics were collected for the different surfaces. Results: Knee adduction moments were increased during the v-cut (119 Nm vs. 164 Nm, $p = 0.02$), and knee external rotation joint moments were increased during the circle run (23 Nm vs. 28 Nm, $p = 0.04$) with the aged surface. No surface effects were seen during the jog-sprint transition. Conclusions: For movements associated with a high risk for non-contact injuries, the age of the AT resulted in greater risk factors for injury potential at the knee joint. Further research comparing injury rates associated with AT should consider mechanical features, specifically surface compliance.

Keywords: artificial turf; surfaces; biomechanics; sports science; stiffness; compliance

Citation: Schrier, N.; Wannop, J.W.; Worobets, J.T.; Stefanyshyn, D.J. Influence of Compliance and Aging of Artificial Turf Surfaces on Lower Extremity Joint Loading. *Biomechanics* **2022**, *2*, 66–75. https://doi.org/10.3390/biomechanics2010007

Academic Editors: Kerstin Witte and Arnold Baca

Received: 2 October 2021
Accepted: 20 January 2022
Published: 4 February 2022

1. Introduction

The first generation of artificial turf from the 1960s, characterized by high surface stiffness and friction properties, has been associated with increased non-contact injury rates when compared to natural grass [1,2]. The decreased surface compliance (how much a surface deforms under a given force) may have caused increased levels of impact leading to increased injury rates [3–6], altered joint movement patterns [7–9], and increased shoe-surface traction [6,10]. Advancements in artificial turf technologies brought about new generations of artificial turf, which were developed to mimic the features of natural grass more closely in terms of compliance and traction.

The third generation artificial turf introduced an underlying shock absorption pad, rubber/sand infill, and longer pile length to reduce traction and increase compliance of the turf surface to represent natural grass more closely. Recent studies comparing injury rates on third-generation artificial turf and natural grass have been inconclusive, finding either no change, an increase, or a decrease in injuries [11–19]. One potential reason for the differences in injury rates between these studies was the difference in mechanical characteristics of the turf surfaces observed. It has been shown that the wear of artificial surfaces can alter the mechanical properties of the surfaces [20]. Specifically, over the course of a season on artificial turf, due to heavy use and environmental factors, certain features such as the rubber/sand infill may become reduced and/or compressed, altering the traction and compliance features of this turf system [21].

It is known that by altering the traction characteristics, both performance and injury rates can be affected. While increasing footwear traction has been shown to improve performance up to a critical threshold [21–24], it has also been shown to lead to an increased risk of injury [18,19,25–27]. Similarly, altering the compliance of the surface has been shown to affect performance [23,28–30]; however, it is unclear how altering the surface compliance of the turf can influence injury rates.

It is commonly believed that joint loading increases can lead to joint injury [31–34]. During biomechanics research, joint loading may be estimated by calculating resultant joint moments, which are representative of the net torque or twisting load on the joint, and joint angular impulse, which is representative of the cumulative loading experienced by the joint during the stance phase (calculated as the integral of the resultant moment vs. time curve). While joint moments and angular impulse calculated from inverse dynamics cannot determine the exact loading on the actual joint structures, they have been used as valid predictors of the total load across a joint [35,36]. By measuring the resultant joint moments of athletes performing on a compliant and non-compliant (compacted) artificial turf surface in a controlled laboratory setting, the influence of compliance on joint loading can be determined and insight into how compliance may influence joint injury risk can be attained.

Dixon, Collop, & Batt [8] evaluated extreme effects of surface compliance by examining differences on asphalt and rubber infill surfaces. This study found no difference in ground reaction force impact peaks from one surface to the other but rather that the athlete adjusted their movement pattern to accommodate the differing compliances. A study by Wannop et al. [30] evaluated how surfaces of different stiffness altered athletic performance and movements patterns. They found increased running and jumping performance on soft surfaces, as well as changes in ankle and knee joint angles. These studies suggest that changes in surface compliance may cause athletes to adjust their movement patterns to prevent increases in force impact peaks or to achieve increased performance. While both studies did find differences in joint kinematics, effects on internal joint moments were not examined preventing further evaluation of injury risk on compliant and non-compliant surfaces. Also, these studies examined athletes performing on completely different surfaces of altered stiffness, it is unknown how smaller changes, such as those seen on the same surface over the course of a season (aged artificial turf versus new artificial turf), can affect these variables.

