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Skin friction related behaviour of artificial turf systems

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Skin-Friction Related Behaviour of Artificial Turf Systems

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1 Skin-friction related behaviour of artificial turf systems

2

3 Abstract

4 The occurrence of skin-friction related injuries is an issue for artificial turf sports pitches and
5 remains a barrier to their acceptance. The purpose of this study was to evaluate the current
6 industry-standard Securisport® Sports Surface Tester that measures skin-surface related
7 frictional behaviour of artificial turf. Little research has been published about the device and
8 its efficacy, despite its widespread use as a standard FIFA Test Instrument. **To achieve a
9 range of frictional behaviours, several ‘third generation’ (3G) carpet and infill
10 combinations were investigated; friction-time profiles throughout the Securisport
11 rotations were assessed in combination with independent measurements of skin
12 roughness before and after friction testing via 3D surface scanning.** The results indicated
13 that carpets without infill had greatest friction (coefficients of friction 0.97 to 1.20) while
14 those completely filled with sand or rubber had similar and lower values independent of
15 carpet type (coefficient of friction ≈ 0.57). Surface roughness of a silicone skin decreased
16 after friction testing, with the largest change on sand infilled surfaces, indicating an ‘abrasive’
17 polishing effect. The combined data show that the silicone skin is damaged in a surface-
18 specific manner, thus the Securisport coefficient of friction values appear to be a poor
19 measure of the potential for skin abrasion. It is proposed that the change in silicone skin
20 roughness improves assessment of the potential for skin damage when players slide on
21 artificial turf.

22 Keywords: *artificial turf, skin-friction, abrasion, turf components, Securisport*

23

24 1. Introduction

25 Skin abrasion injuries in sports are usually considered to be minor and are typically excluded
26 from epidemiological studies as they do not fall under the category of “time-loss” injuries
27 (Fuller et al., 2006; van den Eijnde, Peppelman, Lamers, van de Kerkhof & van Erp, 2014).
28 Yet when players have been questioned on their perceptions of artificial turf, many have
29 highlighted more skin abrasions as a major disadvantage of artificial turf fields over natural
30 grass. This is a concern that can deter player acceptance of these products (Burillo, Gallardo,
31 Felipe, & Gallardo, 2014; Roberts, Osei-Owusu, Harland, Owen, & Smith, 2014; Zanetti,

2009). Of the available studies that have recorded incidences of skin injuries, many have shown greater rates of skin injuries on artificial turf than natural grass fields (e.g. Fuller, Clarke, & Molloy, 2010; Fuller, Dick, Corlette, & Schmalz, 2007; Meyers & Barnhill, 2004). Research into skin-friction for player falling/sliding has largely stagnated because of limited understanding of complex interactions between the turf surface and human skin (Twomey, Petrass, & Fleming, 2014). This increases the challenge of validating mechanical test methods.

The first generation of artificial turf (developed in the 1960s) was especially unforgiving on the skin because it comprised polyamide yarns that are hard and abrasive (Basler, 1989; Eiland & Ridley, 1996; Fleming, 2011). The introduction of softer polyolefin yarns in the 1990s was partly aimed at reducing the occurrence of skin-related injuries (Fleming, 2011). The latest (third) generation (3G) artificial turf uses polyolefin fibres that longer fibre lengths, and rubber 'performance' infills. This combination both improves simulations of the playing properties of natural grass and allows the use of standard studded footwear. Apart from the transition to polyolefin fibres in the 1970s, it appears there has been little improvement in skin-friendliness of turf surfaces. Epidemiological studies indicate that the currently available third-generation surfaces have a greater skin-injury risk than natural grass. Furthermore, the interdependency of material properties complicates product design with the need for possible compromises between factors such as in-game performance and player comfort, player-turf interactions versus ball-turf interactions and yarn softness versus yarn resiliency (Hufenus, Affolter, Camenzind, & Reifler, 2013; Sandkuehler, Torres, & Allgeuer, 2010).

