



Comparison of player perceptions to mechanical measurements of third generation synthetic turf football surfaces

David Cole¹ · Paul Fleming² · Jon Roberts¹ · David James³ · Mickael Benetti⁴ · Katharina Wistel⁴ · Johsan Billingham⁴ · Steph Forrester¹

Accepted: 23 December 2022 / Published online: 15 January 2023
© The Author(s) 2023

Abstract

Mechanical testing of synthetic turf football surfaces is considered essential to ensure player performance and safety. However, it remains unknown how well the mechanical outputs reflect player perceptions of these surfaces. The first objective of this study was to investigate the agreement between the outputs from the Rotational Traction Tester and the Advanced Artificial Athlete with player perceptions across a range of controlled third generation turf football surfaces. The second objective was to identify the modifications to the Rotational Traction Tester and the Advanced Artificial Athlete configurations and output variables that give the strongest agreement with player perceptions. An indoor test area containing ten third generation turf surfaces with controlled hardness and traction properties was constructed. Each surface was tested using the Advanced Artificial Athlete and Rotational Traction Tester in their current configuration and in several modified configurations aimed at better replicating the player–surface interaction. Using a trained panel paired comparisons technique, 18 University footballers (11 males and 7 females) identified differences in the surfaces based on four sensory attributes *Movement Speed*, *Slip*, *Leg Shock* and *Give*. Results indicated strong agreement (correlation coefficients between 0.7 and 1.0) across several Rotational Traction Tester and Advanced Artificial Athlete testing configurations and output variables with player perceptions. It is recommended that the current Rotational Traction Tester is improved through added instrumentation to allow surface stiffness to be evaluated (the rate of generation of traction resistance). It is further recommended that the Advanced Artificial Athlete adopts a new algorithm to improve the accuracy of the surface's Vertical Deformation and Energy Restitution, and the number of drops is reduced from three to one.

Keywords Artificial turf · Perception · Traction · Hardness · Trained panel · Paired comparisons

This article is a part of Topical Collection in Sports Engineering on Football Research, edited by Dr. Marcus Dunn, Mr. Johsan Billingham, Prof. Paul Fleming, Prof. John Eric Goff and Prof. Sam Robertson.

✉ Steph Forrester
s.forrester@lboro.ac.uk

- ¹ Sports Technology Institute, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK
- ² School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, UK
- ³ Labosport UK, Unit 3 Aerial Way, Hucknall, Nottingham NG15 6DW, UK
- ⁴ Football Technology Innovation Subdivision, Fédération Internationale de Football Association (FIFA), Zurich, Switzerland

1 Introduction

Third generation synthetic turf (3G turf) pitches are widely used as an alternative to natural grass in sports such as football and rugby due to their resistance to weather and ability to sustain more intensive use [1]. To ensure these surfaces meet the performance and safety requirements of players, governing bodies such as Fédération Internationale de Football Association (FIFA) and World Rugby have developed a quality programme to assess surface properties through both laboratory and field testing [1, 2]. These tests aim to generate discrete and repeatable measurements to compare against the required standards for player–surface and ball–surface interactions [3, 4]. Player–surface interaction is assessed using the Rotational Traction Tester (RTT, Fig. 1a) and the Advanced Artificial Athlete (AAA, Fig. 1b) [3]. With the aim of quantifying surface traction,

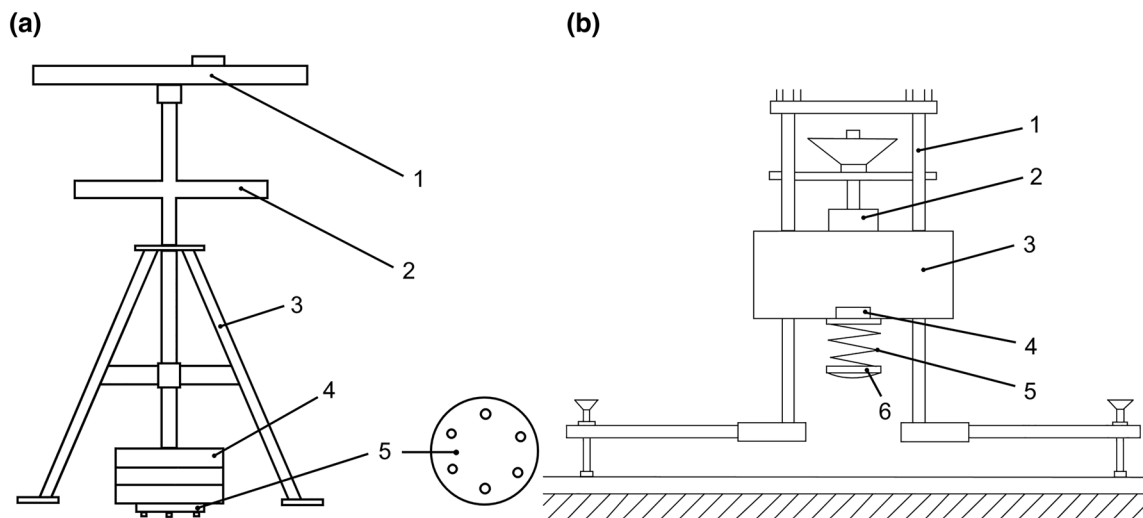


Fig. 1 **a** Rotational Traction Tester (RTT) used to measure surface traction [3]. (1) Torque wrench. (2) Lifting handles. (3) Tripod frame. (4) Weights. (5) Six studded test foot. **b** Advanced Artificial Athlete

(AAA) used to measure surface hardness [3]. (1) Support frame. (2) Electromagnet. (3) 20 kg falling mass. (4) Accelerometer. (5) Linear stiffness spring. (6) 70 mm diameter test foot

the RTT outputs Peak Torque from a rotational interaction between a weighted studded test foot and the surface [3]. To measure surface hardness, the AAA utilises a spring-mass system in a drop test configuration to measure the acceleration throughout impact, from which Shock Absorption, surface Vertical Deformation and Energy Resitution are determined [3].

Despite their widespread use in the pass/fail certification of football surfaces, how well the RTT and AAA reflect the player experience of a surface has been questioned [5–7]. The AAA produces a short dynamic impact curve of < 50 ms, with a measured peak force in the range 2–3 kN to pass the FIFA standard requirements [3, 8, 9]. In contrast, during running on 3G turf a typical foot-strike peaks at around 1–2 kN and lasts about 250 ms [10–12]. Vertical forces of 3 kN have, however, been recorded underfoot during landing from a simulated header [13]. Furthermore, the AAA test foot generally resembles the shape and area of the human heel [3], in contrast to peak player contact forces which typically occur with the whole- or fore-foot in contact with the surface [10–12, 14].

Greater disparity can be found between the RTT and player-surface biomechanical data during cutting and turning movements. The weighted studded test foot generates a vertical force of 0.45 kN and pressure of 26 kPa throughout the $\geq 45^\circ$ rotation [3]. During cutting and turning, players can exert vertical forces of up to 3 kN and peak pressures of up to 500 kPa [15–17]. Furthermore, the planted foot typically rotates less than 10–15° during the turn [13, 18]. Finally, clear differences in design can be observed between the circular six-studded test foot and the studded boot outsoles typically used on 3G turf [16].