Therefore, the purpose of this study was to compare the effects of newly installed (compliant) versus aged (non-compliant) artificial turf on the resultant metatarsophalangeal (MTP), ankle, and knee joint moments during soccer-specific movements. It was hypothesized that as the compliance of the turf surface decreased, the resultant joint moments at all joints would increase, providing support that this mechanical characteristic of artificial turf may play a role in the increase of injury rates on less compliant turf surfaces such as earlier generations of artificial turf [1,2].

2. Materials and Methods

2.1. Participants

Eleven male high-level recreational soccer athletes were recruited for this investigation (mean $\pm$ SD: height, 1.77 $\pm$ 0.07 m; body mass, 72.3 $\pm$ 7.0 kg). The athletes were required to properly fit and perform all movements in a US men's size 9, 10, or 11 Adidas F50 Adizero Artificial Ground SYN (Figure 1) soccer cleat (Adidas AG, Herzogenaurach, Germany). All athletes were free from lower extremity injury or pain for the six months prior to testing and provided informed written consent in accordance with the University's Conjoint Health Research Ethics Board.

Figure 1. Photograph of the shoe used in the experiment.

2.2. Movements

Each athlete performed three different soccer-specific movements during this investigation; a 90° v-cut, a circle run, and a jog to sprint transition. All movements were performed five times at maximal effort with at least 30 s rest between trials and 2 min rest between movement types.

The 90° v-cut movement consisted of the athlete approaching the force platform from a 45° angle with the force plate on his left side, planting his left (outside) foot on the force platform and cutting outwards to his right at a 45° angle (Figure 2, left). The athlete started from rest at a distance such that his third footfall would place his left foot in the middle of the force platform.

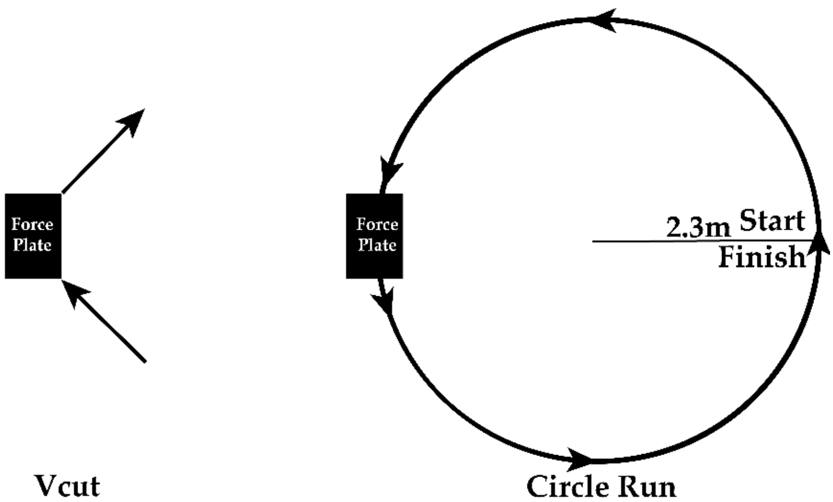

Figure 2. Diagram of the v-cut (**left**) and circle run (**right**) movements.

The circle run consisted of the athlete running along a curve with a 2.3 m radius and planting his left (inside) foot on the middle of the force platform (Figure 2, right). Similar to the v-cut movement, the athlete started from rest at a distance such that his third footfall would land on the force platform. After contact with the force platform, the athlete continued running along the curved path until returning to the starting location.

To determine surface effects during linear accelerations, a jog to sprint transition movement was performed. The athlete started from rest and jogged approximately 7.5 m at a self-determined pace towards the force platform, upon reaching the force plate, the athlete transitioned to a maximal effort sprint, the first stride of which was his left foot on the force platform. To explain this to the athletes, the concept was that they were jogging during a game and suddenly had to sprint for a ball. The athlete was instructed to slow down two strides following contact with the force platform but no sooner.

The order of the different movements was randomized with the athletes receiving adequate time to warm up prior to the test being initiated. During the movements, athletes were instructed to land with their left foot near the center of the force platform to ensure that the foot remained on the force platform for the entire duration of the movement. Through visual inspection, if the left foot was roughly centered on the force platform, the trial was discarded, and the athlete was required to repeat the movement. This resulted in the athletes performing 5–7 trials in each condition.

