Original article

The effects of artificial surface temperature on mechanical properties and player kinematics during landing and acceleration

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Abstract

Background: Artificial turf is considered a feasible global alternative to natural turf by many sports governing bodies. Consequently, its ability to provide a safe and consistent playing surface regardless of climate becomes essential. The aims of this study were to determine the effects of artificial surface temperature on: (1) mechanical properties of the turf and (2) the kinematics of a turf-sport related movement.

Methods: Two identical artificial turf pitches were tested: one with a cold surface temperature ($1.8°C$–$2.4°C$) and one with a warm surface temperature ($14.5°C$–$15.2°C$). Mechanical testing was performed to measure the surface properties. Four amateur soccer players performed a hurdle jump to sprint acceleration movement, with data (contact time, step length and hip, knee and ankle kinematics) collected using CODASport (200 Hz).

Results: The temperature difference had a significant influence on the mechanical properties of the artificial turf, including force absorption, energy restitution, rotational resistance, and the height where the head injury criterion was met. Both step length ($p = 0.008$) and contact time ($p = 0.002$) of the initial step after the landing were significantly longer on the warm surface. In addition, significant range of motion and joint angular velocity differences were found.

Conclusion: These findings highlight different demands placed on players due to the surface temperature and suggest a need for coaches, practitioners, and sports governing bodies to be aware of these differences.

1. Introduction

The use of artificial turf in sport is becoming more common, especially in areas that offer suboptimal climatic conditions for the growth and maintenance of good quality natural turf.[1] Andersson et al.[2] highlighted that movement and tactical play on artificial turf are different from natural turf. For example, soccer (football) players performed fewer tackles and more short passes on artificial surfaces.[2] Additionally, injury patterns have been shown to differ between natural and artificial turfs, although overall injury incidence is similar on both surfaces.[3–5] However, these studies are epidemiological in nature and less is known about the effect of artificial surfaces on the biomechanics of a performer, and specifically how this relates to the mechanical properties of the surface.

Artificial pitches must achieve certification before being used, ensuring the surface is not detrimental to the game-play or the players. The surfaces are required to meet regulatory standards regarding shock absorption, vertical deformation, energy restitution, and linear and rotational traction.[6,7] In addition, some sports require a shock pad underneath the surface and a head injury criterion (HIC) score to be met (including rugby[6]). The HIC is a measure of the likelihood of an impact causing a serious head trauma. The standards differ slightly between sports (e.g., soccer, rugby, American football, and Gaelic football) and were developed based on mechanical data collected from natural turf.[8] Laboratory and field mechanical tests are used to verify surfaces for soccer and rugby worldwide.[6,7] The application of mechanical testing is undoubtedly important for the identification of surface properties, to validate surfaces and

to inform the surface maintenance.[8,9] However, how representative the mechanical criteria tested are of the human–surface interaction is questionable. For example, although a stiffer surface increases the impact force measured mechanically, peak ground reaction forces are not influenced by surface stiffness.[9–11] In addition, little is known about how players respond biomechanically on artificial surfaces with different properties. It is desirable, and expected, that artificial turf exhibits similar mechanical and performance characteristics in different environmental conditions; one of the perceived advantages of artificial turf over natural turf.

One environmental factor that may affect surface properties is surface temperature. Knowledge of the influence that surface temperature can have on the mechanical properties of the artificial turf is necessary for coaches, ground keepers, and facility managers in order to make informed decisions about the use of artificial turf. A number of studies have highlighted that artificial surfaces have a greater surface temperature than natural surfaces. Williams and Pulley[12] compared 2 types of artificial surface (American football and soccer pitches) with natural grass, concrete, and soil surfaces. The artificial surfaces reached maximum surface temperature of 69.4°C, whilst the natural grass pitch reached only 31.4°C on the same day. This underlines the importance of investigating how climatic changes influence the mechanical properties of artificial surfaces. In this regard, Torg et al.[13] found that an increase in surface temperature resulted in greater rotational resistance, which potentially increases athletes' lower limb injury risk. However, it should be noted that artificial surfaces have undergone great technological advances since 1996 and are now regularly used in Fédération Internationale de Football Association (FIFA) regulated competitions.