Researchers have sought to address some of these concerns through creation of their own devices with an increased emphasis on biofidelity [19–25]. Whilst these devices have increased validity in terms of the player-surface interaction mechanics, little research has been conducted to assess whether the resulting measurements relate to players perceptions of the surfaces. Furthermore, their size and mass leads to questions over portability and, therefore, their practicality for use in surface standards testing, while their reproducibility has yet to be demonstrated.

Data related to players' perceptions of football surfaces has often focused upon broad differences between natural and 3G turf pitches or perceived injury risk [26–28]. Little research is available regarding how players perceive specific surface properties under-foot [29]. To address this, a recent study identified the language typically used by players to describe their sensory feelings when interacting with football surfaces and demonstrated the ability of players to reliably detect sensory differences across a range of controlled 3G turf surfaces [30]. This study using a trained panel approach, where each player initially underwent training to distinguish and evaluate perceived surface properties. In addition, the surfaces were presented to each player as paired comparisons, where they had to select which of the two surfaces had 'more' of the sensory attribute of interest.

Following on from the development of a reliable methodology to assess player perceptions of 3G turf surfaces [30], the first objective of this study was to investigate the agreement between the outputs from the RTT and AAA player-surface interaction tests (standard configuration [3] and modified to improve biofidelity) and player perceptions across various rubber crumb (SBR) infilled 3G turfs with

differing surface properties. The second objective was to identify the RTT and AAA test configurations and output variables that provided the strongest agreement with player perceptions of the surfaces.

2 Methods

2.1 Surfaces

Ten 3G turf surfaces were constructed in an indoor testing area to ensure surface properties were controlled and not influenced by environmental conditions [30]. Five of these surfaces were designed to explore the agreement between outputs from the RTT and player perception and the remaining five to explore the agreement between outputs from the AAA and player perception. The surfaces were laid in two rows of five lanes, each 5×1.2 m, banked by 3G turf run-offs (Fig. 2). Each surface was constructed to produce specific Shock Absorption and Peak Torque values based on RTT and AAA testing using the current configurations and test protocols [3]. The five surfaces used for the AAA assessment were constructed to produce various Shock Absorptions whilst maintaining a consistent Peak Torque (H1–H5, Table 1), and the five surfaces used for the RTT assessment were constructed to produce various Peak Torques whilst maintaining a consistent Shock Absorption (T1–T5, Table 1). Visual differences between surfaces, which may have influenced player perceptions, were minimised by using rubber crumb infill throughout and maintaining a consistent free pile height.

Key requirements for the surface creation process included: to create surfaces with carefully controlled differences in Shock Absorption, Vertical Deformation (AAA assessment surfaces) and Peak Torque (RTT assessment surfaces) (Table 1); to ensure minimal visual differences between surfaces to avoid player biases; and to maximise

the range of values relative to the FIFA Quality bounds (Table 1). Whilst the first two of these were achieved, this required some compromise with respect to the FIFA Quality lower bound for Shock Absorption (lowest 62%), Vertical Deformation (lowest 8.1 mm) and Peak Torque (lowest 36 Nm).

2.2 Mechanical devices modifications

In addition to testing the surfaces using the current RTT and AAA configurations [3], the devices were modified to investigate the effects of different interaction characteristics considered to be more aligned with player-surface biomechanical data.

For the RTT, in addition to the standard 46 kg, normal loads corresponding to 66 and 34.6 kg were also investigated. The 66 kg condition was chosen to better represent the upper player vertical loads observed during cutting and turning [15–17] whilst maintaining the usability of this manual test device. The 34.6 kg condition was closer to lower vertical loads observed during the final push-off phase where most foot rotation occurs [18]. A second test foot with a different design was also investigated; this had the same diameter but consisted of many rubber dimples rather than six studs [31]. When using the standard six studded test foot on 3G turf, Peak Torque is observed to occur as each stud reaches the path of the preceding stud [32]. The purpose of the dimpled test foot was to investigate the development of traction forces without stud overlap mechanics affecting the outcome. To investigate the interaction resistance throughout the rotation, instrumentation was fitted to the RTT to record the full torque–angle profile (Fig. 3a). This allowed for the calculation of surface stiffness [32], and for a data quality check on the operator's rotational speed during the test [3]. The instrumentation consisted of a strain gauge torque sensor, calibrated using a digital torque calibration analyser to a resolution of 0.01 Nm and accuracy of ± 0.10 Nm, and

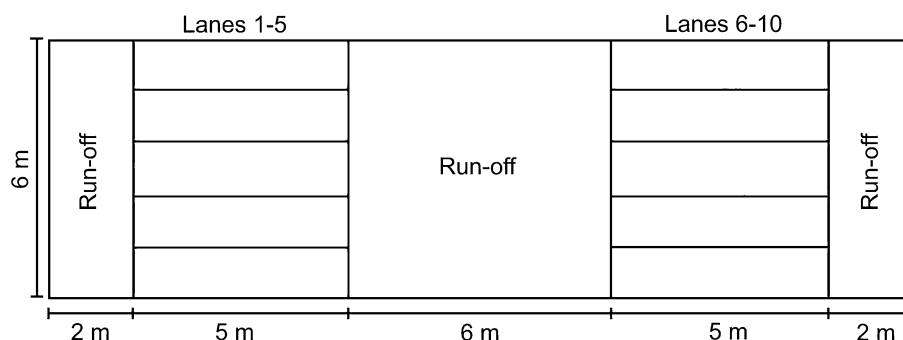


Fig. 2 Layout of the ten lane indoor surface testing area used for player perception and mechanical assessments of the surfaces [30]. Five of the surfaces were designed to explore the agreement between

outputs from the RTT and player perception and the remaining five to explore the agreement between the AAA and player perception. The organisation of the surfaces across lanes was randomised

Table 1 Surface construction details and mechanical test properties for each lane obtained from testing using the RTT and AAA and the current FIFA standards [3]

Surface ID	Shockpad	Carpet	Stabilising infill (2EW sand) (kg/m ²)	Performance infill (SBR)		Total infill Depth (mm)	AAA		RTT Peak torque (N·m)
				Size (mm)	(kg/m ²)		SA (%)	VD (mm)	
AAA assessment surfaces									
H1	Schmitz Pro-Play Sport 20	50 mm Tiger-Turf	17	0.8–2.5	12	33.3 (1.1)	71.0 (0.7)	10.7 (0.3)	47.1 (1.7)
H2	Trocellen	50 mm Tiger-Turf	17	0.8–2.5	12	31.9 (1.3)	68.9 (0.3)	10.2 (0.1)	45.8 (1.7)
H3	Alveo (1 layer)	60 mm Tiger-Turf	15	2.0–4.0	15	37.4 (1.2)	69.8 (0.4)	11.1 (0.2)	42.3 (1.4)
H4	Schmitz ProPlay Sport 15/215	50 mm Tiger-Turf	17	0.8–2.5	12	32.4 (1.4)	61.6 (0.9)	8.1 (0.2)	48.2 (1.3)
H5	Alveo (2 layers)	50 mm Tiger-Turf	17	0.8–2.5	12	33.1 (1.4)	74.7 (0.7)	12.6 (0.5)	46.1 (1.6)
RTT assessment surfaces									
T1	Alveo (2 layers)	60 mm SIS	15	2.0–4.0	15	40.1 (1.7)	76.1 (0.6)	13.2 (0.4)	35.7 (1.3)
T2	Alveo (2 layers)	60 mm Tiger-Turf	15	2.0–4.0	15	40.0 (1.4)	76.9 (0.5)	13.4 (0.3)	39.9 (1.6)
T3	Rigid MDF board	60 mm SIS	15	0.8–2.5	15	39.6 (1.1)	66.3 (0.5)	9.3 (0.2)	47.2 (1.7)
T4	Alveo (2 layers)	60 mm Tiger-Turf	15	0.8–2.5	15	37.3 (1.5)	77.2 (0.3)	13.2 (0.2)	52.7 (1.5)
T5	Alveo (2 layers)	50 mm Tiger-Turf	17	0.8–2.5	12	33.6 (1.3)	75.8 (0.6)	12.6 (0.3)	47.0 (1.5)
Run-offs	Alveo (2 layers)	60 mm Tiger-Turf	0	0.8–2.5	17	40.0 (1.9)	76.0 (0.8)	9.9 (0.4)	41.3 (1.9)
FIFA Quality [3]							55–70	4–11	25–50
FIFA Quality Pro [3]							60–70	4–10	30–45