2.3. Artificial Turf Installation

FIFA 2 star graded artificial turf was installed into the biomechanics laboratory to allow for the kinetic and kinematic data collection on the turf surface (Figure 3). The Ecofill Pro Series 3NX FTS surface, a third-generation infilled surface from Mondo Worldwide was installed based on the manufacturers' specifications. The turf consisted of long monofilament fibers, each having a height of 45 mm and a semi-concave shape with sand/rubber infill. Surface compliance was increased by incorporating a 23 mm shock pad of post-consumer rubber granules under the turf surface.

Figure 3. Photograph of the artificial turf installed in the biomechanics laboratory.

The dimensions of the turf installed in the laboratory were 21 m × 5 m, to ensure that all athletes could perform the movements successfully without limitations due to space. To ensure accurate kinetic data collection, a separate piece of shock pad and infilled turf was isolated from the main section of turf via a separate 60 cm × 90 cm turf plot that was rigidly bolted to the force plate. Following turf installation, mechanical properties of the artificial turf were measured using a Clegg Impact Hammer to verify that the turf was within the manufacturers' specifications for a newly installed surface. Using the Clegg Impact Hammer, a cylindrical mass of 2.25 kg with a diameter of 50 mm (ASTM F355, missile D) was guided down a vertical ventilated tube from a height of 450 mm above the turf surface to measure the magnitude of maximum deceleration [37]. Ten measurements were taken throughout the turf surface and the mean value from the Clegg Impact Hammer was 94 g's.

2.4. Artificial Turf Simulated Wear

Following initial biomechanical testing for all athletes of the three soccer-specific movements on the newly installed artificial turf, the same turf was artificially aged. In this experiment aging of the turf was defined as compaction of the surface, resulting in a decrease in surface compliance as measured by the Clegg Impact Hammer. In order to age the turf, an industrial vibrating plate compactor (Wacker Neuson VP1135, Wacker Neuson, Munich, Germany) was used by walking it back and forth over the surface. Although simply applying compaction to the surface does not simulate all aspects of aging of the surface in a weather-related environment, it allowed comparison in terms of compaction and the primary variable of interest, a decrease in compliance of the surface, which generally occurs through years of play.

During compaction of the surface, numerous Clegg Impact Hammer measurements were taken, with cessation occurring when these values were measured within the manufacturers' specifications for defining turf that is aged, but still playable; values above 190 g's represent a surface requiring replacement. Compaction stopped and the athletes returned for the second set of biomechanical tests when the measurements (n = 10) of the Clegg Impact Hammer averaged 170 g's (1.8 times greater than the newly installed surface). This value falls within the range of values measured on five-year-old turf [38].

2.5. Biomechanical Data Collection

Eight high-speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) operating at 240 Hz recorded kinematic data, while a Kistler force plate (Kistler AG, Winterthur, Switzerland) operating at 2400 Hz simultaneously recorded kinetic data. Only kinetic and kinematic data in which the participant contacted the middle of the force platform were used for analysis. Nine retro-reflective markers were attached to the left lower leg, rearfoot, and forefoot segments for three-dimensional kinematic data collection (three markers per segment). A multi-segment foot model was used to evaluate the effects of the artificial turf on the metatarsophalangeal (MTP) joint, specifically in the sagittal plane which has previously been associated with turf-toe related injuries [2,38]. Double-sided tape was used to attach the markers shoe and lower leg. For the lower leg, the markers were placed on the tibia at the proximal end, on the tibia at the distal end, and mid-distance between these markers on the lateral aspect of the shank. For the rearfoot, markers were placed on the posterior proximal shoe heel, posterior distal shoe heel, and the lateral side of the shoe below the lateral malleolus. For the forefoot, markers were placed slightly more distal than the 1st and 5th metatarsal head as well as on the shoe, at the most distal aspect. Preceding the dynamic trials, a standing static trial was recorded and used to determine knee, ankle, and MTP joint centers. The knee joint center was defined as the midway point between markers placed on the medial and lateral femoral epicondyles, the ankle joint center was defined as the midway point between markers placed on the medial and lateral malleoli and the MTP joint was defined as the midway point between markers placed on the 1st and 5th metatarsal heads. The standing static trials defined segment lengths and the location of segment centers of mass, which were used for inverse dynamics calculations.