There are two testing standards that assess friction and/or the abrasiveness of artificial turf systems. The first is the American Society for Testing and Materials (ASTM) F1015 standard, which determines the relative abrasiveness of a sport surface by measuring the loss of mass of friable foam blocks after pulling it manually across the test surface under a constant static load of 20 lb (89 N) (ASTM International, 2009). The second is that specified by the association football governing body Fédération Internationale de Football Association (FIFA) as part of its accreditation process for artificial turf surfaces. The Securisport Sports Surface Tester (FIFA, 2012b) comprises a test 'foot' with a silicone skin attached (hereafter termed s-skin). The test foot completes five revolutions, at a speed of 40 rpm, across the surface under a constant normal load of 100 N. Histories both of the normal load and horizontal resistance torque experienced by the test foot are recorded via load cells. The histories are then combined to identify the coefficient of friction (COF) for the surface in accordance with

Equation 1. The mean COF is calculated to represent the s-skin-to-surface friction. World Rugby, the Rugby Football League, Gaelic Football (GAA) and Australian Rules Football (AFL) have also adopted the FIFA guidelines for the determination of skin-surface friction. Products (carpet and infills combined) are deemed satisfactory if the measured COF falls between 0.35 – 0.75. However, there is no clear documented justification or detail on how these performance requirements have been determined.

Eq.1
$$\text{COF} = \frac{\text{Horizontal Torque [Nm]}}{(\text{Radius of rotation [m]}) (\text{Normal Force [N]})}$$

Despite the extensive FIFA and World Rugby accredited 3G artificial-turf systems worldwide, there is little published on frictional behaviours of artificial turf or on the standard mechanical testing method currently used to determine skin-surface friction of 3G turf. A recent study challenged the external validity of the Securisport device and sought to develop a modified linear test (Lenehan and Twomey, 2015). Hence, the purpose of this study was to improve the evaluation of the Securisport Sports Surface Tester as a means to assess skin-related frictional behaviours of artificial turf. To achieve a range of frictional behaviours, several 3G carpet–infill combinations were tested and the COF profiles throughout the Securisport five rotations assessed in combination with independent measurements of the s-skin roughness before and after testing.

2. Materials and Methods

The study met institutional ethics requirements.

2.1 Surface Preparation

A monofilament (M) carpet with a 40 mm fibre length and a fibrillated (F) carpet with a 60 mm fibre length were selected to represent the two main categories of yarn used for 3G turf. Monofilament yarns are produced by polymer extrusion to form individual strands that are gathered to form tufts of fibres; while fibrillated tapes are manufactured by cutting polymer films into wide strips and subsequently patterned with longitudinal slits (fibrillation) to give the appearance of grass blades (Sandkuehler et al., 2010). Figure 1 shows the two types of carpet fibre investigated. The infills were styrene-butadiene rubber (SBR) and (industry standard 2EW) silica sand, both commonly used in artificial turf pitches. The specifications

of these turf components are presented in Table 1. For each carpet type, five surface systems were prepared: carpet-only, carpet with sand added to give a 20 mm free-pile height, carpet with SBR to give a 20 mm free pile height, sand added to give 0 mm free pile height and SBR added to give 0 mm free pile height (Table 2). The surface systems were prepared by first raking the carpet to lift the fibres that tended to lie inclined with their intrinsic orientation from the manufacturing process. The infill was applied in layers of 10 mm at a time and conditioned using a standard (30 kg) hand-pulled studded-roller, in accordance with the FIFA Handbook of Test Methods (FIFA, 2012a). The infill depth and free pile height for each surface were measured and recorded before and after each trial based on three measurements across the surface using a simple depth gauge method (Figure 2). After each trial the surface was reconditioned by raking and/or redistribution of infill to ensure consistency of the initial infill depth for each surface. A summary of the specifications for the prepared surfaces is presented in Table 2.