The mean (standard deviation) is from the five test locations for the RTT and AAA and from 10 infill depth measurements on each surface. The field test requirements for FIFA Quality and Quality Pro surfaces are provided for comparison. Adapted from [30]

SA Shock Absorption, VD Vertical Deformation

a Hall effect rotational potentiometer, calibrated following the manufacturer's specifications, to a resolution of 0.5° and accuracy of ±1.0°. The torque and angle data were sampled at 250 Hz and filtered using a second order low-pass Butterworth filter, cut-off frequency 20 Hz. Two stiffness regions were investigated, an initial region of higher stiffness (2.5–15% of Peak Torque) and a secondary region of lower stiffness (50–80% of Peak Torque), calculated as the gradient of the line of best fit to the torque–angle data within that region (Fig. 3b).

For the AAA, the first modification was to increase drop height from 55 to 70 mm, increasing contact time, impact force and impact energy. Although the contact time was not expected to reach the 250 ms associated with running, and the forces and loading rates would be further increased

above those typical of running [10–12], they would better match those from a jump landing [13]. The second modification was to increase the test foot diameter from 70 to 110 mm, providing a closer match to a typical human fore-foot area [14]. The new test foot was manufactured from a solid nylon rod 110 mm in diameter and cut to 60 mm in length (Nylon 6, RS-PRO, density 1.15 kg·m⁻³, compressive modulus 2700 MPa). One end was machined to give a radius of curvature designed to maintain the same height differential between the centre and edge of the foot as the current FIFA standards test foot [3]. The other end was machined to allow attachment to the existing steel test foot via an interference press fit and adhesive tape [8].

A new algorithm to identify the contact phase for the AAA impact was also implemented as previous research

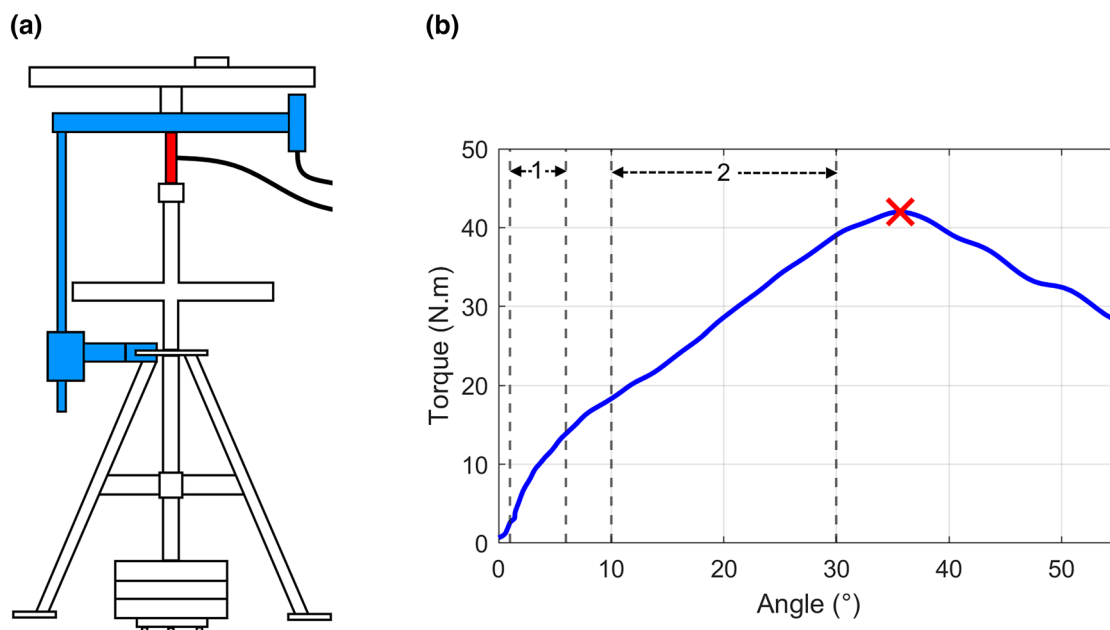


Fig. 3 **a** Rotational Traction Tester with additional digital instrumentation to record torque (red) and angle (blue) throughout the rotation. **b** Example torque–angle profile recorded by the instrumented RTT with the Peak Torque (red X) Initial Stiffness (area 1) and Secondary

Stiffness (area 2) regions highlighted. The stiffness values are determined as the gradient of the line of best fit to the torque–angle data within that region (Colour figure online)

highlighted the current algorithm to under-estimate Vertical Deformation [8]. The new algorithm started by identifying the peak force. It then worked forwards and backwards in the data to locate the points at which the force first dropped below 30 N and, provided the absolute gradient at the point exceeded $10 \text{ kN}\cdot\text{s}^{-1}$, this defined the new initial and final contact times, respectively (Fig. 4a). If the gradient condition was not met, then the algorithm stepped towards the peak force, i.e. forwards for initial contact and backwards for final contact, to find the first time point where the gradient

condition was met to define the initial or final contact time. The time at which first contact occurred was used to set the zero level of surface deformation. The new algorithm also calculated Energy Restitution through determining the area under the force–deformation curve (Fig. 4b).

Surface testing across all ten lanes was completed using the RTT and AAA test devices in their current configuration. Surface testing for every combination of the modifications detailed above was completed for the AAA on all five AAA assessment surfaces and similarly for the RTT on all

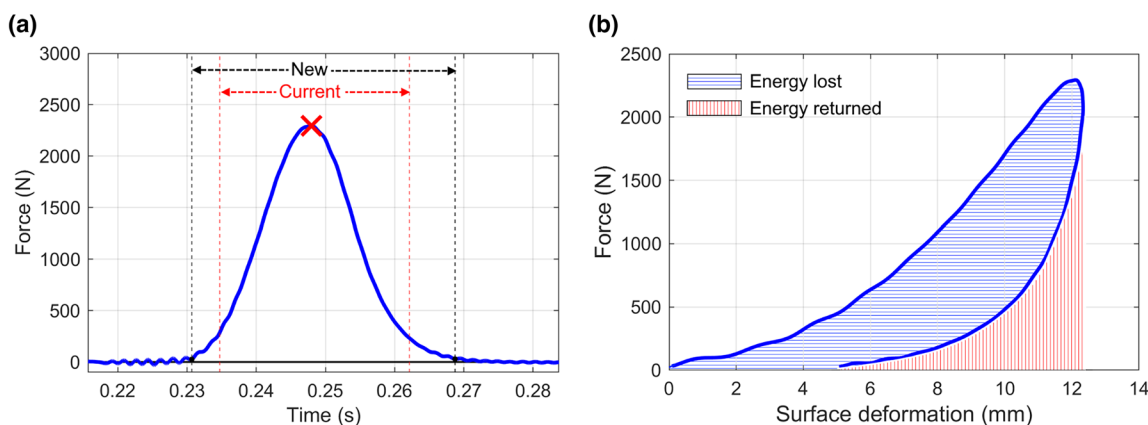


Fig. 4 **a** Example force–time profile from a single AAA impact with peak force (red X), current and new contact periods identified. **b** Example force–deformation profile from an AAA impact illustrating