Processing and analysis of the kinematic and kinetic data were performed with KinTrak 7.0.25 (Human Performance Laboratory, University of Calgary, Calgary, AB, Canada). A fourth-order low pass Butterworth filter with cut-off frequencies of 24 and 100 Hz for kinematic and kinetic data respectively, smoothed the data.

For each trial, utilized translational and rotational outsole traction and internal resultant joint moments at the MTP, ankle, and knee were quantified. Means of the peak values were calculated from the accepted five trials per athlete then averaged across all eleven athletes. The utilized translational outsole traction coefficient was quantified as the peak value for the ratio between the vector sum of the shear force and the vertical force during each trial. The rotational traction was calculated as the peak free moment about the vertical ground reaction force. MTP, ankle, and knee internal resultant joint moments (3-dimensional) were calculated using a standard inverse dynamics approach.

2.6. Statistics

For statistical analysis, the mean of all trials for each participant in each condition was calculated and compared using a paired *t*-test to determine any significant differences across the turf conditions for the variables of interest with a significance level set to $\alpha = 0.05$. Data was formally tested for the violation of normality using a Shapiro-Wilk test. If a significant difference was detected, effect size calculations (Cohen's d) were performed and reported following the method of Cohen [39] and Dunlap et al. [40]. All statistical analysis was performed using SPSS software v12.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. V-Cut

Table 1 highlights all variables for the v-cut movement including ground reaction forces, utilized traction, MTP, ankle, and knee joint moments. No differences were found in the peak ground reaction forces. A significant decrease in peak translational traction utilized by the athletes was seen when performing the movement on the aged turf compared to the newly installed turf (1.29 vs. 0.95, $p = 0.02$).

Table 1. Mean peak values for the v-cut movement on the newly installed and aged artificial turf surfaces.

V-Cut	New	Aged	*p*-Value
Medial Ground Reaction Force [N]	1159 ± 332	1233 ± 410	0.32
Posterior Ground Reaction Force [N]	267 ± 52	246 ± 87	0.28
Anterior Ground Reaction Force [N]	485 ± 189	502 ± 181	0.66
Vertical Ground Reaction Force [N]	1824 ± 413	1888 ± 360	0.49
MTP Extension Angle [deg]	23 ± 10	25 ± 6	0.30
MTP Extension Moment [Nm]	183 ± 68	194 ± 66	0.32
Ankle External Rotation Moment [Nm]	90 ± 30	87 ± 25	0.50
Ankle Eversion Moment [Nm]	116 ± 42	115 ± 42	0.89
Knee External Rotation Moment [Nm]	55 ± 20	55 ± 15	0.99
Knee Adduction Moment [Nm]	119 ± 68	164 ± 69	0.02 *, ES = 0.95
Utilised Translational Traction	1.29 ± 0.44	0.95 ± 0.12	0.02 *, ES = 0.88
Utilised Rotational Traction [Nm]	14.32 ± 1.58	14.84 ± 1.72	0.72

N = Newton, Nm = Newton-meters, deg = degree, MTP = metatarsophalangeal, * = significant difference, ES = effect size.

When evaluating internal joint moments, only frontal plane knee joint moments were found to be significantly different. The aged turf increased the peak internal knee adduction moment by 38% from 119 Nm to 164 Nm ($p = 0.02$). Evaluating the peak angle of the shank relative to the turf surface in the frontal plane highlighted that the aged artificial turf resulted in a smaller angle (greater lean) compared to the newly installed artificial turf (53° vs. 49°, $p = 0.03$).

3.2. Circle Run

Similar to the v-cut movement, no significant differences were found when comparing the peak ground reaction forces for the circle run (Table 2). No difference was seen in the utilized translational or rotational traction. The only significant difference seen in the variables examined occurred in the transverse plane at the knee joint. The peak internal rotation moment increased from 23 Nm to 28 Nm ($p = 0.04$) when performing this movement on the aged artificial turf.

Table 2. Mean peak values for the circle run movement on the newly installed and aged artificial turf surfaces.

