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PERSPECTIVE

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Traction forces generated during studded boot-surface interactions on third-generation artificial turf: A novel mechanistic perspective

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The traction forces generated during studded boot-surface interactions affect player performance and injury risk. Over 20 years of empirical research into traction on third-generation (3G) artificial turf has met with only limited success in supporting the development of safer surfaces and boots. Thus, the purpose of this perspective article is to present a conceptual framework for generating scientific understanding on 3G turf traction through a novel mechanistic approach. A three-stage framework is proposed. Firstly, the hypothesized traction mechanisms and related analytical equations are identified, namely, friction between the boot outsole and surface; shear resistance of the performance infill layer to the outsole; and compressive resistance of the performance infill layer to horizontal stud displacement. Secondly, a Concept Map is generated to visually represent the contribution of the 39 variables identified as directly affecting the traction response. Finally, a Research Roadmap is constructed to guide the direction of future traction studies toward the development of safer surfaces and boots as well as improved mechanical tests to assess surface safety. The proposed framework represents the first attempt to deconstruct boot-surface interactions and hypothesize the science behind the mobilization of traction forces.

KEYWORDS
rubber crumb, studded footwear, third-generation artificial turf, traction

1 | INTRODUCTION

Traction forces refer to the shear forces generated when studded footwear interacts with penetrable surfaces such as natural grass, third-generation (3G) artificial turf (3G turf; Figure 1A) or a hybrid of the two (Figure 1B).[9] Traction is most relevant for movements that involve a change in speed and/or direction and, in general, increased traction forces leads to increased player movement performance[10] at least up to some critical threshold above which traction no longer limits performance.[11] The traction forces developed are a complex interaction between the player, footwear, and surface (the *traction system*[12]).

For 3G turf, it is widely recognized that surface design and state have a significant effect on the traction forces developed.[7,13-19] In particular, increasing the net bulk density of the performance infill layer[20] has been demonstrated to increase the traction forces.[18,19,21,22] In terms of the player contribution, increasing the surface confining (normal) stress