the new algorithm for calculating Energy Restitution based on calculating the area under the force–deformation loading and unloading curves (Colour figure online)

five RTT assessment surfaces. Testing with the RTT (single test) and AAA (three drops) occurred at five equally spaced locations per lane, none within 200 mm of the lane edge, and followed the test protocol given in the current FIFA standards [3]. For the RTT testing, trials were repeated if the operator's rate of rotation deviated by more than 25% from the FIFA standard target value, i.e. outside 54–90°/s. The outputs from this testing are provided as Supplementary Material (Tables S1–S3).

Each trial was processed using custom scripts in Matlab 2020b (Mathworks Inc, Natick, MA, USA). For each device configuration and output variable, two analyses were performed. Firstly, the five surfaces were ranked from lowest to highest, and secondly, a one-way analysis of variance with Tukey–Kramer post-hoc analysis identified which surface pairs were significantly different ($P < 0.05$).

2.3 Player perception

Eleven male (20 ± 2 years, 74.3 ± 6.1 kg, 180 ± 5 cm) and seven female (20 ± 2 years, 64.6 ± 5.3 kg, 173 ± 10 cm) footballers from the University first and second teams formed the trained panel used to evaluate the properties of the five AAA assessment surfaces and five RTT assessment surfaces (Table 1) [30]. Ethical approval from the University ethics committee was acquired before testing, all players provided written informed consent to participate and indicated that they were currently injury-free. The panel had previously worked with the investigators to develop a common language to describe their sensory assessment of football surfaces and gain familiarisation with the test protocol [30].

Each player completed an individual evaluation session to obtain their sensory responses for the five AAA assessment surfaces and five RTT assessment surfaces. Four sensory attributes were used (Table 2); for attributes related to hardness (AAA assessment) a jump and landing was performed with players asked to identify the sensory response during the landing phase, and for attributes related to grip (traction) (RTT assessment) a 180° stop and turn was performed, with players asked to identify their sensory response during the turning phase.

The evaluation sessions started with a brief warm up followed by a recap of the attributes and movement standards.

For each sensory attribute players performed ten pairwise comparisons which covered every paired combination of the five surfaces relevant to that attribute and with the pairs completed in a randomised order (Table 1). The order in which attributes were tested was also randomised, however, all ten pairs for each attribute were completed before moving onto the next attribute. Players were allowed to repeat movements on a surface as many times as they wished and were given time to rest for a self-determined period between each pair. After completing the movements on a pair of surfaces, the player informed the experimenter which of the two surfaces resulted in more *Leg Shock/Give/Movement Speed/Slip* (dependent on the attribute being tested). After every 2–4 player sessions, the surfaces were reconditioned and retested using the RTT and FieldTester [8] to ensure their properties remained consistent.

The player's response to each paired comparison was recorded in Excel and subsequently processed in Matlab. For each sensory attribute, agreement between players was assessed using Friedmans T statistic, followed by post-hoc analysis using Tukey's honestly significant difference test to identify significant differences between surfaces ($P < 0.05$) and the order in which the five surfaces were ranked.

2.4 Data processing

To assess the agreement between each mechanical variable and player attribute, three assessment criteria were used (Fig. 5, Table 3).

The first criterion assessed the strength of the relationship between the mechanical and perception data using the Spearman's correlation coefficient. Larger absolute correlation coefficients were given higher assessment criterion 1 scores.

The second criterion assessed the number of significant differences between surfaces identified by the players that were also identified by the mechanical variable. The number of surface pairs deemed as significantly different by the players and by the mechanical variable was expressed as a percentage of the total number of surface pairs (i.e. ten for both traction and hardness in this study) and a higher percentage resulted in a higher assessment criterion 2 score. Thus, where an attribute identified several significant differences between surfaces that were also identified by the mechanical

Table 2 Sensory attributes identified by the players and used to measure their perceptions of the test surfaces [30]

Property	Attribute name	Definition	Movement	Instruction
Hardness	Leg Shock	The amount of shock felt in the knees	Jump and landing	Two footed landing with minimal bend in knees
	Give	The amount of deformation felt under foot		
Grip (traction)	Movement Speed	The speed at which turns can be performed at	Stop and turn	Foot planted perpendicular to direction of travel. Accelerate out of the turn
	Slip	The likelihood of slipping whilst turning		

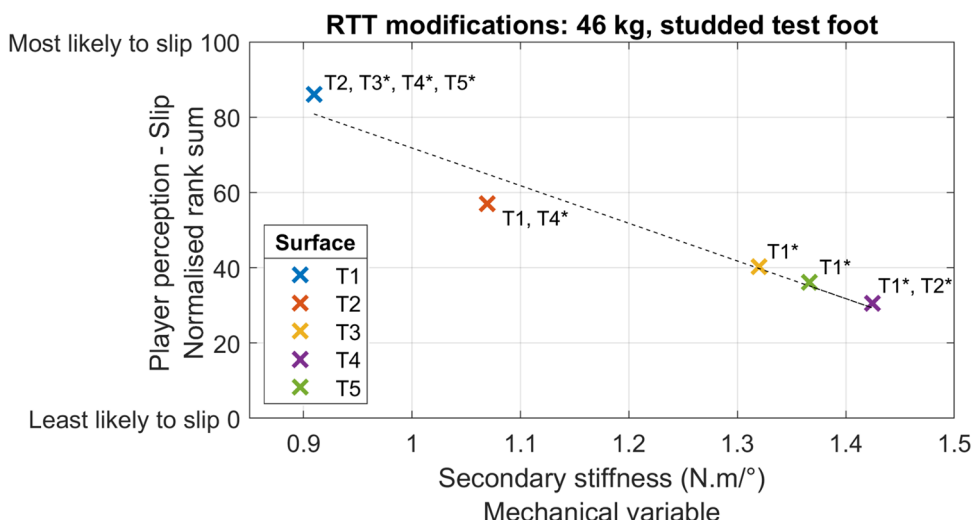


Fig. 5 Example graph displaying the relationship between the mechanical variable (Secondary Stiffness) and player sensory attribute (*Slip*) expressed as the normalised rank sum. The rank sums were normalised on the scale 0–100, where 0 and 100 are the minimum and maximum possible values respectively, i.e. the normalised rank sum removes sensitivity to the number of players or surfaces used in testing. The Spearman’s correlation coefficient for this data was 1.0, resulting in a top score of 4 for assessment criterion 1 (Table 3). Annotations next to surface crosses indicate the surface pairs which

the players identified as being significantly different ($P < 0.05$). An asterisk next to the surface annotation indicates that the mechanical variable was also significantly different ($P < 0.05$). In this example players identified five significantly different pairs in *Slip* (T1–T2, T1–T3, T1–T4, T1–T5, T2–T4) and four of these pairs were also identified as significantly different based on the mechanical variable Secondary Stiffness (T1–T3, T1–T4, T1–T5, T2–T4). This gave a percentage of 40%, i.e. four surface pairs from a maximum of ten surface pairs, and assessment criterion 2 score of 2