To identify the effect of different surfaces, Potthast et al.[14] investigated the biomechanics of soccer players performing a free kick on 3 surfaces composed of different materials. The authors found that soccer players' decelerations, shot velocities, and shot accuracy were all lower when performing on an artificial turf with a combined sand and rubber infill, compared to performance on natural turf or artificial turf with an entirely rubber infill. As a result, Potthast et al.[14] highlighted that consideration should not only be given to describe differences between artificial and natural turfs, but also differences among artificial turf surfaces.

Other studies examining player responses on different surfaces have largely investigated hard court surfaces or natural turf.[15–17] When investigating the properties of 3 different natural turfs, Stiles et al.[16] found running on the hardest surface only resulted in the second highest peak loading rate, whilst the surface that was ranked joint-lowest in terms of hardness showed the highest peak loading rate. Although McMahon and Greene[18] found surface stiffness influenced contact time and step length, other studies found no significant effect on sprinting time, ground contact time, or step length.[19,20] These findings add to the theory that athletes adapt their leg stiffness to the stiffness of the surface on which they move.[21,22] Athletes' ability to adjust their leg stiffness through flexion/extension changes[23] indicates that fixed energy devices, such as the Artificial Athlete or Clegg

Hammer, should not be seen as substitutes for human movement testing.[1] In addition, as McMahon and Greene[18] originally found in their study of the influence of track compliance on running, artificial surface properties can be engineered to optimise technique and movement efficiency. Collectively, these studies conclude that the mechanical characteristics of the surface influence the player–surface interaction. Therefore, in the interests of ensuring athlete safety and preserving the integrity of the sports in question, it is critical to determine the specific effects of surface properties on athletic performance. The aims of this study were to determine the effects of artificial surface temperature on: (1) mechanical properties of the turf and (2) the kinematics of a turf-sport related movement. The movement chosen to investigate this issue was a landing with forward momentum followed by acceleration. The landing and the first step were of particular interest as landings followed by acceleration are a commonly used dynamic movement in soccer and rugby.[2]

2. Materials and methods

2.1. Participants

Four amateur soccer players (1.85 ± 0.22 m; 79.3 ± 9.1 kg; 20.8 ± 0.5 years) gave written informed consent to participate in the study, which was approved by the Cardiff Metropolitan University's Ethics Committee. Three players were left foot dominant and 1 was right foot dominant. Dominance was defined as the leg that the players would use to push off into the sprint following the landing. All players were free from injuries at the time of testing and had no serious lower limb injuries in the past 12 months. The participants all wore standardised soccer boots (Copa Mundial; Adidas, Herzogenaurach, Germany) in their size and their own soccer clothing. A standardised soccer-specific warm-up that the players were familiar with was used prior to both testing sessions. Between trials the players wore substitute (bench) coats to limit the effect of the cold air temperature on their subsequent performance.

2.2. Data collection

All testing was performed on 2 identical third generation (3G) artificial turfs (65 mm pile height; White Horse Contractors, Abingdon, UK), 1 outdoor and 1 indoor. Both surfaces were regularly used for elite rugby and soccer training. The mechanical and biomechanical testing took place on 2 consecutive days; the outdoor surface on Day 1 and the indoor surface the following day. Both artificial turfs had fulfilled the standards and regulations for rugby and soccer training and competitive use when installed and were both maintained according to FIFA[7] and World Rugby[6] guidelines.

2.2.1. Mechanical testing

An independent, regulated surface testing institution (Labosport Ltd., Nottingham, UK) performed the standardised mechanical tests[6,7] to determine the surface mechanical properties. For all surface properties, the data were collected at 6 different locations on each surface. During testing, the outdoor artificial turf had a surface temperature between 1.8°C and 2.4°C, whilst the indoor turf ranged between 14.5°C and 15.2°C. The

Table 1
Fédération Internationale de Football Association (FIFA) One and Two Star[7] and International Rugby Board (IRB)[6] regulations for the mechanical properties tested in this study.