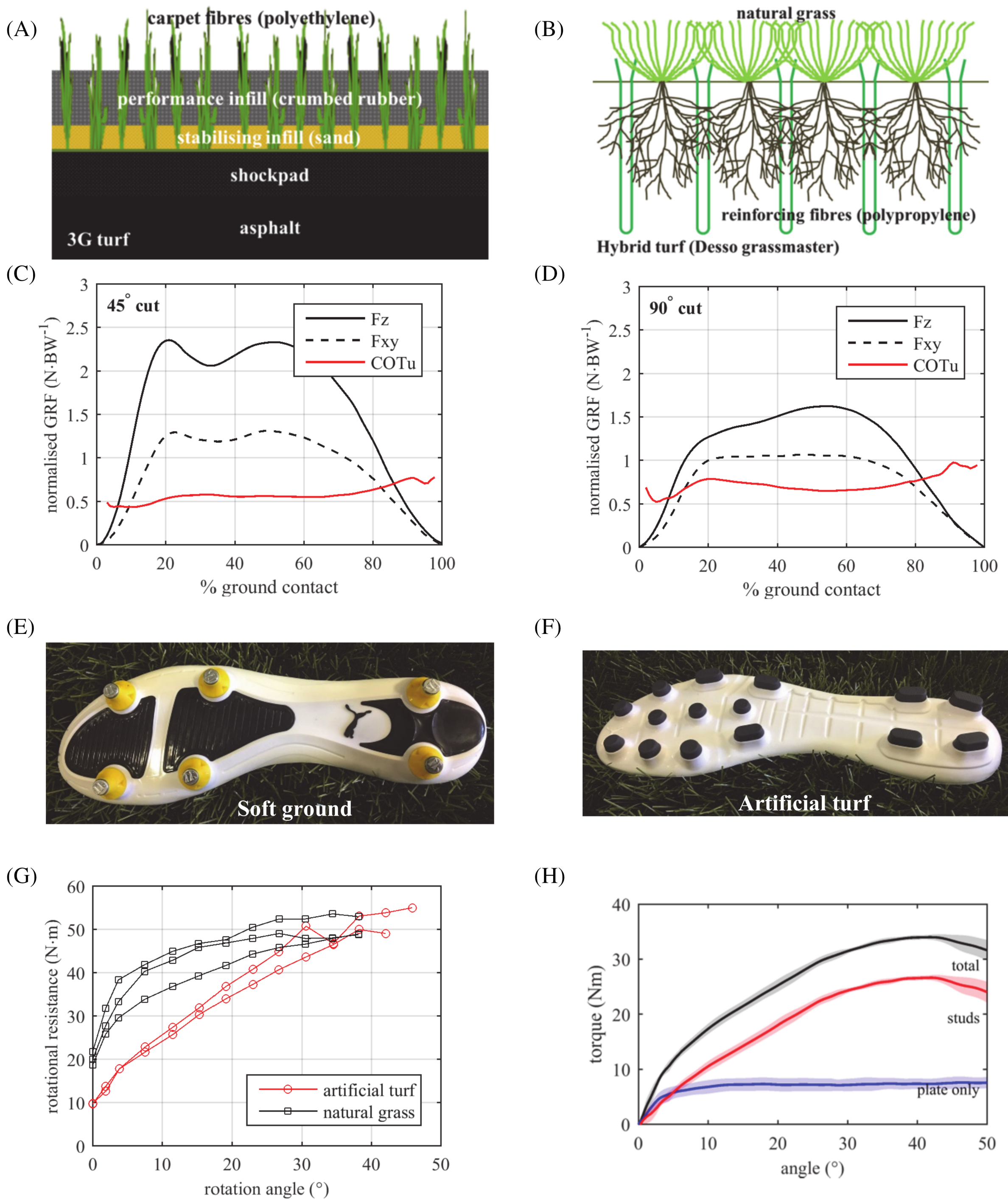

FIGURE 1 A, Typical structure of a 3G turf surface system consisting of an upper carpet layer comprising of 40-65 mm polyethylene fibres with stabilizing (sand) and performance (crumbed rubber) infills.[1] The shockpad layer is commonly included to increase the shock absorption properties of the surface; B, Typical structure of a reinforced natural grass hybrid surface system where the natural grass is reinforced with 200 mm polypropylene fibres inserted to a depth of 180 mm on a 20 mm grid (Desso GrassMaster)[2]; C-D, Typical vertical and horizontal ground reaction forces and resulting player utilized coefficient of traction (uCOT) for 45° and 90° cutting movements on 3G turf (adapted from[3]); E-F, Typical outsole designs for soft ground (wet natural grass pitches) and 3G turf pitches[4,5]; G-H, Rotational angle versus torque for the Fédération Internationale de Football Association (FIFA) standard test[6] conducted on 3G turf and natural grass (adapted from[7]) and 3G turf.[8] The latter shows the measured total resistance (plate and studs) and individual contributions of the plate (measured) and studs (calculated as total minus plate).[8] Note that both G and H, illustrate a high initial rate of increase in resistance over the first few degrees followed by a relatively linear but lower rate of increase until a peak/plateau in resistance at around 40° of rotation

has consistently been shown to increase the traction forces[15,18,19,21,23-26] (Figures 1C to 1D), whereas stud geometry and configuration have both been demonstrated to affect the traction forces[4,18,21,27-29] (Figures 1E and 1F). It is also recognized that environmental variables will affect the traction forces[20,21]; however, only surface moisture content has been widely studied[4,22,24,25,30] with mixed results perhaps due to the challenges in measuring and controlling the surface moisture content. Thus, it appears that many variables can affect the traction forces (Figure 1G) and that the detailed design and state of 3G turf systems are highly relevant in this regard.

The traction system response should represent an acceptable comprise between minimizing injury risk and maximizing performance.[31-33] It has been suggested that existing studded footwear designs allow players to achieve the desired level of traction from a performance perspective and that injury risk is the greater on-going issue.[34] Incidence of injury in soccer and other sports commonly played with studded footwear is relatively high, eg, 22 injuries per 1000 match playing hours and 3.5 injuries per 1000 training playing hours have been reported for soccer.[35] Combined with the worldwide popularity of soccer, these injuries carry a major cost in terms of both treatment and loss of productivity due to time off work.[36] For example, Ball[37] estimated the cost to the UK economy to be ~£1 billion per annum. The greatest injury risk factor associated with boot-surface interactions is foot fixation on the surface leading to excessive rotational traction,[32,38-40] which, in turn, leads to excessive loading of the ankle and knee joints.[41] For example, cutting movements have been proposed as the primary mechanism for anterior cruciate ligament tears due to the rapid deceleration and twisting of the ligament.[42,43] On this basis, current outsoles are typically designed to minimize rotational traction, thereby reducing knee loading in the transverse and frontal planes[44] while maintaining sufficient translational traction to enable performance.[45] However, traction-related injuries to the ankle and knee continue to represent a major challenge for sports played with studded footwear,[46] particularly on 3G turf.[47]

Boot-surface traction has been widely investigated through empirical player and/or mechanical testing studies (Tables 1 and 2). Despite an abundance of research over the last 20 years, limited progress has been made into understanding how traction forces are generated and how they can be modulated through surface and boot design. Understanding from player studies has been limited by the complexity of the traction system and the resulting challenges in identifying the contribution of individual independent variables, combined with few direct measurements on the detailed kinematics and kinetics of the interaction. For example, very limited data currently exists on how the boot interacts with the surface; including the normal stresses a player applies to the surface, the translational/rotational kinematics of the boot, and the compression/shear response of the surface. The mechanical studies have typically been based on devices that provide a poor representation of the player interaction with the surface, limiting the external validity of these devices.[80] These limitations include a fixed normal load/stress, which is substantially lower than the dynamic stresses a player applies to the surface; acceleration of the boot from an initial static condition, whereas, in reality, the boot lands with a velocity of around 2-3 $m \cdot s^{-1}$ then decelerates rapidly; and using peak force/torque as the measure of traction despite this occurring at far greater displacements than a boot undergoes in player interactions.[59] Some mechanical studies have recognized the importance of the early development of traction forces/torques as more representative of the player experience and have reported this as a stiffness response, ie, the slope of the displacement-force or angle-torque curve (Figure 1H).[26,54,56] However, scientific understanding of the mechanisms that control the generation of traction forces remains very poor, constraining our ability to truly optimize, or predict, traction forces under given conditions. This limitation needs to be addressed if playing conditions that find the right balance between performance and injury risk are to be achieved.

This perspective article proposes that a new mechanistic approach is needed for studying the traction forces generated during boot-surface interactions on 3G turf. It is based on the premise that improved scientific understanding of the mechanisms that contribute to the traction forces generated provides a robust foundation to inform the next generation of safer surfaces and boots. The mechanistic approach is developed within a conceptual framework comprising three main stages. Stage one is a deconstruction of the mechanics of the boot-surface interaction to hypothesize the key mechanisms at work and define analytical mechanical equations describing these mechanisms. Stage two builds a Concept Map of the key variables that affect the traction response; utilizing the outcomes of stage one combined with the existing literature to identify these variables. Stage three defines a Research Roadmap to guide the direction of future traction studies. The framework represents the first attempt to deconstruct boot-surface interactions and hypothesize the science behind the mobilization of traction; no comparative approach currently exists. Its fundamental importance is in the potential to modulate injury risk through direct scientific understanding rather than the current inefficiency of empiricism (trial and error). While the framework has been developed for 3G artificial turf, a similar approach could equally be applied to natural grass or hybrid turf sports surfaces.