Circle Run	New	Aged	*p* Value
Lateral Ground Reaction Force [N]	963 ± 303	1000 ± 268	0.34
Posterior Ground Reaction Force [N]	336 ± 96	307 ± 94	0.15
Anterior Ground Reaction Force [N]	119 ± 62	125 ± 47	0.59
Vertical Ground Reaction Force [N]	1353 ± 245	1308 ± 195	0.13
MTP Extension Angle [deg]	27 ± 7	25 ± 7	0.13
MTP Extension Moment [Nm]	85 ± 54	92 ± 67	0.74
Ankle Internal Rotation Moment [Nm]	79 ± 22	81 ± 18	0.60
Ankle Inversion Moment [Nm]	124 ± 44	136 ± 40	0.18
Knee Internal Rotation Moment [Nm]	23 ± 14	28 ± 13	0.04 *, ES = 0.71
Knee Adduction Moment [Nm]	114 ± 28	113 ± 35	0.85
Utilized Translational Traction	0.95 ± 0.17	0.99 ± 0.18	0.23
Utilized Rotational Traction [Nm]	17.00 ± 3.06	16.47 ± 3.42	0.43

N = Newton, Nm = Newton-meters, deg = degree, MTP = metatarsophalangeal, * = significant difference, ES = effect size.

3.3. Jog-Sprint Transition

No significant differences were found in the peak ground reaction forces when movements were performed on the different turfs (Table 3). Further, when examining the internal joint moments associated with the jog to sprint transition period, no significant differences were seen in the frontal or transverse plane at the MTP, ankle, or knee joint.

Table 3. Mean peak values for the jog to sprint transition movement for newly installed and aged artificial turf surfaces.

Jog-Sprint Transition	New	Aged	*p* Value
Posterior Ground Reaction Force [N]	207 ± 143	224 ± 143	0.69
Anterior Ground Reaction Force [N]	503 ± 61	523 ± 74	0.09
Vertical Ground Reaction Force [N]	1611 ± 185	1613 ± 218	0.97
MTP Extension Angle [deg]	31 ± 4	32 ± 4	0.55
MTP Flexion Moment [Nm]	78 ± 12	78 ± 14	0.50
Ankle External Rotation Moment [Nm]	37 ± 12	39 ± 16	0.82
Ankle Inversion Moment [Nm]	13 ± 13	15 ± 12	0.76
Knee External Rotation Moment [Nm]	59 ± 10	55 ± 16	0.45
Knee Abduction Moment [Nm]	127 ± 38	108 ± 31	0.14
Utilized Translational Traction	1.16 ± 0.17	1.13 ± 0.24	0.70

N = Newton, Nm = Newton-meters, deg = degree, MTP = metatarsophalangeal.

4. Discussion

The purpose of this study was to compare the effects of simulated wear of artificial turf on internal joint moments at the metatarsophalangeal, ankle, and knee joint during soccer-specific movements. It was hypothesized that as artificial turf ages and loses compliance, joint loading (estimated from joint moments) would increase, suggesting that the athlete may be at a greater risk of suffering a joint injury during play. The hypothesis was only partially supported in that knee joint moments were increased in the frontal plane during the v-cut and in the transverse plane in the circle run movement with the less compliant turf, with a large effect size (>0.71), being present for both movements. When evaluating the effects of aged artificial turf on joint moments for a linear movement, such as the jog to sprint transition, the hypothesis was not supported as joint moments did not increase with turf wear.

With the movements associated with a high risk for non-contact injury due to their explosive nature and high joint moments in the non-sagittal plane, such as the v-cut and circle run, the fact that the aged turf caused greater joint moments is a cause for concern as previous research has linked these joint moments with increased injury risk [32,33]. Since no change was seen in the magnitude of the ground reaction force components or ankle joint moment for these movements, the increase in joint moments occurring at the knee is likely linked to modified lean angles seen on the aged turf. This is supported by the fact that athletes had a reduced shank angle in the frontal plane relative to the floor in the aged turf condition during the v-cut, generating a greater moment arm when calculating internal joint moments at the knee. This observation suggests that increased injury risk was due to modified movement patterns rather than increased force magnitudes, which is in agreement with Dixon, Collop, & Batt [8] who also found that increasing surface compliance did not influence ground reaction force impact peaks but rather joint kinematics. Further, the less compliant surface leading to increased joint moments in the non-sagittal planes was similar to the findings when comparing turning on a relatively soft newly installed turf compared to a stiff plastic sport surface [23].