Table 3 Scoring thresholds used for each of the assessment criteria to determine the level of agreement between the mechanical variable and player attribute. Different scoring thresholds were used for the RTT and AAA variables in assessment criterion 3, to reflect the differences in repeatability of the two test devices

Score	Assessment criterion 1	Assessment criterion 2	Assessment criterion 3	
	Spearman’s correlation coefficient (absolute)	Number of significantly different pairs identified by players and mechanically (% of maximum)	Measurement repeatability (average standard deviation expressed as % of total range)	
	RTT & AAA	RTT & AAA	RTT	AAA
4	1.00	≥ 80	< 10	
3	0.80–0.99	60–79	10–19.9	< 5
2	0.70–0.79	40–59	20–29.9	5–9.9
1	0.60–0.69	20–39	30–39.9	10–14.9
0	< 0.60	< 20	≥ 40	≥ 15

A score of 4 was not enabled for the AAA assessment criterion 3 due to the high repeatability in the AAA measurements leading to the potential for this criterion to dominate the scoring across all AAA test configurations and variables. The full details of the RTT and AAA design configurations, mechanical variables, sensory attributes and surface pairs that this analysis was applied is provided as Supplementary Material (Table S4)

variable the result was a high score. Conversely, where an attribute identified few significant differences between surfaces, or several significant differences that were not identified by the mechanical variable, the result was a low score.

The third criterion assessed the level of measurement repeatability in the mechanical variable. The mean of the standard deviations from the five individual tests on each

surface, was expressed as a percentage of the overall range in that variable across the five surfaces. A lower percentage indicated higher measurement repeatability (i.e. a greater ability to discriminate between surfaces) and a higher assessment criterion 3 score.

The scores for each assessment criterion were summed to produce an overall score for that mechanical variable,

ranging from 0 to 12 (RTT) or 0 to 11 (AAA). The higher the overall score, the more appropriate the device modification and mechanical output variable combination in terms of level of agreement with player perceptions.

3 Results

3.1 Rotational Traction Tester

Mechanical variables Peak Torque and Secondary Stiffness produced the highest overall scores for *Movement Speed* and *Slip* across all RTT configurations (Fig. 6). For the studded test foot, lower normal loads (lower applied mass) favoured Peak Torque and higher normal loads favoured Secondary Stiffness, supporting the relevance of instrumenting the RTT. Initial Stiffness scored weakly throughout, while the dimpled test foot scored lower than the studded test foot, particularly for *Slip*. There was little to choose between the performance of the two sensory attributes (*Movement Speed* and *Slip*); in combination, the current RTT configuration (46 kg and studded test foot) generated the highest scores for both Peak Torque and Secondary Stiffness (7 and 7, respectively, for *Movement Speed* and 8 and 8, respectively, for *Slip*).

3.2 Advanced Artificial Athlete

Mechanical variable Vertical Deformation generally produced the highest overall scores across most AAA configurations; however, all variables scored highly except for Energy Restitution calculated using the current algorithm (Fig. 7). Changes to the AAA drop height and test foot diameter resulted in consistent systematic changes to the mechanical variables across the five AAA assessment surfaces and, consequently, had little effect on the scores, with no clear improvements over the current configuration, i.e. 55 mm drop height and 70 mm test foot diameter. Notably, for most device configurations there was little difference between using the first drop versus the mean of the second and third drops. Energy Restitution demonstrated the greatest benefit from the new algorithm, with the energy absorbed and returned calculated from the force–deformation curve giving much stronger agreement with both sensory attributes in comparison to the value calculated from the falling mass inbound and outbound velocities [3]. The attribute *Give* consistently generated slightly higher scores than *Leg Shock*, principally due to higher correlation coefficients.

Fig. 6 Overall assessment scores for each mechanical variable and RTT device configuration against **a** *Movement Speed*, and **b** *Slip*. The numbers within each bar indicate the contribution of that assessment criterion to the overall score for that bar. The boxed configuration on the x-axis represents the current FIFA RTT device design [3]. The individual values for each assessment criterion are given as Supplementary Material (Table S5)