2 | TRACTION MECHANISMS PREPARATION

2.1 | Previous literature

Stage one of the framework is to hypothesize the mechanisms that control the generation of boot-surface traction forces. These have been given some consideration for natural grass with three mechanisms identified: friction between the outsole and surface; "ploughing" traction as each stud clears a path through the surface; and "skin" friction between the stud material and the soil.[81,82] The third mechanism was proposed to occur when sufficient moisture was present for the soil to flow round the "ploughing" stud, otherwise the soil undergoes shear failure as it is displaced by the stud. Clarke and Carré[29] suggested that stud "ploughing" dominates the traction forces and recognized the important role of normal stress applied through the outsole in determining the shear strength of the surface. Other factors affecting the shear strength include moisture content, size, shape, and cohesion of the soil particles[12,82] as well as turf root depth.[2] While theoretical equations have been proposed to describe the stud "ploughing" traction forces,[56] which explicitly define the stud(s) effect, the surface design/state effects are embedded within generalized terms, which do not identify the specific surface design/state variables important to the generation of traction forces. Furthermore, although the term stud

TABLE 1 Variables from the traction literature selected for inclusion in the Concept Map

Group	Independent variable	Reference	Study type	Effect
	Body mass (normal load)	Serensits and McNitt[15]	M-R	✓
		Smeets et al[25]	M-R	✓
		Severn et al[19]	M-R	✓
		Livesay et al[26]	M-R	✓
		Webb[21]	M-T	✓
		Kuhlman et al[23]	M-T	✓
		Wannop and Stefanyshyn[24]	M-both	✓
		Severn et al[18]	M-both	✓
Player	Movement	Brock et al[48]	P-B_Tr	✓
		Blackburn[3]	P-B_Tr	✓
		Bennett et al[49]	P-B	✓
		Strutzenberger et al[50]	P-B	✓
		Kaila[51]	P-B	✓
		Wong et al[52]	P-B	✓
		Galbusera et al[53]	M-R	✓
		Smeets et al[25]	M-R	✓
	Movement intensity	Wannop and Stefanyshyn[24]	M-both	~
Player dynamics	Vertical GRF	See normal load above		
	Horizontal GRF vector alignment	McGhie & Ettema[54]	P-B_Tr	~
	Stud configuration	Severn et al[19]	M-R	~
		Webb[21]	M-T	✓
		Severn et al[18]	M-both	✓
	Stud geometry	Brock et al[48]	P-B_Tr	~
Boot design		Müller et al[27]	P-B_Tr	✓
		Bennett et al[49]	P-B	~
		Müller et al[28]	P-P	✓
		Sterzing et al[4]	P-P	✓
		Clarke and Carré[29]	M-T	✓
	Outsole normal stress	See normal load above		
	Outsole translation/rotation	Galbusera et al[53]	M-R	✓
		Villwock et al[55]	M-R	✓
		Fujikake et al[7]	M-R	✓
Player-boot dynamics		Livesay et al[26]	M-R	✓
		Webb[21]	M-both	✓
	Stud translation	See outsole translation/rotation above		
	Number of studs in contact	Webb[21]	M-T	✓
	Studs area ⊥ to hGRF vector	See stud geometry above		
	Net Radius of Studs in Contact	Severn et al[18]	M-R	✓

(Continues)

TABLE 1 Continued

3G turf design	Performance infill material	Zanetti et al[56]	P-B	✓
		Burillo et al[57]	M-R	✗
		Villwock et al[58]	M-R	~
		Zanetti et al[56]	M-T	✓
	Performance infill size range	El Kati[59]	P-B_Tr	~
		El Kati[59]	M-R	✓
		Severn et al[19]	M-R	✓
	Fibre type (monofilament/fibrillated)	Burillo et al[57]	M-R	✓
		Villwock et al[58]	M-R	✗
	Fibre (tuft) density	Webb[21]	M-both	✓
3G turf history	Age	Sánchez-Sánchez et al[22]	M-R	✓
		Sánchez-Sánchez et al[60]	M-R	✓
		Burillo et al[57]	M-R	✗
		Wannop et al[61]	M-both	✓
	Usage	Burillo et al[57]	M-R	✗
	Maintenance	Burillo et al[57]	M-R	✗
3G turf state	Unloaded performance infill depth	Mo[62]	P-B_Tr	✓
		El Kati[59]	M-R	✓
		Mo[62]	M-T	✓
	Unloaded performance infill NBD	Sánchez-Sánchez et al[22]	M-R	✓
		Webb[21]	M-both	✓
		Severn et al[18]	M-both	✓
		Severn et al[19]	M-both	✓
	Free pile height	combined with Performance Infill Depth		
Environmental	Surface moisture	De Clercq et al[30]	P-B_Tr	~
		Sterzing et al[4]	P-P	✗
		Sánchez-Sánchez et al[22]	M-R	✗
		Smeets et al[25]	M-R	✗
		Wannop and Stefanyshyn[24]	M-both	✓
	Surface temperature	Charalambous et al[63]	P-B	✓
		Charalambous et al[63]	M-R	✓

"ploughing" resistance has been widely used in past literature, suggesting a continuous long movement path, in the context of real-player boot-surface interactions stud movement during surface contact tends to be small (of the order of millimeters[59,75]) and, therefore, stud "displacing" resistance may be a better descriptor.