Mechanical property	FIFA One Star	FIFA Two Star	IRB
Force absorption (%)	55–70	60–70	55–70
Vertical deformation (mm)	4–9	4–8	4–10
Energy restitution (%)	—	—	20–50
Rotational resistance (N·m)	25–50	30–45	30–45
HIC (m)	—	—	≤1000 HIC at ≥1.3 m

Abbreviation: HIC = head injury criterion.

mechanical tests were those included in the World Rugby[6] and FIFA One and Two Star regulations,[7] with the specifications provided in Table 1. A portable measuring device, the Advanced Artificial Athlete (AAA; Deltec Equipment, Duiven, The Netherlands), was used to measure the mechanical properties tested, following the guidelines of World Rugby Regulation 22.[6]

The mechanical properties measured were defined as:

- Force absorption (%): The ability of the surface to reduce the impact force of a load, typically called shock absorption. Impact forces are referenced against concrete, a non-shock absorbing surface, with a higher percentage reflecting a softer surface.
- Vertical deformation (mm): The deformation of the surface under an applied load.
- Energy restitution (%): The energy returned by the surface after an applied load.
- Rotational resistance (N·m): The torque produced when a studded disc is rotated on the turf. A low value indicates low resistance (low traction), whilst a high value indicates excessive traction; both extremes can cause injuries.[1]
- HIC (m): A measure of the likelihood of an impact causing a serious head trauma. For example, an HIC ≤1000 from a height of 1.3 m is necessary for the surface to be certified for use in rugby.[6]

2.2.2. Biomechanical testing

Following a standardised warm-up used for both conditions, the participants performed a counter movement hurdle jump (hurdle height: 0.68 m) followed by landing and dynamic 5 m acceleration (Fig. 1). Kinematic data were collected using a CODA Sport CX1 3D motion analysis system (Charnwood Dynamics Ltd., Leicester, UK), sampling at 200 Hz.[24] Two CODA scanners were positioned adjacent to the plane of movement (Fig. 1). The hurdle position and direction of travel were altered according to the player's leg dominance (the leg initiating the sprint). Active markers were positioned laterally on the near side and medially on the far side of the body. Markers on the lateral side included the metatarsal phalangeal joint of the fifth toe (MTP 5), lateral malleolus, lateral epicondyle of the femur, greater trochanter and greater tubercle of the femur. The only marker placed on the medial side was on the metatarsal phalangeal joint of the first toe (MTP 1). Markers and battery boxes were fixed to boots and skin using double-sided adhesive tape, with electrical tape used to fix the boxes securely. Each partici-

pant completed 10 trials in which the landing (first contact) and the first step (second contact) were analysed. Following each trial, players had a 3-min rest, reducing the risk of fatigue.

2.3. Data analysis

The data were filtered using a Butterworth low pass filter at 20 Hz, determined using residual analysis of the coordinate data.[25] The data were normalised to 100% stance, exported to MATLAB (Version R2008b; The MathWorks Inc., Natick, MA, USA) and analysed with a custom written program. The global axes were defined as vertical (z), anterior-posterior (y), and medio-lateral (x). Analysis was restricted to flexion/extension in the sagittal plane, occurring about the x axis. To determine touch-down and take-off events, the instances of peak z acceleration of the MTP 5 and MTP 1 markers were used.[24,26] To determine step length, the y-coordinate of the foot marker at touchdown on landing was subtracted from the opposite foot marker y-coordinate on touchdown of the first step following the landing. The instantaneous y velocity of the greater trochanter (GT) marker was identified at touchdown and take-off for the landing ground contact. During the landing ground contact, discrete sagittal plane joint kinematic parameters were identified for the hip, knee, and ankle from marker coordinate data. Joint angles were defined based on a local coordinate system providing relative sagittal plane angles, where 180° was used to describe full extension (plantar flexion) and thus a straightened joint. Increase in angle defined extension for each joint and touchdown, peak flexion and take-off angles and peak flexion and extension velocities were calculated. Statistical analyses were conducted using SPSS for Windows (Version 17.0; SPSS Inc., Chicago, IL, USA). Results of Shapiro–Wilks ($p > 0.05$) and skewness and kurtosis (within ±1) statistics enabled normality to be assumed. Paired samples t tests identified significant differences ($p < 0.05$) between surfaces for each parameter. The effect sizes of the differences were calculated, with bias corrected (Hedges g).