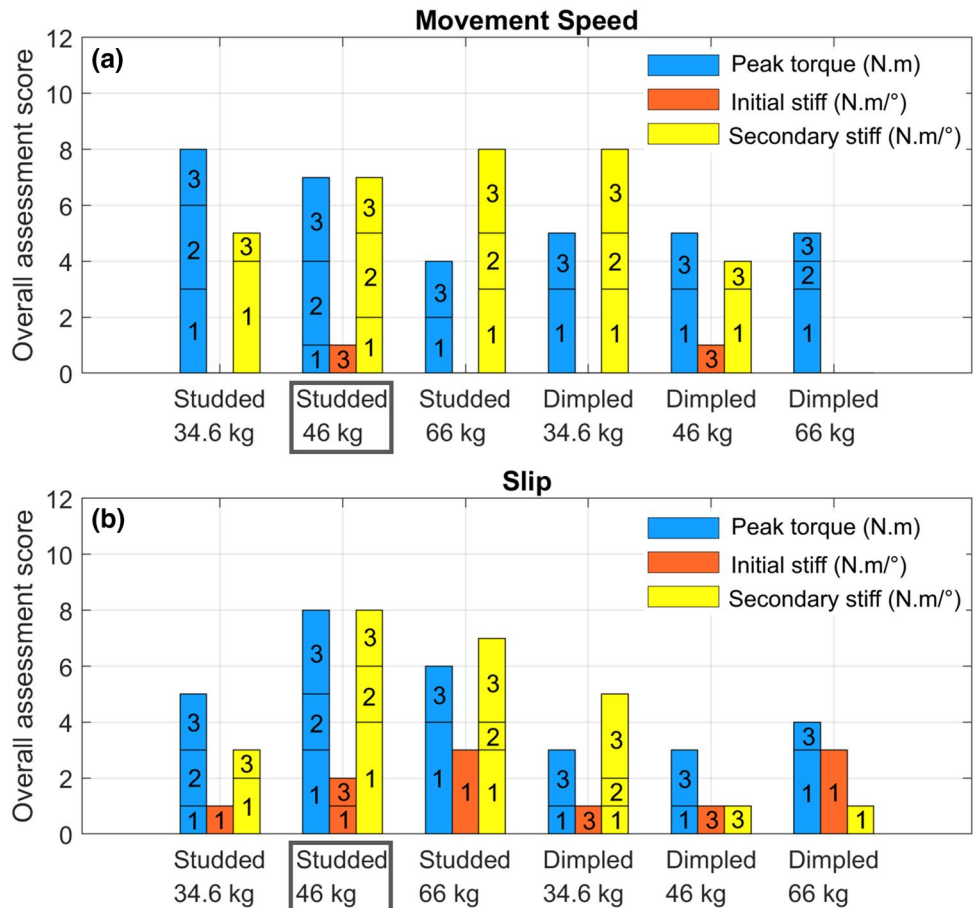
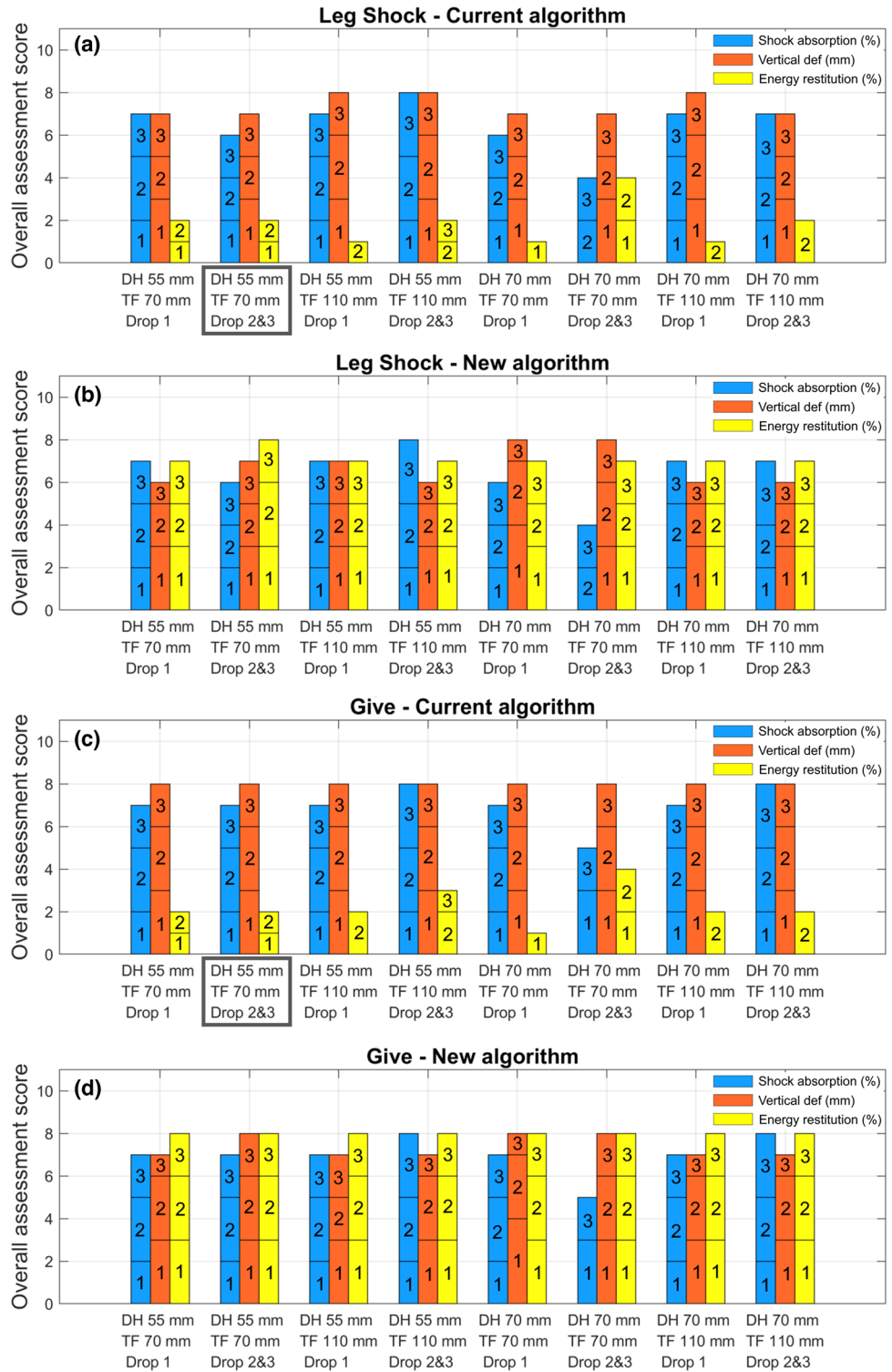


Fig. 7 Overall assessment scores for each mechanical variable and AAA device configuration against **a** *Leg Shock & Current algorithm*, **b** *Leg Shock & New algorithm*, **c** *Give & Current algorithm*, and **d** *Give & New algorithm*. The numbers within each bar indicate the contribution of that assessment criterion to the overall score for that bar. The boxed configuration on the x-axis represents the current FIFA AAA device design [3]. The individual values for each assessment criterion are given as Supplementary Material (Table S6)



4 Discussion

The first objective was to investigate the agreement between mechanical surface performance variables obtained using the RTT and AAA and player perceptions across various 3G turf football surfaces. Overall, there was strong agreement

between several mechanical variables and sensory attributes (Figs. 6, 7) supporting the relevance of the mechanical test devices in the quality assurance process for approving football surfaces. The second objective was to investigate whether changes to the devices, either in test method, hardware or data processing, or all three, could improve on this

agreement. There was evidence to support the inclusion of Secondary Stiffness for the RTT (requiring the addition of a torque transducer and angle potentiometer). There was also evidence for using a new algorithm to calculate Vertical Deformation and Energy Restitution more accurately from the accelerometer data for the AAA, while using only one drop should also be considered.

Changes to the RTT static normal load had little effect on the overall score, but gave differing trends for Peak Torque versus Secondary Stiffness (Fig. 6). During a RTT test there are two main mechanisms contributing to the development of traction forces [33]. The first relates to the interaction between the ploughing studs and performance infill-fibres mix, and the second relates to the interaction between the flat underside of the test foot and the confined carpet layer beneath. For 3G turf surfaces, the stud–infill interaction resistance becomes increasingly important as rotation progresses, representing the dominant contributor to Peak Torque and with stud spacing dictating the angle at which this occurs [33]. Changes to the normal load affects the level of compression in the performance infill beneath the test foot and, therefore, all the contributors to rotational resistance [33]. The difference in trends between Peak Torque and Secondary Stiffness may result from the mechanisms being affected to a differing degree by the changes in normal load, while the lack of overall effect may result from all surfaces showing a similar trend of increasing traction with increased normal load, and vice versa. The poorer performance of the dimpled test foot most likely results from the mechanisms of traction not closely enough representing those in player–surface interactions, notably the lack of a contribution from studs interacting with the performance infill.

The addition of a torque transducer and rotational potentiometer to the RTT allowed for the full torque–angle profile to be captured, and stiffness to be calculated in two regions leading up to Peak Torque (Fig. 3b). Furthermore, this allowed the operator’s rate of rotation to be monitored to ensure this was close to the value specified in the FIFA standard [3]. In this study, 6% of trials were repeated as the rate of rotation deviated by more than 25% from the FIFA standard with all falling below the lower limit of 54°/s. Although the effect of rate of rotation on traction remains unknown, given the strain-rate dependency of polymeric materials in 3G turf [34], having some control over this variable appears beneficial to improve test reproducibility. Further work is required to explore an acceptable range for rate of rotation. Overall, Secondary Stiffness performed equivalently to Peak Torque, typically having a slightly higher correlation coefficient but being slightly less repeatable (Fig. 6). Given that Secondary Stiffness is the gradient of the torque–angle curve from 50 to 80% of Peak Torque, it represents a more direct measure of the resistance forces generated by the studs ploughing through the performance

infill than Peak Torque, as it is not influenced by stud overlap mechanics. This more direct measure of the resistance forces can be advantageous for other types of football surfaces, e.g. natural grass, where Peak Torque may not be triggered by stud overlap [25]. Furthermore, the calculation of stiffness is considered less susceptible to noisy data as it is calculated from the gradient of the line of best fit over a specific portion of the torque–angle curve (Fig. 3) compared to Peak Torque which relies on one point.