Similar traction mechanisms have been suggested to be present for 3G turf,[21] although the mechanical response and behavior of the rubber crumb material, most commonly used as the performance infill layer, is likely to differ substantially from that of rootzone soil under typical player loading conditions.[80] Severn[20] and Webb[21] both proposed simple lists of variables that control the generation of the traction forces for 3G turf and classified the variables under four broad contributing factors; movement (player), footwear, surface, and environment. However, these were not linked to specific traction mechanisms and the contribution of each variable was, at best, only qualitatively described.

2.2 | Qualitative description of the contact phase

Prior to detailing the hypothesized traction mechanisms for 3G turf, it is relevant to provide a context for these by qualitatively describing a typical player boot-surface interaction; in this case, a stop and turn (Figure 2).[59] The interaction can be divided into three phases: (1) engagement: from initial contact through to the boot reaching a pseudo-static condition on the surface (~ initial 20% of contact); (2) midstance: during which the boot can be considered pseudo-static on the surface (~ middle 55% of contact); and (3) disengagement: from the boot starting to lift off from the surface through to toe-off (~ final 25% of contact). The main characteristics of each phase are summarized later.

During the early engagement phase, only the studs are in contact with the surface and the forces are low due to the low resistance provided by the unconfined performance infill layer. The process of stud penetration into the surface may lead to localized areas of higher density compressed performance infill around the base of each stud.[21] It is not until the outsole contacts with the surface that the normal and traction forces (and stresses) start to increase rapidly as the performance infill layer beneath the boot is confined and compressed leading to increased shear and compressive stiffnesses (Figure 2).[59] In agreement with this observation, several mechanical testing studies have reported traction forces to be strongly dependent on the normal stress applied to the surface.[23-26] This increase in traction force corresponds to a rapid deceleration of the boot from a resultant impact velocity of ~2-3 $m \cdot s^{-1}$ to quasi-static. This short timescale phase (<80-90 ms) is characterized by high peak forces, pressures, and loading rates indicating its relevance to both performance and injury.

Midstance is of longer duration (100-200 ms) and is characterized by moderate forces and pressures supported by this phase typically representing a maximum outsole contact area. The performance infill layer is globally confined and compressed by the vertical load applied through the outsole and locally compressed by the horizontally displacing studs. However, limited data suggests that boot translations/rotations during this second phase are small (only a few mm/degrees[59,75]). The pseudo-static nature of this phase combined with moderate forces and normal stress suggest that it is of lesser relevance to injury.

During disengagement (100-150 ms), the forces and contact area decrease to zero, and the boot velocity increases as the player lifts the boot off the surface, typically heel first with the toe being the last point of contact. As the forces and contact area decrease, the pressure applied to the surface also decreases rapidly reducing the shear and compressive stiffnesses of the performance infill layer and, therefore, reducing the resistance to horizontal stud displacement. The decreasing

TABLE 2 Variables from the traction literature not included in the Concept Map

Group	Independent variable	Reference	Study type	Effect
Player	Fatigue	Silva et al[64]	P-B_Tr	✗
	Boot mass	Sterzing et al[4]	P-P	✗
	Boot comfort	Sterzing et al[4]	P-P	✗
	Prototype boots	Wannop and Stefanyshyn[65]	P-B	✓
		Wannop and Stefanyshyn[65]	M-both	✓
	Commercial boots	Silva et al[64]	P-B_Tr	✗
		Sun et al[66]	P-B_Tr	~
		Schrier et al[67]	P-B_Tr	✓
		De Clercq et al[30]	P-B_Tr	~
		McGhie and Ettema[34]	P-B_Tr	~
		Driscoll et al[68]	P-B_Tr	~
		Müller et al[69]	P-B_Tr	✓
		Sterzing et al[70]	P-B_Tr	~
		Müller et al[27]	P-B	~
		Stefanyshyn et al[71]	P-B	~
		Sterzing et al[72]	P-B	✓
		Sterzing et al[4]	P-B	~
		Queen et al[73]	P-B	~
Boot design		Gehring et al[74]	P-B	~
		Kaila[51]	P-B	✗
		Kirk et al[75]	P-B	✗
		Serensits and McNitt[15]	M-R	✓
		Galbusera et al[53]	M-R	✓
		Smeets et al.[25]	M-R	✓
		Drakos et al[76]	M-R	✗
		Villwock et al[55]	M-R	✓
		Livesay et al[26]	M-R	✓
		Kuhlman et al[23]	M-T	✓
		Müller et al[69]	M-T	✓
		Sterzing et al[70]	M-T	✓
		Kent et al[17]	M-both	✓
		Schrier et al[67]	M-both	✓
		Wannop et al[61]	M-both	✓
		Wannop and Stefanyshyn[24]	M-both	✓
		Stefanyshyn et al[71]	M-both	~
		Wannop et al[77]	M-both	✓
		Shorten et al[78]	M-both	✓

(Continues)

TABLE 2 Continued

	Shockpad (Yes/No)	Sánchez-Sánchez et al[60]	M-R	~
		Burillo et al[57]	M-R	✗
		El Kati[59]	M-R	✗
3G turf design	Carpet mass	Sánchez-Sánchez et al[22]	M-R	✗
	Pile mass	Sánchez-Sánchez et al[22]	M-R	✗
	Pile dtex	Sánchez-Sánchez et al[22]	M-R	✗
	Pile length	Sánchez-Sánchez et al[22]	M-R	✗
3G turf state	Unloaded stabilizing infill (N)BD	Sánchez-Sánchez et al[22]	M-R	✓
3G turf	Multiple 3G surfaces	McGhie and Ettema[54]	P-B_Tr	✗
		McGhie and Ettema[34]	P-B_Tr	~
		Lake and Underdown[79]	P-B	✗
		Potthast[13]	P-B	✓
		Potthast et al[14]	P-B	✓
		Serensits and McNitt[15]	M-R	✓
		Villwock et al[55]	M-R	✗
		Fujikake et al[7]	M-R	✓
		Livesay et al[26]	M-R	~
		Kent et al[16]	M-both	✓
		Kent et al[17]	M-both	✓
		Severn et al[18]	M-both	✓
		Potthast et al[14]	M-both	✓
		Severn et al[19]	M-both	✓