It was interesting to note that during a linear movement, such as the jog to sprint transition, no changes were seen between the newly installed and aged artificial surface in terms of forces or joint moments. It appears that for linear type movements, changes in compliance associated with turf wear are not related to increased injury risks. As previous research has found that increasing compliance may increase performance during linear movements [23,30], the firmer-aged artificial turf may provide a benefit in this linear movement scenario without increasing injury risk.

One of the main concerns from earlier generations of turf and their limited compliance was the development of turf-toe or overloading of the capsuloligamentous complex caused by hyperextension at the MTP joint [39]. This study found that there were no differences in MTP joint angles/moments on the newly installed and aged turf surface. This suggests that the aged turf would not be more likely to elicit these forms of injury during the movements examined. Perhaps during more extreme MTP joint flexing scenarios, such as those seen in American Football when an opposing player causes an excessive force on an already flexed joint (explained by Rodeo et al. (1990) [37] as one of the common scenarios for turf-toe), differences in surface compliance may play a role in injury risk.

Previous work has shown that as artificial surfaces wear, their mechanical properties can be altered [20]. The practical implications of this current study are that it provides a reason to consider turf mechanical features when evaluating injury rates on these surfaces. The lack of inclusion of this information could be the reason for current inconclusive results in whether a turf surface is more or less susceptible to injury rates compared to natural grass [11–18]. Further, by implementing more stringent guidelines for turf replacement and maintaining acceptable compliance features, injury rates occurring on artificial turf may be reduced.

A major limitation associated with this study was the approach to represent artificial turf wear. The main purpose of this manuscript was to simulate wear through compaction as this is a major factor associated with actual turf wear over years of play. Environmental factors such as rain, adding saturation levels to the turf and sun exposure, adding degradation elements to the turf, could also affect its mechanical performance. Longitudinal mechanical testing of turf surfaces in varying climates could help to evaluate how these characteristics change with various environmental factors, as well assessing how field maintenance can influence the aging effect and the corresponding influence on athlete biomechanics would be of interest. Another limitation was using joint moments to represent joint loading. Joint moments are only a surrogate of loading occurring at the joint and do not provide information into loading occurring in different individual structures (muscle, ligament, bone), however, with current technology this approach is the best attempt to determine what is occurring at the joint.

In conclusion, it can be seen that for lateral movements, aged artificial turf may be more susceptible to injury risk at the knee, as seen by the increased frontal and transverse internal joint moments [32,33]. Future research examining the effects of artificial turf on injury rates should not only consider the generation features of turf but also the wear and mechanical aspects associated with the pitch as this manuscript has shown that these may also be factors that can affect joint loading. As well, further research should be performed to evaluate turf wear and mechanical aspects of artificial turf on injury rates.