Table 1

Figure 1

Figure 2

Table 2

2.2 Data Collection

Silicone skin L7350 (Maag Technic AG, Switzerland) and the Securisport Sports Surface Tester (Deltec Equipment, Netherlands), shown in Figure 3, were used to conduct the frictional measurements in accordance with the FIFA-08 test method (FIFA, 2012a). The s-skin samples were cut to the required 15 x 8 cm, washed using deionized water and dried at ambient conditions for 24 hours. An initial appraisal of the s-skin for manufactured consistency was undertaken via simple friction measurements on a calibrated steel block; s-skin samples were rejected if either too smooth or rough in accordance with the FIFA test procedure. The test foot and s-skin were then attached to the Securisport and a normal load of 100 N was applied via the pneumatic ram. The control software drove the motor to rotate the foot across the sample surface system at a rotational speed of 40 rpm for five revolutions. The radius of rotation was 0.2 m to the centre of the foot of width 0.08 m, hence a radius range of 0.16 – 0.24 m. Instead of reporting the single value of the mean COF, as specified in FIFA-08,

1 the complete raw-data files of normal load and horizontal torque for each trial were saved for
2 off-line analysis. Three trials were conducted for each surface system with each trial using a
3 new s-skin sample. In the standard FIFA test method, the sliding force of the s-skin sample
4 (traversing 100 mm) on a polished steel plate before and after Securisport testing quantified
5 changes in sliding force and ‘abrasion’ of the s-skin. An initial assessment of this method
6 identified inconsistent results after Securisport testing and hence, a separate technique was
7 explored to investigate s-skin roughness, using optical microscopy and 3D-scanning
8 techniques.

9 The s-skin samples were analysed using an optical microscope (Olympus BX51-SC30) at a
10 magnification of 10x, for further subjective observation of surface morphologies before and
11 after testing. To determine roughness of the s-skin surface, roughness profiles were
12 characterized by 3D scanning (Taylor Hobson Precision Talyscan 150). These were
13 completed on the new s-skin samples before Securisport testing and on the **after** test s-skin
14 samples. To remove any superficial infill or fibre material particles from the tested s-skin,
15 samples were sonicated for 10 min using deionized water and dried before surface
16 characterization. The 3D scanning covered a scan area of **4 mm² (2 mm × 2 mm)** selected
17 from the midpoint of all s-skin samples (75 mm and 40 mm from the long and short edges
18 respectively) – to standardize the inter-sample comparisons. Scanning was carried out at a
19 speed of 1000 µm/s using an inductive diamond probe, giving an output of the root mean
20 square area surface roughness value (Sq), as shown in Equation 2. Root mean square surface
21 roughness (Sq) of an area was defined as the mean of the profile height deviations (**Z**) from
22 the mean value, measured within the evaluation length (L = 2 mm) across the measured trace
23 in both x and y directions.

24 Eq. 2
$$Sq = \left[\frac{1}{L^2} \int_0^L \int_0^L Z(x,y)^2 dx dy \right]^{1/2}$$

26 ***Figure 3***

28 *2.3 Data Processing*

29 The raw values of normal load and horizontal torque from the Securisport were low-pass
30 filtered using a zero-lag Butterworth filter (MATLAB R2015a, The Mathworks Inc., MA,

USA) to remove high-frequency data noise. A filter frequency of 3.5 Hz was selected based on a power analysis of the signals. The coefficient of friction as a function of time was then calculated according to Equation 1. The 3D surface scanning used the Talymap Basic 3.1.2 software to determine the surface roughness for the designated area of each s-skin sample, according to Equation 2.