Tables 1 and 2:
Study type: P-B-Tr = player biomechanical study (direct traction measures, ie, GRFs);
P-B = player biomechanics study (indirect traction measures, eg, joint loading);
P-P = player performance study (indirect traction measures, eg, time to complete task);
M-R = mechanical rotation traction study;
M-T = mechanical translational study;
M-both = mechanical rotational & translational study.
Effect: ✓ = independent variable had a significant effect on at least one direct measure of traction;
~ = independent variable had a significant effect on at least one indirect measure of traction and/or approached significance in at least one direct measure of traction;
✗ = independent variable had no significant effect on any direct or indirect measure of traction.

forces/pressures suggest that this phase is less relevant to injury, with slipping potentially representing the greatest risk to players.

2.3 | Traction mechanisms

Based on the foregoing, the mechanisms controlling the generation of traction forces during player boot-surface interactions on 3G turf can be hypothesized together with the relevant analytical mechanical equations. The latter is given in their most general form, aimed at capturing the key variables applicable to both player and mechanical boot-surface traction. The time dependency of variables has been recognized, although, in many of the simpler mechanical tests, some of this time dependency disappears, eg, most apply a constant normal load (and stress) to the surface.

For 3G turf, the performance infill layer is central to the generation of traction forces, interacting with the boot outsole and studs. This layer comprises performance infill and carpet fibres and both are expected to play an important role. The fibres serve to hold the performance infill in place, making it less mobile and, therefore, increasing the shear resistance of this layer as well as the local resistance to the displacing studs.[83] The performance infill is a particulate material, typically crumbs of recycled styrene butadiene rubber (SBR) from used tyres or another polymer, with a particle size of around 0.5-2 mm. The mechanical behavior of crumbed SBR, either with or without the reinforcing fibres, has received little attention in the research literature. The limited evidence available indicates that, unlike soils, crumbed SBR particles more readily compress and distort when providing traction resistance rather than flow or shear.[19,80] This observation is central to the mechanisms detailed below.

Mechanism 1: Outsole-surface shear resistance and friction

The outsole applies a horizontal shear force at the boot-surface interface, which is initially opposed by a shear resistance provided by the confined and compressed performance infill layer beneath the boot (comprising the performance infill