3. Results

The results of the mechanical testing revealed the cold (outdoor) and warm (indoor) surfaces significantly ($p < 0.05$)
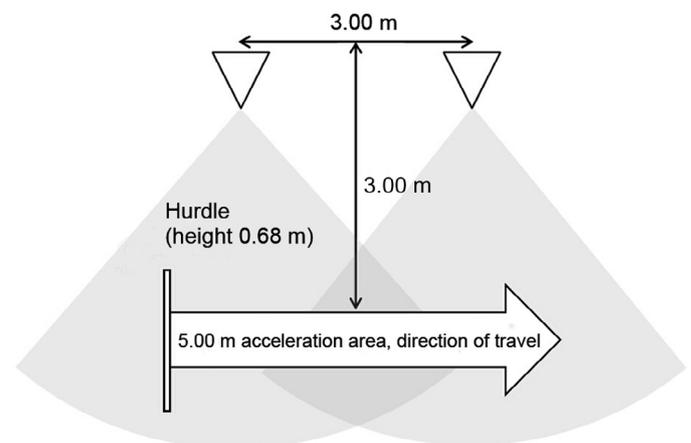

Fig. 1. The data collection set-up, showing the 2 CODA scanners (triangles). The fields of view (shaded areas) provided at least a 7.00 m data capture volume.

Table 2
Mechanical properties of the cold and warm artificial surfaces (mean ± SD).

Mechanical property	Cold	Warm	p value	Effect size (g)
Force absorption (%)	47.60 ± 2.43	62.20 ± 1.49	<0.01*	−6.68
Vertical deformation (mm)	5.10 ± 0.42	8.80 ± 0.39	<0.01*	−8.42
Energy restitution (%)	44.00 ± 2.39	41.50 ± 0.63	0.08	1.32
Rotational resistance (N·m)	33.00 ± 2.07	38.00 ± 0.82	<0.01*	−2.93
Head injury criterion (m)	1.00 ± 0.06	1.40 ± 0.06	0.04*	−6.15

* Significant difference between surfaces ($p < 0.05$).

differed in their force absorption (47.6% *vs.* 62.2%, respectively) and vertical deformation (5.1 mm *vs.* 8.8 mm) properties (Table 2). The rotational resistance (33 N·m *vs.* 38 N·m) and HIC values (≤1000 at 1.0 m *vs.* 1.4 m) were also significantly greater for the warm surface.

Table 3 provides the results of ground contact parameters during the landing and first step of the acceleration on each surface. At landing, there were no significant differences in the contact time or horizontal velocity between conditions, however both the contact time ($p = 0.002$; $g = −0.58$) and the length ($p = 0.008$; $g = −0.47$) of the first step were significantly higher on the warmer artificial turf. Table 3 also provides the discrete angles at touchdown, peak joint flexion angle and take-off during the first step. Knee angular kinematics demonstrated significant differences at touchdown, take-off, and peak knee flexion between the conditions ($p < 0.01$). Significantly higher hip touchdown angle was also evident on the warm surface ($p = 0.004$), with non-significant differences at the hip later in the movement showing a small effect (e.g., peak hip flexion, $g = −0.41$).