2.4 Statistical Analysis

All statistical analyses were performed using SPSS (v22, SPSS Inc., Chicago, USA). An independent samples t-test was used to compare the mean change in surface roughness between the two unfilled carpets (monofilament and fibrillated). A three-way ($2 \times 2 \times 2$) mixed-design factorial analysis of variance (ANOVA) compared mean changes in surface roughness according to three factors: carpet type (monofilament and fibrillated), infill type (rubber and sand), infill depth (half, full). For the ANOVA analysis, Greenhouse-Geisser adjustment to the degrees of freedom was applied if sphericity was violated. Cohen's d effect sizes (**difference in means divided by the pooled standard deviation**) were calculated and defined as small ($d \leq 0.2$), medium ($0.2 < d < 0.8$), and large ($d \geq 0.8$) (Cohen, 1992). Unless specified, data were expressed as mean $\pm$ standard deviation (SD) and statistical significance was set at $p < 0.05$.

3. Results

3.1 Frictional Behaviour

The three tests on each surface had highly repeatable COF profiles (Figure 4). A representative COF against time relationship is presented for each of the ten turf systems in Figure 5. The profiles indicate a rapid rise in COF in the first 0.3 s to a maximum that represents the coefficient of static friction, followed by a surface-specific response until the second or third rotation (3 – 4.5 s) after which COF tended to stabilise although oscillate slightly about a (surface dependent) steady-state value. The respective COF values are summarized in Table 3.

Figure 4

Figure 5

Table 3

The s-skin had largest frictional resistance when it moved across carpet-only surfaces M1 and F1, with the fibrillated carpet exhibiting a greater steady-state COF value of 1.2 and 0.97 for the monofilament carpet. However, all the silicone skin samples tested on surface sample F1 were ripped off the foot before the trial was completed; causing the sudden drop in COF value as represented by the dashed line on the F1 profile in Figure 4b. For both carpet-only surfaces, the COF continued to increase beyond the static friction phase (time ≤ 0.3 s), but at a lesser rate, and reached a peak COF early in the second rotation, before continuing to oscillated about this peak value for the remainder of the test.

Coefficients of friction tended to decrease with increasing infill height/decreasing free pile height. Coefficients for the partially filled SBR surfaces (M3 and F3) tended to track the corresponding unfilled surface profile to a similar peak COF early in the second rotation, before dropping slightly to a stable value between the unfilled and fully-filled surfaces (0.7 – 0.8). The partially filled sand surfaces (M2 and F2) also continued to increase beyond the static friction phase but to a much lesser extent than the unfilled and partially SBR filled surfaces. Coefficient of friction for the fully-filled surfaces (M4, M5, F4 and F5) peaked at the end of the static friction phase and, notably, all converged to a similar steady-state COF of 0.57 ± 0.03 , independent of the carpet or infill used.

3.2 Infill Depth

Surfaces were prepared with repeatable infill depths and free pile heights (Table 2). Infill depth decreased after Securisport testing of the surface (Figure 6). The partially filled sand surfaces (M2 and F2) had least change in infill depth after testing, whereas fully-filled surfaces had greater absolute changes in infill depth. The SBR-filled surfaces tended to show a greater decrease in infill depth than the sand filled surfaces, with the greatest decrease in infill depth being for the fully filled SBR monofilament carpet (M5) that decreased by 5 mm (from 35 to 30 mm).

Figure 6

3.3 Surface Roughness of Silicone Skin

After testing values of surface roughness (Sq) of the s-skin together with that of the new s-skin are presented in Figure 7. All after-test s-skin samples had surface roughness values less than the original s-skin. The s-skin samples from the unfilled fibrillated carpet (F1) had a 73% greater decrease in surface roughness ($p < 0.001$) than the unfilled monofilament carpet (M1) ($\Delta Sq = 0.77 \pm 0.01 \mu m$ and $0.44 \pm 0.05 \mu m$ respectively), indicating that more s-skin abrasion occurred **and the effect size was large ($d = 9.15$)**. In contrast, the filled fibrillated carpet systems (F2–F5) had a 66% smaller decrease ($p < 0.001$) in s-skin surface roughness than the filled monofilament carpet systems (M2–M5), suggesting that less s-skin abrasion occurred, **again with a large effect size ($d = 2.26$)**. The sand-filled surface systems (M2, M4, F2 and F4) had 47% greater decrease ($p = 0.0034$) in s-skin surface roughness than the respective SBR-filled surfaces (M3, M5, F3 and F5), suggesting that more s-skin abrasion occurred **and with a medium effect size ($d = 0.60$)**. Similarly, the fully-filled surfaces (M4, M5, F4 and F5) had a 70% greater decrease ($p < 0.001$) in s-skin surface roughness than the partially-filled surfaces (M2, M3, F2 and F3), indicating that more s-skin abrasion occurred **and with a large effect size ($d = 0.85$)**. Subjective visual analysis of the s-skin samples under the optical microscope corroborated the measurements of roughness (Figure 8). Distinct raised surface morphology seen as reflective regions on the new s-skin (Figure 8a) were absent on after-test s-skin samples from the sand-filled surface M4 (Figure 8b) and the SBR-filled surface M5 (Figure 8c).