Changes to AAA drop height and test foot did not improve overall scores compared to the current configuration. The changes tended to result in systematic differences to the mechanical variables, rarely changing the ranking order of the surfaces and, therefore, having little impact on the correlation coefficients with the sensory attributes. The players appeared to be better at identifying differences between surfaces with respect to the surface deformation, highlighted by the high scores seen between AAA Vertical Deformation and *Give*, and to a lesser extent *Leg Shock* (Fig. 7). Thus, it appears that players were using the amount of deformation sensed under foot, more so than the amount of shock sensed in the knees, when assessing the surfaces’ hardness regardless of attribute.

The new contact algorithm for the AAA, developed to identify the contact phase between the test foot and surface more accurately, affected the values of Vertical Deformation and Energy Restitution. Vertical Deformation using the new algorithm increased in magnitude, more so for more compliant surfaces, thereby increasing the range of values recorded across all the test surfaces and the ability of mechanical testing to differentiate between surfaces. However, the increased accuracy of the new algorithm resulted in a small reduction in test repeatability as the initial and final contact points no longer coincide with easily identifiable maxima and minima in the velocity data during impact [8]. Energy Restitution had the largest increase in scores for the new algorithm. The new algorithm is based on calculating the energy stored and returned from the surface force–deformation curve. This improves on the current algorithm which considers only the inbound and outbound kinetic energy of the falling mass [3] neglecting changes in potential energy of the falling mass and energy stored in the spring rather than the surface (Fig. 1b). Overall, the first drop performed as well as the mean of the second and third drops. While the first drop typically had slightly lower repeatability, the difference was not large enough to change the scores. In this controlled laboratory study, where the test surfaces were regularly reconditioned to ensure consistency, it was expected that the mean of the second and third drops would be more repeatable than the first drop. It is likely that this is partly due to the first drop compacting the surface beneath the test foot, and thereby removing some of the inter-location surface variability, as well as benefitting from being the mean of two

drops. This raises the question as to whether using one drop at each of the 19 field test locations [3] is a better solution where quantifying spatial variability in surface properties is one of the aims of testing, with the additional benefit of greatly reducing the number of tests required per pitch [3].

A key outcome of this study was the strong agreement between several mechanical variables and player perceptions. There are two factors that may have influenced this result. Firstly, to investigate the agreement between the mechanical devices and the players, a level of control over the surfaces and players was needed to reduce the number of confounding variables and provide confidence that the results were an outcome of the differences in behaviour between the surfaces. Testing was conducted in a laboratory environment with care taken to ensure consistency across each surface lane, unlike in the field where areas of low and high usage can result in spatial variability in hardness and traction [34]. Care was taken in the design and creation of the surfaces to control their appearance such that there were minimal visual identifiers that could have influenced a player's decisions; in the field, this level of control is unlikely to be feasible. The use of a laboratory environment also meant climatic factors did not affect the surfaces properties. It is worth noting that the hardness and traction properties of the surfaces were typical of those found in the field (Table 1). Secondly, greater control was placed over the players' preparedness than in previous studies [27, 35]; the trained panel paired comparisons approach involved the players in defining the attributes and movements prior to their assessment of the surfaces [36, 37]. This provided confidence that the differences between surfaces perceived by players were an outcome of sensory feedback and not differences in individual techniques. The use of sensory attributes developed by the trained panel added further confidence to the results, knowing that players rated the surfaces using language they understood, rather than their interpretation of the industry terms of traction and hardness. Furthermore, the players were able to compare laboratory surface pairs immediately; unless two pitches are located next to each other, it is unlikely a similarly immediate stimulus could be achieved in the field. This likely inability to compare surfaces immediately may reduce the level of perceivable differences in the field, with only larger differences between surfaces identifiable. The impact of each of these factors and, therefore, the extent to which the results can be extended to outdoor 3G turf football pitches, remains unknown.

The surface creation requirements meant that no surfaces at the stiffer and low traction ends of the FIFA Quality limits could be included in the study (Table 1). In addition, four of the five RTT assessment surfaces sat above the compliant end of the FIFA Quality limits. However, there was nothing in the results to indicate that the outcomes are not applicable across the full FIFA Quality range. In particular, for

the RTT assessment one of the surfaces was designed to be stiffer than the others and sit within the FIFA Quality limits (surface T3; Table 1); the results from this surface were well aligned with those from the remaining four with no indication that the difference in stiffness affected the players' perception of *Slip* or *Movement Speed*.

The scoring allocation used within the assessment criteria (Table 3) determined the final scores for each device modification and, therefore, the outcomes from this study. The bands used for each assessment criterion were carefully and objectively selected to ensure that, on average, each criterion contributed an equal weighting to the final score. This approach minimised the opportunity for experimenter bias, ensured a wide range of scores, and identified the device modifications that performed best across all three criteria.

While further evidence to support the results of this study is needed, the focus should remain on players with significant on-going experience of different football surfaces and those most likely to be sensitive to boot-surface interactions, thereby avoiding the need for studies with infeasibly large numbers of players. Future work should also explore how well the results from this highly controlled laboratory-based study carry over to outdoor real world football surfaces and the introduction of several confounding factors such as visual appearance of the surfaces and changes in footwear.

This study involved only rubber crumb infilled 3G turf surfaces; how well the results may extrapolate to other football surface types, such as hybrid, natural turf, non-filled and alternative infills, requires further study. However, the proposed additional instrumentation for the RTT and new algorithm for the AAA provides the opportunity for a much more detailed understanding of a surface's response to simulated player loading, both in the laboratory and the field. This has the potential to support the development of future football surfaces to better meet the requirements of players.

5 Conclusions

Strong agreement was observed between surface performance variables obtained using the RTT and AAA and player perceptions across a range of controlled 3G turf surfaces. Modifying the current RTT and AAA test methods demonstrated potential to improve this agreement. For the RTT, this involves adding instrumentation to allow the calculation of Secondary Stiffness and to monitor the operator's rate of rotation. For the AAA, this involves using a new algorithm to process the acceleration data to generate more accurate estimates for Vertical Deformation and Energy Restitution, as well as reducing testing frequency to one drop. Further work to validate these upgrades to the RTT and AAA using outdoor 3G turf football pitches, as well as exploring their applicability to other types of football

surfaces, is planned to provide further evidence to support the findings of this indoor study.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12283-022-00398-x>.

Acknowledgements The authors would like to thank Schmitz B.V., Trocellen, Sekisui Alveo, CCGrass, Tencate Grass, TigerTurf, Aggregate Industries and Murfitts Industries for providing resources to construct the surfaces used in this research.

Funding This research was funded by the Fédération Internationale de Football Association.

Data availability The datasets generated during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest Paul Fleming and Johsan Billingham serve as Guest Editors for the Football Research topical collection in Sports Engineering, neither were involved in the blind peer review process of this paper. Paul Fleming and Steph Forrester serve on the Editorial Board of Sports Engineering. David James is a director of the International Sports Engineering Association. The remaining authors have no conflict of interest.

Research involving human participants and/or animals This study was approved by Loughborough University's Ethics Review Subcommittee.