Table 3 provides the mean ± SD of the range of motion (ROM) from touchdown to peak flexion and peak flexion to take-off during the landing stance (first contact after the hurdle). Although 5 of the 6 joint ROMs were higher on the warm surface, only ankle ROM from peak dorsiflexion to take-off showed a significant change between the surfaces, itself accompanied by a small effect size (cold: 32.3° ± 9.4°; warm: 35.9° ± 7.8°; $p = 0.04$; $g = −0.36$). Additionally, peak dorsiflexion and peak hip extension angular velocities were both significantly higher on the warm turf ($p = 0.02$, $p = 0.01$, respectively). The ankle underwent dorsiflexion after touchdown, followed by extension from 50% of stance to take-off; a pattern consistent in both conditions. The knee elicited a significantly more flexed position at touchdown on the cold surface (131.0° ± 13.8°) than the warm surface (149.4° ± 12.8°). Peak flexion and take-off knee angles also significantly differed between the cold and warm surfaces. On both surfaces, the hip underwent extension after touchdown, followed by a period of flexion between ~20% and ~60% of stance and extension to

Table 3
Landing stance kinematics and joint kinematics for the 2 surfaces (mean ± SD).

Kinematic parameter	Cold	Warm	p value	Effect size (g)
Landing stance kinematics				
Contact time$_{Landing}$ (s)	0.27 ± 0.05	0.26 ± 0.04	0.33	0.19
Horizontal velocity$_{Landing}$ (m/s)	3.94 ± 0.38	3.91 ± 0.34	0.67	0.07
Contact time$_{1st step}$ (s)	0.19 ± 0.03	0.21 ± 0.03	<0.01*	−0.58
Step length$_{1st step}$ (m)	0.98 ± 0.12	1.05 ± 0.14	0.01*	−0.47
Landing stance joint kinematics				
Touchdown ankle (°)	116.2 ± 8.6	117.1 ± 8.3	0.37	−0.09
Touchdown knee (°)	131.0 ± 13.8	149.4 ± 12.8	<0.01*	−1.20
Touchdown hip (°)	152.3 ± 10.2	157.5 ± 8.4	<0.01*	−0.48
Peak ankle dorsiflexion (°)	73.0 ± 7.1	72.5 ± 8.4	0.69	0.06
Peak knee flexion (°)	118.8 ± 11.3	134.4 ± 8.9	<0.01*	−1.33
Peak hip flexion (°)	145.9 ± 7.5	150.1 ± 10.0	0.05	−0.41
Take-off ankle (°)	105.3 ± 10.5	108.4 ± 10.8	0.08	−0.25
Take-off knee (°)	145.2 ± 13.8	160.5 ± 6.5	<0.01*	−1.23
Take-off hip (°)	172.0 ± 9.1	174.7 ± 13.0	0.10	−0.21
Touchdown to peak dorsiflexion ankle ROM (°)	43.2 ± 9.6	44.6 ± 13.6	0.39	−0.10
Touchdown to peak flexion knee ROM (°)	12.2 ± 7.4	15.0 ± 8.7	0.07	−0.30
Touchdown to peak flexion hip ROM (°)	6.4 ± 7.8	7.5 ± 10.1	0.34	−0.11
Peak dorsiflexion to take-off ankle ROM (°)	32.3 ± 9.4	35.9 ± 7.8	0.04*	−0.36
Peak flexion to take-off knee ROM (°)	26.4 ± 8.8	26.1 ± 9.4	0.83	0.03
Peak flexion to take-off hip ROM (°)	26.1 ± 8.0	24.7 ± 8.7	0.37	0.15
Peak ankle dorsiflexion angular velocity (°/s)	900.5 ± 202.3	977.3 ± 296.7	0.02*	−0.26
Peak ankle plantar flexion angular velocity (°/s)	−697.4 ± 144.2	−735.8 ± 143.2	0.20	0.23
Peak knee flexion angular velocity (°/s)	−298.6 ± 112.4	−348.3 ± 151.2	0.05	0.32
Peak knee extension angular velocity (°/s)	370.9 ± 101.9	356.6 ± 109.7	0.41	0.12
Peak hip flexion angular velocity (°/s)	−225.8 ± 97.3	−253.5 ± 97.1	0.19	0.25
Peak hip extension angular velocity (°/s)	417.0 ± 97.3	472.8 ± 165.1	0.01*	−0.36

* Significant difference between surfaces ($p < 0.05$).
Abbreviation: ROM = range of motion.

take-off. Peak hip extension velocity occurred shortly after touchdown and was significantly greater on the warm surface.