The L7350 s-skin specified in Securisport testing had a surface roughness of $1.281 \pm 0.121 \mu m$, typical of common silicone-skin models used as surrogates ($0.722 - 1.166 \mu m$; Derler, Schrade, & Gerhardt, 2007; Goiato, Pesqueira, Santos, & Dekon, 2009). However, these surface roughness values are less than reported values for human skin, that range from $6.1 \mu m$ (Trojahn et al., 2015) to $256.4 \mu m$ (Pacheco, Martins-Costa, Zapata, Cherit, & Gallegos, 2005).

Figure 7

Figure 8

4. Discussion

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The purpose of this study was to improve the evaluation of the Securisport Sports Surface Tester as a means to assess the skin-surface related frictional behaviours of artificial turf systems. A range of ten 3G carpet – infill combinations was tested that successfully achieved a range of frictional behaviours, as seen in COF histories from the Securisport, as well as in the independent assessments of s-skin surface roughness before and after Securisport testing. The results provide a relevant dataset from which to evaluate the Securisport Sports Surface Tester.

The skin-surface frictional behavior of an artificial turf system depends on the roughness properties both of the s-skin and the surface system under test. Thus, it is suggested that skin-surface frictional behaviors of different artificial turf systems can be compared only under conditions where s-skin roughness is consistent and it is differences in surface alone that are causing the differences in frictional behaviour. The current results indicate that this is not the case for tests carried out using the the Securisport Sports Surface Tester. The range of COF profiles from the 10 surface systems tested (Figure 5), combined with the range of surface roughness values for the after-test s-skin samples, indicates that the s-skin is damaged in a surface-specific manner during the Securisport testing, most notably in the earlier rotations. It is suggested from these findings that both the state of the artificial turf surface and the changing s-skin contribute to the COF profiles produced and, in particular, the steady-state COF values obtained during the latter rotations. This questions the use of the values of COF from the Securisport Tester to compare frictional properties and differentiate among artificial turf systems. In the Lenenhan and Twomey (2015) study, only abrasion using the FIFA method of change in coefficient of friction of the s-skin on a steel block before and after testing on the turf was reported and a trend of increasing abrasion with increasing depth of infill added to the (63 mm fibre length) carpet was identified. Further, it was notable that with the specified depth of sand (below) and rubber (above) for the carpet system investigated, abrasion was 122% which is greater than the acceptable FIFA compliance value of maximum 30%. Lenehan and Twomey (2015) did not report the coefficient of friction for the s-skin on the artificial turf, precluding direct comparison with this study. However, assuming that the increased COF for the s-skin on a steel block after-testing arises from the s-skin being smoother, then the relationship they observed between increased infill depth and increased abrasion is in agreement with the similar and large effect size ($d = 0.85$) difference between the partially-filled and fully-filled surfaces in this study. Furthermore, they

1 reported large variability for the COF of the skin on steel block after-testing **supporting the**
2 direct measurement of s-skin roughness as **conducted in this study**.