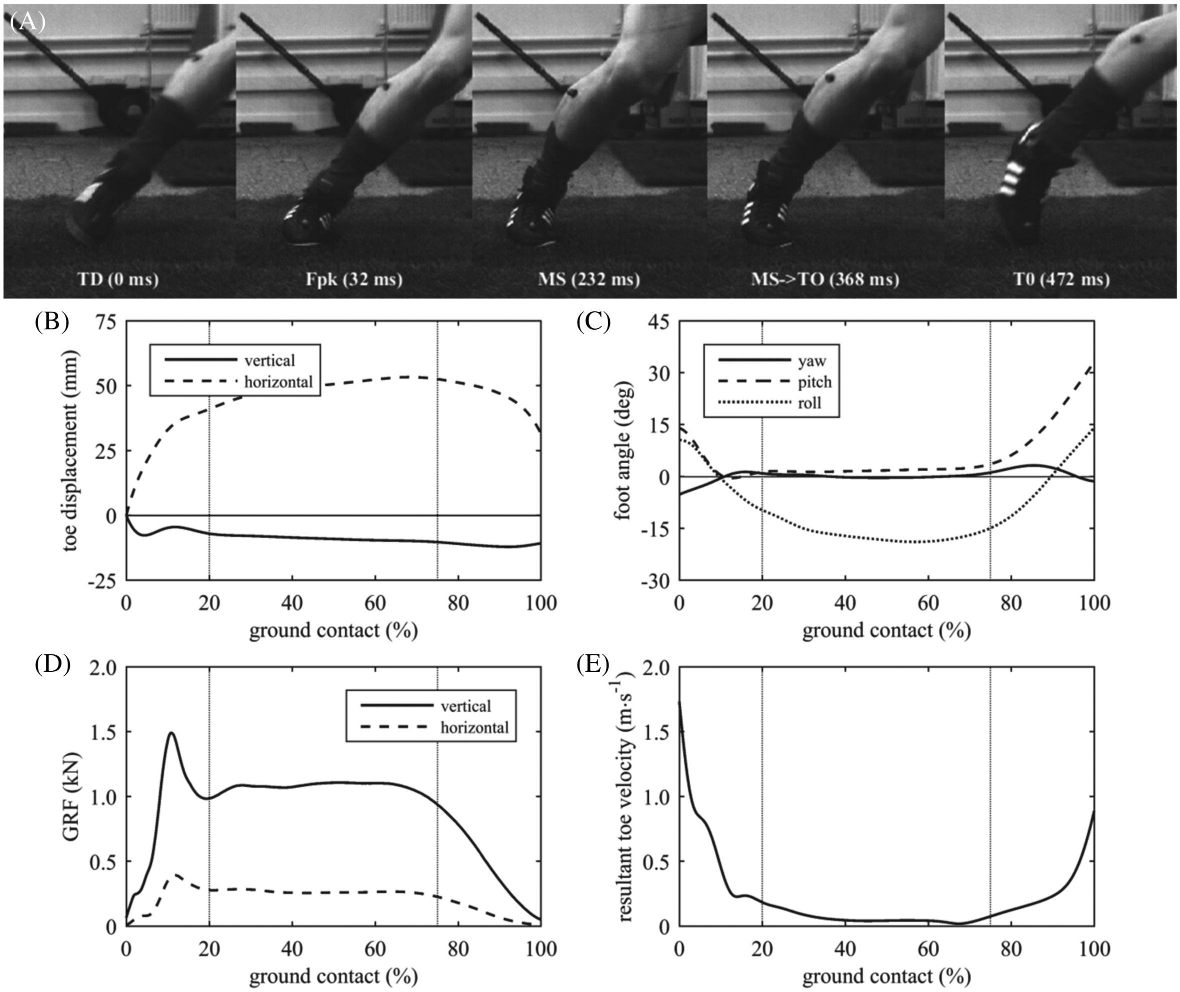

FIGURE 2 Typical data from the ground contact phase of a stop and turn movement on 3G turf (adapted from[59]). A, Key instances from left to right: touchdown (TD); loading peak vertical force (Fpk); midstance (MS); early toe-off (MS → TO); toe-off (TO); B, Toe marker displacement; C, Foot angles; D, Ground reaction forces; and E, Toe marker resultant velocity. In subplots B-E, the two vertical lines separate the ground contact phase into the three phases of engagement, midstance, and disengagement

and carpet fibres; Figure 3A). This shear resistance force ($F(t)$)/torque ($T(t)$) is governed by the shear modulus of this layer and the horizontal displacement of the outsole:

$$\text{For } F(t) < (COF \times F_N(t)) \; : \; F(t) = G(t) \times \left(\frac{A(t) \times \Delta x(t)}{H(t)} \right) \tag{1}$$

$$\text{For } T(t) < (COF \times F_N(t) \times r_{\text{FRIC}}(t)) \; : \quad T(t) = G(t) \times \left(\frac{J(t) \times \Delta\theta(t)}{H(t)} \right), \tag{2}$$

where COF is the coefficient of friction between the outsole and surface (assumed constant throughout ground contact), $F_N(t)$ is the normal force applied to the surface through the outsole, $r_{\text{FRIC}}(t)$ is the friction radius of the outsole in contact with the surface, $G(t)$ is the shear modulus of the performance infill layer beneath the outsole, $A(t)$ is the area of the outsole in contact with the surface, $J(t)$ is the polar moment of inertia for the outsole in contact with the surface, $\Delta x(t)\,/\Delta\theta(t)$ is the displacement of the outsole across the surface, and $H(t)$ is the depth of the performance infill layer. This shear resistance has not been identified in the previous literature on traction mechanisms. It may be more relevant for 3G turf surface systems due to the compressible nature of the performance infill layer and may contribute to the typically observed rapid increase in traction force/torque over the first few mm/degrees of movement.[21,26,53,55]

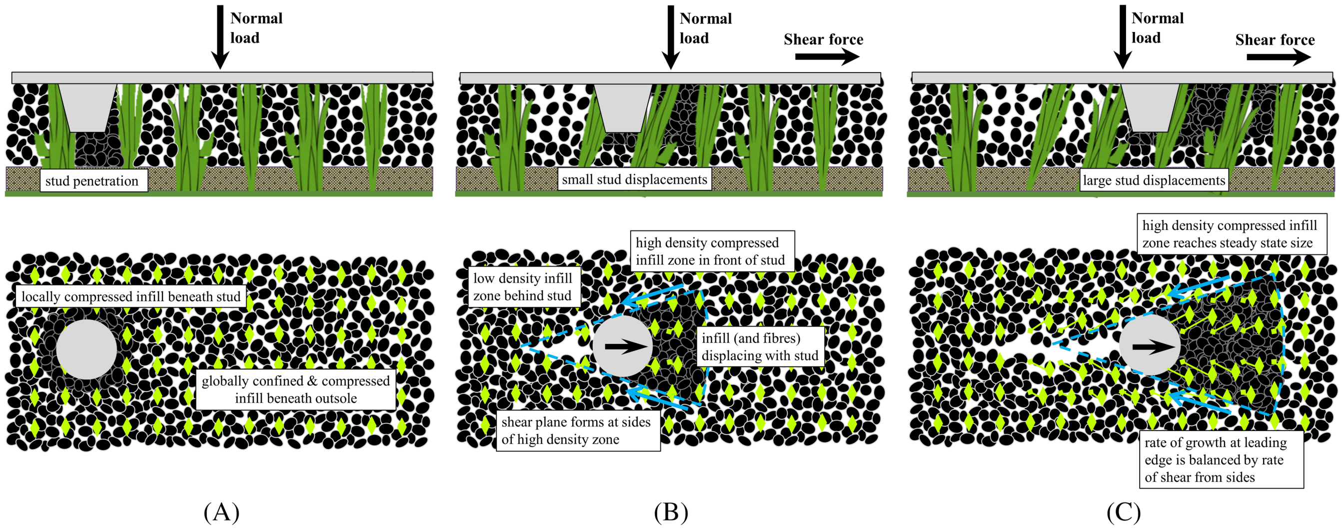

FIGURE 3 Schematic illustrating the mechanism of shear resistance generated by the performance infill layer (comprising of the performance infill and fibres) to horizontal displacement of a single stud. A, Zero stud displacement: a localized zone of high density compressed infill forms beneath the stud due to the stud penetration process; B, Small stud displacements: as the stud starts to displace horizontally, a zone of high density compressed infill forms in front of the stud that grows and moves with the stud. This compressed infill zone grows at leading edge, whereas a shear planes form along the sides of this zone where infill is shed. A secondary zone of low density less compressed infill is left in the path created by the stud; C, Large stud displacements: the zone of high density compressed infill in front of the stud reaches a steady-state size where the rate of growth at the leading edge is balanced by the rate of shear from the sides