4. Discussion

Previous studies have revealed that environmental characteristics can influence the mechanical properties of artificial turf and, consequently, the movement characteristics and energetics of athletes.[18,19] The aims of this study were to determine the effect of surface temperature on artificial turf mechanical properties and to investigate how these mechanical differences affect kinematics in a turf-sport related movement.

The temperature difference between the 2 surfaces ranged between 12.1°C and 13.4°C, a factor which resulted in significantly different mechanical properties with some large effect sizes (Table 2). Despite these differences, all the properties of the cold surface would have passed the governing body regulations except force absorption (47.6% ± 2.4%; Table 2). The standards require force absorption of 55%–70% for FIFA One Star, 60%–70% for FIFA Two Star,[7] and 60%–75% for IRB certification.[6] Importantly, the artificial surface had passed all standards previously and had been approved on the day of testing. This highlights a key problem: the standards are tested under "good" climatic conditions, but the surfaces are used in a variety of conditions. The present study has shown that changes in climatic conditions, such as surface temperature, have an influence on the surface's characteristics. Unfortunately, those responsible for deciding if a pitch is suitable for play do not have access to the mechanical testing equipment when evaluating a turf. It would be unfeasible for sports governing bodies to provide all artificial turf users with this equipment (e.g., AAA). Consequently, it appears necessary to further investigate the effect of temperature on surface characteristics in order to improve best practices for users of artificial surfaces. The stiffness of the surfaces was of particular interest, given that previous studies reported that surface stiffness influences performance and technique parameters (e.g., contact time and step length[18]). The significantly "harder" cold surface (lower force absorption and vertical deformation) would be considered a stiffer surface.

Following the identification of the mechanical differences between the surfaces, this study provided an exploratory investigation into the influence those differences had on the performance of an acceleration following landing; a common dynamic movement performed in turf-sports. The results of the present study (Table 3) concur with McMahon and Greene;[18] increased contact time (first stance) and step length were exhibited on the warm surface, with its significantly higher force absorption and vertical deformation (lower stiffness). The results indicated that the surface differences did not affect the contact time during the high impact landing contact, but the first stance contact time was significantly longer on the warm surface. The degree to which this would influence player performance cannot be specified from this study, but the differences in the kinematic parameters indicate an effect.

The initial acceleration phase is crucial in field sports, for example, during a counter attack or when avoiding a tackle. On an individual athlete basis, a significantly longer step on 1 surface versus another will improve acceleration (providing the step is not excessively long[27,28]). The movement analysed in the present study was a complex and realistic sporting movement; the players had to absorb the impact of landing from the hurdle jump before accelerating over 5 m. A significant difference found in the present study was a longer first step on the warm surface (Table 3). Whilst there were no significant differences for the horizontal hip velocity and contact time during the landing, the longer step length may be indicative of an improved initial acceleration phase in the warm condition. Future studies should investigate the influence that different surface characteristics have on the subsequent steps during these rapid acceleration movements.

There was a tendency by the participants to show an increased ROM during the landing stance on the warm surface, although only 1 ROM significantly differed (Table 3). Murphy et al.[28] found that in addition to decreased contact times, faster athletes had a decreased ROM at the knee than slower athletes. Therefore, these ROM results may indicate that actually the cold surface was more conducive to faster initial accelerations. Further, it is possible that the increased step length in the warm condition was a cumulative product of the small ROM differences. In contrast, Kerdok et al.[19] found that athletes increased their leg stiffness (decreasing ROM) in response to decreasing surface stiffness. With ROM directly related to lower limb stiffness,[21] future work could extend the current findings by directly investigating the relationship between surface mechanics and lower extremity stiffness during sporting movements.