Author Contributions: Conceptualization, D.J.S. and J.T.W.; methodology, D.J.S. and J.T.W.; formal analysis, N.S. and J.W.W.; investigation, N.S. and J.W.W.; data curation, N.S.; writing—original draft preparation, N.S.; writing—review and editing, N.S., J.W.W., D.J.S. and J.T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received was funded by Adidas AG.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the University of Calgary.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Adkinson, J.W.; Requa, R.K.; Garrick, J.G. Injury rates in high school football. *Clin. Orthop. Relat. R* **1974**, *99*, 131–136. [CrossRef]
2. Bowers, K.D.; Martin, R.B. Turf-toe: A shoe-surface related football injury. *Med. Sci. Sports* **1976**, *8*, 81–83. [CrossRef] [PubMed]
3. James, S.L.; Bates, B.T.; Osternig, L.R. Injuries to runners. *Am. J. Sport Med.* **1978**, *6*, 40–50. [CrossRef] [PubMed]
4. Cavanagh, P.R.; Lafortune, M.A. Ground reaction forces in distance running. *J. Biomech.* **1980**, *13*, 397–406. [CrossRef]
5. Frederick, E.C.; Clarke, T.E.; Hamill, C. The effect of running shoe design on shock attenuation. In *Sports Shoes and Playing Surfaces*; Frederick, E.C., Ed.; Human Kinetics: Champaign, IL, USA, 1984; pp. 190–198.
6. Nigg, B.M.; Frederick, E.C.; Hawes, M.R.; Luethi, S.M. Factors Influencing Short-Term Pain and Injuries in Tennis. *Int. J. Sport Biomech.* **1986**, *2*, 156–165. [CrossRef]
7. Hamill, J.; Bates, B.; Holt, K. Timing of lower extremity joint actions during treadmill running. *Med. Sci. Sport Exer.* **1992**, *24*, 807–813. [CrossRef]
8. Dixon, S.J.; Collop, A.C.; Batt, M.E. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med. Sci. Sport Exer.* **2000**, *32*, 1919–1926. [CrossRef]
9. Stergiou, N.; Bates, B.T. The relationship between subtalar and knee joint functions as a possible mechanism for running injuries. *Gait Posture* **1987**, *6*, 177–185. [CrossRef]
10. Stucke, H.; Baudzus, W.; Baumann, W. On friction characteristics of playing surfaces. In *Sport Shoes and Playing Surfaces*; Human Kinetics: Champaign, IL, USA, 1984; pp. 87–97.
11. Meyers, M.C. Incidence, Causes, and Severity of High School Football Injuries on FieldTurf versus Natural Grass: A 5-Year Prospective Study. *Am. J. Sport Med.* **2004**, *32*, 1626–1638. [CrossRef]
12. Ekstrand, J.; Timpka, T.; Hägglund, M. Risk of injury in elite football played on artificial turf versus natural grass: A prospective two-cohort study. *Brit. J. Sport Med.* **2006**, *40*, 975–980. [CrossRef]
13. Fuller, C.W.; Dick, R.W.; Corlette, J.; Schmalz, R. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: Match injuries. *Br. J. Sport Med.* **2007**, *41*, i27–i32. [CrossRef] [PubMed]
14. Steffen, K.; Andersen, T.E.; Bahr, R. Risk of injury on artificial turf and natural grass in young female football players. *Br. J. Sport Med.* **2007**, *41*, i33–i37. [CrossRef] [PubMed]
15. Aoki, H.; Kohno, T.; Fujiya, H.; Kato, H.; Yatabe, K.; Morikawa, T.; Seki, J. Incidence of injury among adolescent soccer players: A comparative study of artificial and natural grass turfs. *Clin. J. Sport Med.* **2010**, *20*, 1–7. [CrossRef] [PubMed]
16. Bjørneboe, J.; Bahr, R.; Andersen, T.E. Risk of injury on third-generation artificial turf in Norwegian professional football. *Br. J. Sport Med.* **2010**, *44*, 794–798. [CrossRef] [PubMed]
17. Ekstrand, J.; Hägglund, M.; Fuller, C.W. Comparison of injuries sustained on artificial turf and grass by male and female elite football players. *Scand. J. Med. Sci. Sport* **2011**, *21*, 824–832. [CrossRef]
18. Wannop, J.W.; Luo, G.; Stefanyshyn, D.J. Footwear traction and lower extremity noncontact injury. *Med. Sci. Sport Exer.* **2013**, *45*, 2137–2143. [CrossRef]
19. Mack, C.D.; Kent, R.W.; Coughlin, M.J.; Shiue, K.Y.; Weiss, L.J.; Jastifer, J.R.; Wojtys, E.M.; Anderson, R.B. Incidence of lower extremity injury in the National Football League: 2015 to 2018. *Am. J. Sport Med.* **2020**, *48*, 2287–2294. [CrossRef]
20. Sánchez-Sánchez, J.; Felipe, J.L.; Burillo, P.; del Corral, J.; Gallardo, L. Effect of the structural components of support on the loss of mechanical properties of football fields of artificial turf. *PI Mech. Eng. PJ Sport* **2014**, *228*, 155–164. [CrossRef]
21. Wannop, J.W.; Luo, G.; Stefanyshyn, D.J. Footwear traction at different areas on artificial turf and natural grass surfaces. *Sports Eng.* **2012**, *15*, 111–116. [CrossRef]
22. Luo, G.; Stefanyshyn, D. Identification of critical traction values for maximum athletic performance. *Footwear Sci.* **2011**, *3*, 127–138. [CrossRef]
23. Schrier, N.M.; Wannop, J.W.; Lewinson, R.T.; Worobets, J.T.; Stefanyshyn, D. Shoe traction and surface compliance affect performance of soccer-related movements. *Footwear Sci.* **2014**, *6*, 69–80. [CrossRef]
24. Worobets, J.; Wannop, J.W. Influence of basketball shoe mass, outsole traction, and forefoot bending stiffness on three athletic movements. *Sport Biomech.* **2015**, *14*, 351–360. [CrossRef] [PubMed]
25. Lambson, R.B.; Barnhill, B.S.; Higgins, R.W. Football cleat design and its effect on anterior cruciate ligament injuries: A three-year prospective study. *Am. J. Sport Med.* **1996**, *24*, 155–159. [CrossRef] [PubMed]
26. Torg, J.S.; Quedenfeld, T.C.; Landau, S. The shoe-surface interface and its relationship to football knee injuries. *J. Sports Med.* **1974**, *2*, 261–269. [CrossRef] [PubMed]
27. Wannop, J.W.; Worobets, J.T.; Stefanyshyn, D.J. Footwear traction and lower extremity joint loading. *Am. J. Sport Med.* **2010**, *38*, 1221–1228. [CrossRef] [PubMed]
28. McMahon, T.; Greene, P. The influence of track compliance on running. *J. Biomech.* **1979**, *12*, 893–904. [CrossRef]
29. Nigg, B.M.; Anton, M. Energy aspects for elastic and viscous shoe soles and playing surfaces. *Med. Sci. Sport Exer.* **1995**, *27*, 92–97. [CrossRef]
30. Wannop, J.W.; Kowalchuk, S.; Esposito, M.; Stefanyshyn, D. Influence of Artificial Turf Surface Stiffness on Athlete Performance. *Life* **2020**, *10*, 340. [CrossRef] [PubMed]