3 The direct measurement of s-skin surface roughness and the change from before to after
4 testing provide a useful estimate of the damage done to the s-skin from the Securisport test.
5 This improves measurement of skin-related damage, in addition to or instead of the frictional
6 measurement made by the Securisport. The damage to the s-skin is probably a function of the
7 surface-system roughness, so comparing the s-skin damage across a consistent surface
8 exposure 'path' (five rotations corresponds to a mean path length of 6.3 m, at constant speed
9 and normal load) should improve isolation of the abrasive effects of different surface
10 systems.

11 All after-test samples had decreased surface roughness, indicating abrasion and material loss
12 and importantly, a smoothing of the initially rougher silicone skin via a 'polishing' type
13 process (Evans & Cullis, 2008; Nemli, Akbulut, & Zeković, 2007). Samples tested on the
14 carpet-only and sand-filled surfaces had greater abrasion (less after-test surface roughness)
15 than the respective SBR-filled surfaces. The **medium effect size ($d = 0.60$) for the change in**
16 **surface roughness between the two infills most likely arises from the** comparatively rigid
17 sand particles **being** more abrasive **compared to the** deformable rubber particles. For
18 silicone skin samples tested on carpet-only surfaces, the large effect size (**$d = 9.15$**) **for the**
19 **increased abrasion of the fibrillated carpet compared to the monofilament carpet** may
20 arise from the twisting of the tufted-ends (near the carpet backing) of the fibrillated fibres
21 leading to increased stiffness and scraping of the soft silicone skin. Adding infill to the
22 carpets eliminates this carpet-base effect, thereby reducing the abrasiveness.

23 **Indeed, in the presence of infill, the abrasion two carpet types was clearly reversed.**
24 **There was a large effect size ($d = 2.26$) for the** lower abrasiveness of the fibrillated fibres
25 (as reflected by less change in the s-skin surface roughness after testing) than for **the**
26 **monofilament fibres which** can be attributed to the thinner fibre thickness **for the former**
27 **carpet (0.1 mm versus 0.3 mm; Table 1)**. As the test-foot traverses the surface, the initial
28 net-like structure of the fibrillated fibre gives way and splits into smaller fibre-strands. These
29 less resilient individual fibre-strands are in turn, less abrasive than the monofilament fibres
30 and hence, inflicted less damage on the silicone skin. For both carpets, further increase of
31 infill level led to a transition to the sandpaper-effect of infill particles on the skin samples.
32 Moreover, the 'fibrillated' fibre carpet reduced the mobility of the infills under testing

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(Figure 6), perhaps an effect of the ‘honeycomb’ nature of the slitted fibres that holds the infill between fibres.

Comparison of changes in surface roughness with the steady-state COF provides further evidence for the validity of the Securisport Sports Surface Tester. Surfaces F1 and F3 had greatest and least change in s-skin surface roughness. Although surface F1 also had the greatest steady-state COF, indeed the s-skin sample tore away from the test foot during these tests, surface, **surface** F3 had the second greatest steady-state COF despite minimal damage to the s-skin. Thus, although s-skin surface roughness measurements can provide a valid means of assessing the damage done to the s-skin on the different surfaces, this does not necessarily reflect the skin-surface frictional behaviour, i.e the results suggest no direct link between measured COF and change in s-skin surface roughness.

This study was based on the Securisport Surface Tester, specified by international governing bodies of sport, such as FIFA, to assess s-skin friction of 3G artificial football pitches. Although previous studies have criticised the Securisport because of its lack of biofidelity (Ingham, 2013; Verhelst, Rambour, Verleysen, & Degrieck, 2009) these studies did not specifically evaluate the device or present evidence of more appropriate test inputs. Current knowledge on the mechanics of players sliding on artificial turf surfaces is lacking and poses a limitation to the design of better testing devices. Outcomes of this study provide recommendations for the future direction of mechanical assessment of skin-surface behaviour of artificial turfs. To quantify frictional behaviours of surfaces, and so allow comparisons among surfaces, more consistent s-skin roughness conditions throughout testing are necessary. Thus, for assessments of friction, a more robust surrogate s-skin that will not undergo highly dynamic and surface-specific changes in surface roughness is required. While for assessment of damage to the s-skin, the current s-skin is appropriate. However, direct measurement of roughness is likely to be more reliable than the indirect method currently used.