The angles of the lower limb joints during the landing stance exhibited some significant differences between the surfaces, with a more flexed position evident on the cold surface. At the knee, in particular, participants exhibited significantly greater flexion at touchdown, peak flexion, and take-off. The established associations between hip and knee kinematics and anterior cruciate ligament injury risk[29] support the further investigation of the significant and the small but non-significant differences evident in the present study. When considering the angular velocities, peak ankle dorsiflexion and peak hip extension velocities were significantly higher on the warm surface, perhaps indicative of a better performance. Specifically, the ankle exhibited a higher dorsiflexion angular velocity during the first 10% of stance (weight acceptance), whilst the hip extended with a greater angular velocity at touchdown.

This study used tests of mechanical properties accredited by international sports governing bodies and kinematic analyses to compare 2 identical artificial turfs with different surface temperatures. The differences between surfaces identified in this study highlight a need for stakeholders to consider how climatic factors influence the mechanical and biomechanical responses of artificial turf. A direct comparison between turf mechanical properties and biomechanics would enhance understanding of how well mechanical testing reflects athletes' movements on the turf. Subsequently, biomechanical testing could be integrated into the surface testing process, providing a direct measure of how the surface affects athletes' performance as opposed to inferring this information from mechanical property testing. The small sample size ($n = 4$) in this study limits the generalised

ability of these findings, whilst the analysis is limited to the sagittal plane. However, the purpose was to explore the effect of surface temperature on mechanical properties and athletes' kinematics when they are performing a turf-sport related movement on the surfaces. The findings support a need for further, more in-depth and substantial studies of artificial surface conditions.

5. Conclusion

This study found that surface temperature influenced the mechanical properties of artificial turf. Specifically, the cold surface (1.8°C–2.4°C) condition in this study produced a significantly "harder", stiffer surface. The disparate mechanical properties in the 2 surface conditions appeared to yield biomechanical differences, whereby longer step lengths, a more extended knee posture, and higher ankle and hip angular velocities were recorded on the warm surface (14.5°C–15.2°C). These results indicate that a change in an artificial turf's mechanical properties can affect an athlete's landing and acceleration mechanics. This will have substantial performance and injury implications for players either playing or training on artificial surfaces in cold climatic conditions. For example, a player consistently playing or training on a harder, colder artificial surface may be exposed to different demands than a player on a softer, warmer surface. Such inconsistencies may bring the integrity of artificial surfaces under question. Consequently, these findings should be used to inform turf users, manufacturers, and researchers investigating the suitability of artificial surfaces for cold conditions.

Authors' contributions

LC and HLW carried out the study data collection and analysis and drafted the manuscript; GI and WP participated in the study design and coordination and revised the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

None of the authors declare competing financial interests.

References

1. Fleming P. Artificial turf systems for sports surfaces: current knowledge and research needs. *Proc Inst Mech Eng Part P: J Sports Eng Technol* 2011;**225**:43–64.
2. Andersson H, Ekblom B, Krustrup P. Elite football on artificial turf versus natural grass: movement patterns, technical standards, and player impressions. *J Sports Sci* 2008;**26**:113–22.
3. Ekstrand J, Timpka T, Hagglund M. Risk of injury in elite football played on artificial turf versus natural grass: a prospective two-cohort study. *Br J Sports Med* 2006;**40**:975–80.
4. Fuller CW, Dick RW, 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 Sports Med* 2007;**41**(Suppl. 1):i20–6.
5. Steffen K, Andersen TE, Bahr R. Risk of injury on artificial turf and natural grass in young female footballers. *Br J Sports Med* 2007;**41**(Suppl. 1):i33–7.
6. World Rugby. Regulation 22, standard relating to the use of artificial rugby turf. Available at: http://playerwelfare.worldrugby.org/?documentid=57; 2008 [accessed 20.10.2013].