Informed consent All participants provided voluntary informed consent prior to participating in this study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. FIFA (2021) Member association handbook: FIFA quality programme for football turf. <https://www.fifa.com/technical/football-all-technology/standards/football-turf>. Accessed 24 May 2022
2. World Rugby (2020) Facilities and equipment: artificial surfaces. <https://www.world.rugby/the-game/facilities-equipment/surfaces/performance-specification>. Accessed 14 Dec 2022
3. FIFA (2015) FIFA quality programme for football turf: handbook of test methods. <https://www.fifa.com/technical/football-technology/standards/football-turf>. Accessed 24 May 2022
4. FIFA (2015) FIFA quality concept for football turf: handbook of requirements. <https://www.fifa.com/technical/football-technology/standards/football-turf>. Accessed 24 May 2022
5. Nigg BM (1990) The validity and relevance of tests used for the assessment of sports surfaces. *Med Sci Sport Exerc* 22:131–139
6. Twomey DM, Connell M, Petrass LA (2014) Rotational traction testing: How can we improve the current test device? *Procedia Eng* 72:919–924
7. Dixon SJ, Batt ME, Collop AC (1999) Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects. *Int J Sports Med* 20:209–218. <https://doi.org/10.1055/s-2007-971119>
8. Cole DC, Fleming PR, Morrison KM, Forrester SE (2020) Evaluation of the advanced artificial athlete and hall effect sensors for measuring strain in multi-layer sports surfaces. *SN Appl Sci* 2(3):1–14. <https://doi.org/10.1007/s42452-020-2178-5>
9. Fleming P, Watts C, Gunn J, Forrester S (2020) Hardness safety testing of artificial turf. *MDPI Proc* 49(1):130. <https://doi.org/10.3390/proceedings2020049130>
10. Meijer K, Dethmers J, Savelberg HH, Willems P, Wijers B (2006) The influence of third generation artificial soccer turf characteristics on ground reaction forces during running. *ISBS-Conference Proceedings Archive*
11. Müller C, Sterzing T, Lange J, Milani TL (2010) Comprehensive evaluation of player-surface interaction on artificial soccer turf. *Sport Biomech* 9:193–205. <https://doi.org/10.1080/14763141.2010.511679>
12. Low DC, Dixon SJ (2016) The influence of shock-pad density and footwear cushioning on heel impact and forefoot loading during running and turning movements. *Int J Surf Sci Eng* 10:86–99. <https://doi.org/10.1504/IJSURFSE.2016.075319>
13. El Kati R (2012) Effect of mechanical behaviour of artificial turf on player-surface interaction in soccer. Doctoral Thesis, Loughborough University
14. Mcpoil TG, Vicenzino B, Cornwall MW, Collins N (2009) Can foot anthropometric measurements predict dynamic plantar surface contact area? *J Foot Ankle Res* 2(1):1–9. <https://doi.org/10.1186/1757-1146-2-28>
15. Blackburn S, Brachet P, Nicol AC, Walker C (2003) Player/ground interaction on artificial turf. *Proceedings of the International Society of Biomechanics XIXth Congress*, pp 6–11.
16. McGhie D, Etema G (2013) Biomechanical analysis of surface-athlete impacts on third-generation artificial turf. *Am J Sports Med* 41:177–185
17. Wong P, Chamari K, Mao DW et al (2007) Higher plantar pressure on the medial side in four soccer-related movements. *Br J Sports Med* 41:93–100
18. Driscoll H, Kirk B, Koerger H, Haake S (2012) Influence of outsole design on centre of rotation during turning movements. *Procedia Eng* 34:301306. <https://doi.org/10.1016/j.proeng.2012.04.052>
19. Nunome H, Inoue K, Shinkai H, Kozakai R, Suito H, Ikegami Y (2014) A novel comparison between standard and new testing procedures to assess shock absorbency of third generation artificial turfs. *Sport Eng* 17:103–112. <https://doi.org/10.1007/s12283-013-0146-7>
20. Yukawa H, Ueda T, Kawamura S (2015) Shock attenuation properties and deformation behavior of sports surfaces by two-dimensional impact test. *Procedia Eng* 112:284–289
21. Brachet P, Nicol AC, Walker CA (2003) Mechanical properties of an artificial turf using servo-hydraulic and drop-weight impact testers. *XIXth Congress of the International Society of Biomechanics*
22. McNitt AS, Middour RO, Waddington DV (1997) Development and evaluation of a method to measure traction on Turfgrass surfaces. *J Test Eval* 25:99107
23. Cawley PW, Heidt RS Jr, Scranton PE Jr, Losse GM Jr, Howard ME Jr (2003) Physiologic axial load, frictional resistance, and the football shoe-surface interface. *Foot Ankle Int* 24(7):551556

24. Livesay GA, Reda DR, Nauman EA (2006) Peak torque and rotational stiffness developed at the shoe-surface interface: the effect of shoe type and playing surface. *Am J Sports Med* 34:415–422
25. Villwock MR, Meyer EG, Powell JW, Fouty AJ, Haut RC (2009) Football playing surface and shoe design affect rotational traction. *Am J Sports Med* 37:518–525
26. Strutzenberger G, Edmunds R, Nokes LD, Mitchell ID, Mellalieu SD, Irwin G (2020) Player-surface interactions: perception in elite soccer and rugby players on artificial and natural turf. *Sport Biomech* 21(9):1021–1031. <https://doi.org/10.1080/14763141.2020.1720279>
27. Zanetti EM (2009) Amateur football game on artificial turf: players' perceptions. *Appl Ergon* 40:485–490. <https://doi.org/10.1016/j.apergo.2008.09.007>
28. Roberts JR, Osei-Owusu P, Mears AC, Harland AR (2020) Elite players' perceptions of football playing surfaces: a qualitative study. *Res Q Exerc Sport* 91:239–251. <https://doi.org/10.1080/02701367.2019.1660757>
29. Sánchez-Sánchez J, García-Unanue J, Jiménez-Reyes P, Gallardo A, Burillo P, Felipe JL, Gallardo L (2014) Influence of the mechanical properties of third-generation artificial turf systems on soccer players' physiological and physical performance and their perceptions. *PLoS ONE* 9:27–32. <https://doi.org/10.1371/journal.pone.0111368>
30. Cole D, Forrester S, Fleming P et al (2022) Development and evaluation of a sensory panel for collecting reliable player perceptions of third generation synthetic turf football surfaces. *Sports Engineering*
31. FIH (2017) Hockey turf and field standards. <http://www.fih.ch/media/13414908/fih-hdfs-part-2-hockey-fields.pdf>. Accessed 24 May 2022
32. Webb C, Forrester S, Fleming P (2014) Rotational traction behaviour of artificial turf. *Procedia Engineering* 72:853–858
33. Forrester S, Fleming P (2019) Traction forces generated during studded boot-surface interactions on third-generation artificial turf: a novel mechanistic perspective. *Eng Rep* 1:1–21. <https://doi.org/10.1002/eng2.12066>
34. Fleming P (2011) Artificial turf systems for sport surfaces: current knowledge and research needs. *Proc Inst Mech Eng Part P J Sport Eng Technol* 225:43–63
35. Burillo P, Gallardo L, Felipe JL, Gallardo AM (2014) Artificial turf surfaces: Perception of safety, sporting feature, satisfaction and preference of football users. *Eur J Sport Sci* 14:437447. <https://doi.org/10.1080/17461391.2012.713005>
36. Rogers L (2017) *Discrimination testing in sensory science: a practical handbook*. Woodhead, United Kingdom
37. Delattre N, Cariou A (2018) Women perception of shoe cushioning as a function of mechanical properties of footwear using a sensory trained panel method. *Footwear Sci* 10:11–19. <https://doi.org/10.1080/19424280.2017.1403973>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.