31. Sharma, L.; Hurwitz, D.E.; Thonar, E.A.; Sum, J.A.; Lenz, M.E.; Dunlop, D.D.; Schnitzer, T.J.; Kirwan-Mellis, G.; Andriacchi, T.P. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheumatol.* **1998**, *41*, 1233–1240. [CrossRef]
32. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; Succop, P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am. J. Sport Med.* **2005**, *33*, 492–501. [CrossRef]
33. Stefanyshyn, D.J.; Stergiou, P.; Lun, V.M.Y.; Meeuwisse, W.H.; Worobets, J.T. Knee angular impulse as a predictor of patellofemoral pain in runners. *Am. J. Sport Med.* **2006**, *34*, 1844–1851. [CrossRef] [PubMed]
34. Shin, C.S.; Chaudhari, A.M.; Andriacchi, T.P. The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *J. Biomech.* **2008**, *42*, 280–285. [CrossRef] [PubMed]
35. Hurwitz, D.E.; Sumner, D.R.; Andriacchi, T.P.; Sugar, D.A. Dynamic knee loads during gait predict proximal tibial bone distribution. *J. Biomech.* **1998**, *31*, 423–430. [CrossRef]
36. Thorp, L.E.; Sumner, D.R.; Block, J.A.; Moisio, K.C.; Shott, S.; Wimmer, M.A. Knee joint loading differs in individuals with mild compared with moderate medial knee osteoartritis. *Arthritis Rheumatol.* **2006**, *54*, 3842–3849. [CrossRef] [PubMed]
37. American Society for Testing and Materials [ASTM]. *ASTM F355 Standard Test Method for Impact Attenuation of Playing Surface Systems and Materials 2010*; ASTM International: West Conshohocken, PA, USA, 2010. [CrossRef]
38. Rodeo, S.A.; O'Brien, S.; Warren, R.F.; Barnes, R.; Wickiewicz, T.L.; Dillingham, M.F. Turf-toe: An analysis of metatarsophalangeal joint sprains in professional football players. *Am. J. Sport Med.* **1990**, *18*, 280–285. [CrossRef] [PubMed]
39. Cohen, J. A power primer. *Psychol. Bull.* **1992**, *112*, 155–159. [CrossRef] [PubMed]
40. Dunlap, W.P.; Crtina, J.M.; Vaslow, J.B.; Burke, M.J. Meta-analysis of experiments with matched groups or repeated measures designs. *Psychol. Methods* **1996**, *1*, 170–177. [CrossRef]