From frictional profiles obtained from the Securisport trials, there was a general trend of larger frictional changes occurring during the initial rotations taper off to oscillations about a stable coefficient of friction. The major surface-specific changes in the s-skin occurred during the first two rotations where the COF peaked for all the surfaces, so a useful modification would be to alter the operation of the Securisport to improve consistency and realistic movement profiles. In addition, the repeated rotation of the test foot also disturbs the carpet fibre and infill for subsequent rotations. Hence, a possible improvement would be to monitor

the frictional behaviour as a moving test foot is lowered onto the turf surface and brought to a controlled stop in a linear motion. This motion improves representation of decelerations of a player as he/she slides on the playing surface, and so provide greater insights to frictional mechanisms involved in skin-surface interactions.

5. Conclusions

The Securisport Sports Surface Tester is the current industry-standard equipment to assess skin-surface frictional behaviours of artificial-turf surfaces. The results of this study question the validity of this mechanical device, primarily because of the changing roughness states of the s-skin throughout the test that do not then isolate the contribution of the sport surface in the measurement of the COF. Thus, the measured COF is not related to the actual s-skin damage and therefore the existing Securisport does not provide a reliable measurement of s-skin damage. This is particularly relevant for comparisons of frictional behaviours of artificial turf systems, which is the basis of the testing standards and product development. This study has also demonstrated that the direct measurement (via 3D scanning) of s-skin surface roughness before and after Securisport testing provides a useful means to assess s-skin damage for a given surface. Notably, this damage should be considered independently to frictional behaviours of surfaces as the two are not necessarily related. The current results also inform debate on the development of techniques to assess s-skin-surface frictional behaviours of artificial turf systems.

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Tables and Figure Captions

Table 1. Product specifications of carpets and infills used in the study

Carpets	Material	Pile width (mm)	Pile length (mm)	Tufts/m ²	Fibres/ tuft	Fibres/ m ²	Fibre thickness (mm)
Monofilament	Polyethylene	1	40	26400	12	316800	0.30
Fibrillated	Polyethylene	10.5	60	18200	2	36400 ^a	0.10
Infills ^b	Size range (mm)	Bulk density ^c (g/cm ³)					
Sand	0.25 – 0.71	1.56					
Styrene-butadiene rubber (SBR)	0.8 – 1.8	0.45					

^a Each 10.5 mm-wide fibre is pre-slit with 7 staggered slits and when fully split, produces 8 fibre-strands

^b Data obtained from technical specification sheets of respective infills

^c According to test method ASTM D5603, 8

Table 2. Mean and standard deviation of measured properties of the prepared surface systems before testing

Surface system code	Carpet type (pile length in mm)	Infill type	Infill depth (mm)	Free-pile height (mm)
M1	Monofilament (40)	None	0.0	40.0 ^a
M2	Monofilament (40)	Sand	20.7 ± 0.1	18.0 ± 0.1
M3	Monofilament (40)	SBR	22.4 ± 0.2	17.1 ± 0.2
M4	Monofilament (40)	Sand	35.3 ± 0.2	3.3 ± 0.2
M5	Monofilament (40)	SBR	35.0 ± 0.4	4.2 ± 0.2
F1	Fibrillated (60)	None	0.0	60.0 ^a
F2	Fibrillated (60)	Sand	33.8 ± 0.1	22.8 ± 0.1
F3	Fibrillated (60)	SBR	36.6 ± 0.1	17.0 ± 0.1
F4	Fibrillated (60)	Sand	51.0 ± 0.1	3.3 ± 0.1
F5	Fibrillated (60)	SBR	52.1 ± 0.1	4.0 ± 0.1

^a Full pile-length exposed

Table 3. Summary of the static, maximum and steady-state COF values measured on each test surface. The values are the mean $\pm$ standard deviation based on three trials for each test surface.