7. Federation Internationale de Football Association (FIFA). Quality concept for football turf. Available at: http://www.fifa.com/mm/document/af developing/pitchequip/fqc_football_turf_folder_342.pdf; 2009 [accessed 20.10.2013].
8. Meijer K, Dethmers J, Savelberg HCM, Willems P, Wijers B. The influence of third generation artificial soccer turf characteristics on ground reaction forces during running. *Proceedings of the 24th Symposium of the International Society of Biomechanics in Sports*. Salzberg, Austria. July 14–18; 2006.
9. Nigg BM, Yeadon MR. Biomechanical aspects of playing surfaces. *J Sports Sci* 1987;**5**:117–45.
10. Nigg BM. The validity and relevance of tests used for the assessment of sports surfaces. *Med Sci Sports Exerc* 1990;**22**:131–9.
11. Dixon SJ, Batt ME, Collop AC. Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects. *Int J Sports Med* 1999;**20**:209–18.
12. Williams CF, Pulley GE. Synthetic surface heat studies, Brigham Young University. Available at: http://cahe.nmsu.edu/programs/turf/documents/brigham-young-study.pdf; 2003 [accessed 20.11.2013].
13. Torg JS, Stilwell G, Rogers K. The effect of ambient temperature on the shoe-surface interface release coefficient. *Am J Sports Med* 1996;**24**:79–82.
14. Potthast W, Verhelst R, Hughes M, Stone K, De Clercq D. Football-specific evaluation of player–surface interaction on different football turf systems. *Sports Tech* 2010;**3**:5–12.
15. Pedroza A, Fernandez S, Heidt RJ, Kaeding C. Evaluation of the shoe–surface interaction using an agility maneuver. *Med Sci Sports Exerc* 2010;**42**:1754–9.
16. Stiles VH, Dixon SJ, Guisasola IN, James IT. Biomechanical response to variations in natural turf surfaces during running and turning. *J Appl Biomech* 2011;**27**:54–63.
17. Dura JV, Hoyoa JV, Martinez A, Lozano L. The influence of friction on sports surfaces in turning movements. *Sports Eng* 1999;**2**:97–102.
18. McMahon TA, Greene PR. The influence of track compliance on running. *J Biomech* 1979;**12**:893–904.
19. Kerdok AE, Biewener AA, McMahon TA, Weyand PG, Herr HM. Energetics and mechanics of human running on surfaces of different stiffnesses. *J Appl Physiol* 2002;**92**:469–78.
20. Stafilidis S, Arampatzis A. Muscle-tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci* 2007;**25**:1035–46.
21. Farley CT, Houdijk HH, Strien CV, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol* 1998;**85**:1044–55.
22. Ferris DP, Liang K, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. *J Biomech* 1999;**32**:787–94.
23. Dixon SJ, Collop AC, Batt ME. Compensatory adjustments in lower extremity kinematics in response to a reduced cushioning of the impact interface in heel–toe running. *Sports Eng* 2005;**8**:47–55.
24. Bezodis IN, Thomson A, Gittoes MJR, Kerwin DG. Identification of instants of touchdown and take-off in sprint running using an automated motion analysis system. *Proceedings of the 25th Symposium of the International Society of Biomechanics in Sports*. Ouro Preto, Brazil. August 23–27, 2007.
25. Winter DA. *Biomechanics and motor control of human movement*. 4th ed. Hoboken, NJ: John Wiley and Sons Inc.; 2009.
26. Ast S, Kogel J, Reh J, Lieres und Wilkau HC, Charalambous L, Irwin G. Identification of touchdown and toe-off in turf-sport specific movements using kinematic data. *Proceedings of the 31th Symposium of the International Society of Biomechanics in Sports*. Taipei, China. July 7–11, 2013.
27. Hunter JP, Marshall RN, McNair PJ. Interaction of step length and step rate during sprint running. *Med Sci Sports Exerc* 2004;**36**:261–71.
28. Murphy AJ, Lockie RG, Coutts AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sports Sci Med* 2003;**2**:144–50.
29. Hewitt TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations–update 2010. *N Am J Sports Phys Ther* 2010;**5**:234–51.