Mechanism 2: Outsole-surface friction

Once the horizontal force exceeds the maximum static friction force available, the outsole begins to "slide" over the surface and the shear resistance force ($F(t)$)/torque ($T(t)$) remains constant, controlled by dynamic friction[81]:

$$\text{For } F(t) \geq (COF \times F_N(t)) : \qquad F(t) = COF \times F_N(t) \tag{3}$$

$$\text{For } T(t) \geq (COF \times F_N(t) \times r_{\text{FRIC}}(t)) : \qquad T(t) = COF \times F_N(t) \times r_{\text{FRIC}}(t). \tag{4}$$

The surface in contact with the outsole is a complex mix of fibres (free pile) and performance infill, hence *COF* lies somewhere between the value for each of these components (0.2-1.0[84]). Experimental evidence indicates that static and dynamic *COF* are very similar and can be represented by a single value (Figure 1H).[8]

Mechanism 3: Stud horizontal displacement resistance

During translation and/or rotation of the boot, each stud will apply a horizontal pressure to the performance infill layer, which is resisted by a local stiffness response of this layer.[21,29,56,81] For 3G turf, it is hypothesized that this leads to compression and increased density of the performance infill in front of each stud in a localized zone. As the stud translates this compressed zone (in the shape of a flat cone) grows in width and length (volume) and as the infill nearest the stud reaches a limiting density and stiffness, a pseudo-rigid block of infill forms (Figure 3B). The cone angle is a function of the angle of friction of the rubber particulate, which, in turn, is affected by the initial net bulk density, ie, the performance infill density in isolation. Similarly, the displacing stud leaves behind a lower density and stiffness performance infill zone in its path, due to lateral compression and elastic recovery of the performance infill layer.

For the simplified situation of a single stud displacing through a uniformly confined and compressed performance infill layer beneath the outsole with the horizontal force applied in the same direction throughout, the resistance force ($F(t)$)/torque ($T(t)$) is governed by the localized stiffness of the high-density performance infill layer zone in front of the stud, ie,

$$\Delta x(t) < \Delta x_{\text{CRIT}} : \qquad F(t) = A(t) \times \left(\frac{E(t) \times \Delta x(t)}{x_0} \right) \tag{5}$$

$$r(t)\Delta\theta(t) < [r\Delta\theta]_{\text{CRIT}} : \qquad T(t) = A(t) \times r(t) \times \left(\frac{E(t) \times r(t)\Delta\theta(t)}{L_0} \right), \tag{6}$$

where $E(t)$ is the localized elastic modulus of the performance infill layer, $A(t)$ is the area of the stud perpendicular to the pushing direction, $\Delta x(t)/r(t)\Delta\theta(t)$ is the displacement of the stud through the performance infill layer, $r(t)$ is the net radial position of the stud (from the center of rotation), and x_0/L_0 is the zero strain performance infill layer length.

It is further hypothesized that, for large stud displacements, the high-density zone in front of each stud reaches a steady-state size leading to a plateau in resistance. More specifically, as the compressed zone grows a shear plane forms along the sides through which performance infill is lost. At some critical stud displacement $\Delta x_{\text{CRIT}}(t)/[r\Delta\theta]_{\text{CRIT}}(t)$, a steady state is reached, where the net volume gain of the high-density compression zone is zero, ie, the performance infill material "lost" from the sides and behind the compressed zone is balanced by that "gained" at the front of the zone (Figure 3C). This steady-state stud displacement resistance force ($F(t)$) /torque ($T(t)$) plateau is given by

$$\Delta x(t) \geq \Delta x_{\text{CRIT}}(t) : \qquad F(t) = A(t) \times \left(\frac{E(t) \times \Delta x_{\text{CRIT}}(t)}{x_0} \right) \tag{7}$$

$$r(t)\Delta\theta(t) \geq [r\Delta\theta]_{\text{CRIT}}(t) : \qquad T(t) = A(t) \times r(t) \times \left(\frac{E(t) \times [r\Delta\theta]_{\text{CRIT}}(t)}{L_0} \right). \tag{8}$$

Note that the critical displacement is a function of the normal stress applied to the performance infill layer (since the normal stress affects the local elastic modulus of this layer, $E(t)$), and, therefore, can change during a movement.

For simplicity, the foregoing has considered the situation of a single stud moving within the confined and compressed performance infill layer beneath the outsole. Real outsoles are configured with multiple studs with several implications for the traction response. The critical stud displacement condition may never be reached due to the high-density zone in front of a stud encountering a lower density performance infill zone triggering a decrease in resistance. This low-density zone may have been left by another stud or represent the boundary of the performance infill layer confined by the outsole. For example, the Fédération Internationale de Football Association (FIFA) rotational traction test[6] typically demonstrates a peak torque at around 40° corresponding to the compressed zone of performance infill in front of each stud extending into the lower density zone of performance infill left by the preceding stud (Figure 4).[21] This principal is used in the forefoot region of current outsole designs to help minimize rotational resistance; the studs are arranged in an oval pattern with minimal stud spacing leaving little room for the development of a large compressed zone in front of each stud and, hence, for the build-up of resistance (Figure 1F). Furthermore, considering each stud to exist with an expanding zone of high-density performance infill in front ultimately leads to stud-infill zone interaction effects. This may explain the lower than expected total resistance observed experimentally when multiple studs are present either in series or parallel[21] negating the use of simple superposition to estimate the resistance from multiple studs.

2.4 | Limitations

The hypothesized mechanisms and mechanical equations detailed earlier represent the first stage in the conceptual framework for boot-surface traction. Some support for these mechanisms and equations has already been demonstrated.[8] However, it should be emphasized that there is currently limited direct experimental evidence for these mechanisms, particularly related to the important contribution of studs displacing through the performance infill layer. Thus, it is expected that future refinements will be needed as scientific understanding progresses. Furthermore, it should also be emphasized that real-player boot-surface interactions are complex and not all this complexity has been represented within the aforementioned equations. For example, many outsoles are contoured rather than flat, which may lead to additional resistance mechanisms to those detailed earlier.