Test Surface	Static COF	Maximum COF	Steady-state COF
M1	0.61 ± 0.03	1.12 ± 0.05	0.97 ± 0.02
M2	0.53 ± 0.02	0.91 ± 0.05	0.78 ± 0.02
M3	0.56 ± 0.02	0.98 ± 0.05	0.75 ± 0.02
M4	0.72 ± 0.01	0.78 ± 0.07	0.59 ± 0.01
M5	0.70 ± 0.02	0.71 ± 0.01	0.59 ± 0.01
F1	0.67 ± 0.01	1.46 ± 0.07	1.26 ± 0.04
F2	0.65 ± 0.03	1.05 ± 0.06	0.74 ± 0.09
F3	0.64 ± 0.05	1.23 ± 0.07	0.95 ± 0.07
F4	0.68 ± 0.03	0.68 ± 0.02	0.54 ± 0.02
F5	0.73 ± 0.02	0.73 ± 0.02	0.58 ± 0.01

Figure 1. Carpet types, a) is a 'Monofilament' and b) a 'Fibrillated'. Note the slit film yarn in b) can be opened to form a 'honeycomb' type structure reportedly useful to 'hold' the infill.

Figure 2. Schematic showing the measurement of infill depth and free-pile height of a filled artificial turf surface (not drawn to scale).

Figure 3. The Securisport® apparatus, showing the key components of this current industry standard test.

Figure 4. COF profiles of trials conducted on test surfaces a) M1 and b) F4, demonstrating the repeatability of the Securisport results.

Figure 5. COF profiles of a) monofilament surfaces M1 – M5 and b) fibrillated surfaces F1 – F5. The five rotations are demarcated by the vertical lines, at intervals of 1.5s. The transition from a solid line to a dashed line for surface F1 denotes the point at which the s-skin sample detached from the test foot, beyond which the data collected were excluded from analysis.

Figure 6. Decrease in infill depth for each surface, determined by the difference between infill depth measured before and after each trial. Error bars indicate the standard deviation for each data set.

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2
3 1 Figure 7. Root mean square surface roughness value (Sq) of the original s-skin and the s-skin
4 2 after Securisport testing on each of the test surfaces. Error bars indicate the standard
5 3 deviation for each data set.
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9 4 Figure 8. Microscope images at a magnification of 10x of a) original s-skin, b) s-skin after
10 5 testing on surface M4 and c) s-skin after testing on surface M5.
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Figure 1. Carpet types, a) is a 'Monofilament' and b) a 'Fibrillated'. Note the slit film yarn in b) can be opened to form a 'honeycomb' type structure reportedly useful to 'hold' the infill.

Figure 2. Schematic showing the measurement of infill depth and free-pile height of a filled artificial turf surface (not drawn to scale).

Figure 3. The Securisport® apparatus, showing the key components of this current industry standard test.

Figure 4. COF-time profiles of trials conducted on test surfaces a) M1 and b) F4, demonstrating the repeatability of the Securisport results.

Figure 5. COF versus time profiles of a) monofilament surfaces M1 – M5 and b) fibrillated surfaces F1 – F5. The five rotations are demarcated by the vertical lines, at intervals of 1.5s. The transition from a solid line to a dashed line for surface F1 denotes the point at which the *s-skin* detached from the test foot, beyond which the data collected was excluded from analysis.

Figure 6. Decrease in infill depth for each surface, determined by the difference between infill depth measured before and after each trial. Error bars indicate the standard deviation for each data set.

Figure 7. Root mean square surface roughness value (Sq) of the original s-skin and the s-skin after Securisport testing on each of the test surfaces. Error bars indicate the standard deviation for each data set.

Figure 8. Microscope images at a magnification of 10x of a) original s-skin, b) s-skin after testing on surface M4 and c) s-skin after testing on surface M5.