Although previous studies have suggested that stud-surface friction contributes to the traction forces,[21,81] the aforementioned description of how the studs and performance infill layer interact suggest that this may be negligible for 3G turf surface systems. The performance infill around the leading edge of the stud sits within the compressed zone, which displaces with the stud, suggesting that the interface shear forces are too small to overcome the static friction between the stud and performance infill.

3 | CONCEPT MAP DEVELOPMENT

Stage two of the framework is the development of a Concept Map identifying the variables that directly affect the traction response during boot-surface interactions. Map development followed the process outlined by Trochim[85] with the main steps outlined below.

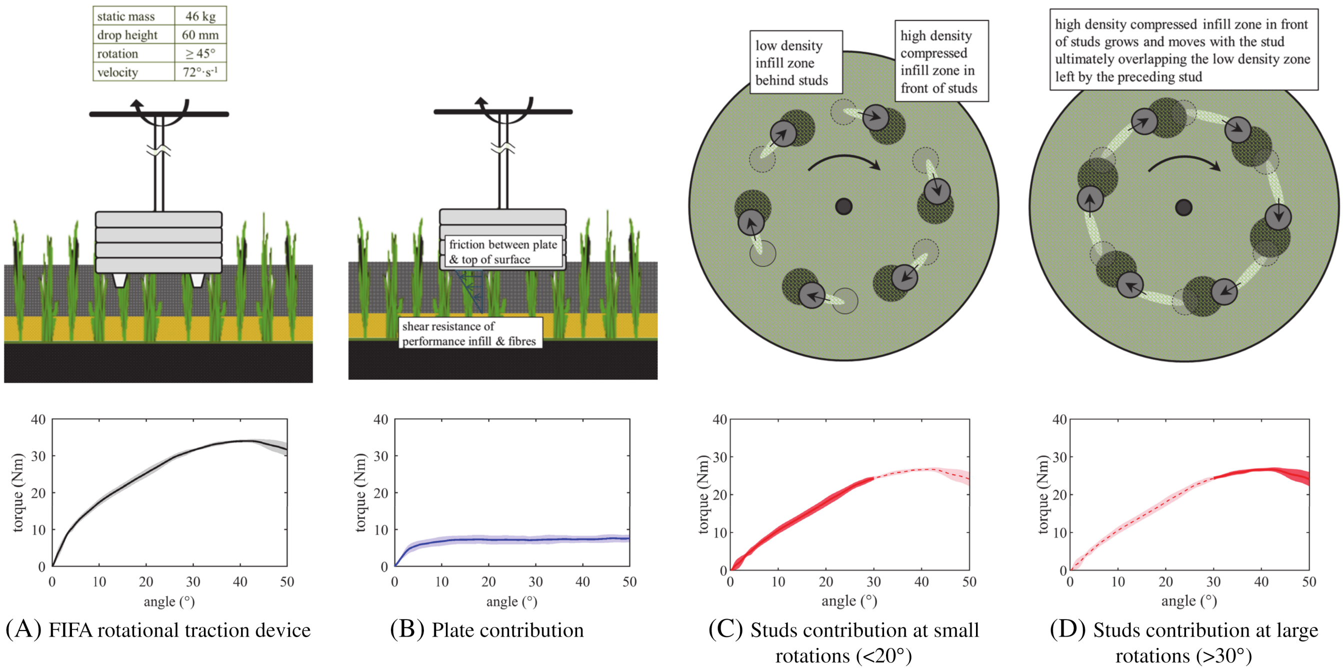

FIGURE 4 Schematic demonstrating the relationship between the typical torque-angle profile obtained from a Fédération Internationale de Football Association (FIFA) rotational traction test and the mechanisms of shear resistance contributing to this profile. A, FIFA rotational traction device[6] and a typical torque-angle output profile[8]; B, Plate contribution to the shear resistance which plateaus when the coefficient of friction is overcome; C, Small rotation angles studs contribution to the shear resistance showing an approximately linear increase in resistance as angle increases; D, Large rotation angles studs contribution to the shear resistance showing a plateau or peak followed by reduced resistance corresponding to the high density compressed infill zone in front of each stud overlapping the low density less compressed infill left in the path of the preceding stud. For simplicity the performance infill and fibres have been combined in these schematics and the darker the shading the higher density the performance infill

The preparation step defined the focus for the conceptualization. In brief, the intention was to include all variables that could directly affect the traction forces during boot-surface interactions on 3G turf, structured to provide a simple visualization of their hierarchy.

To identify variables a three-step approach was used, firstly, all variables within the analytical mechanical equations (Equations (1)-(8)) were included. Secondly, the existing literature was scrutinized to identify all independent variables that had been included within 3G turf boot-surface traction studies. If there was strong evidence to support the variable affecting traction forces, the variable was automatically included. Strong evidence was based on either statistical significance (or approaching significance, ie, $p < 0.10$) being reported for at least one direct measure of traction or where no direct measures were reported, statistical significance in at least one indirect measure of traction. If there was weak or no evidence, the variable was discussed in the context of the mechanisms and a decision was made on whether it should be included. Thirdly, the authors brainstormed for the inclusion any further variables, not already identified, which could affect traction based on the hypothesized mechanisms.

Identification of relevant existing literature was performed in January 2019 and an inclusive approach was used where no study was ruled out based on quality of the evidence provided (Figure 5). Sources included journal papers, conference papers, and postgraduate theses on player and mechanical assessment of traction and both direct (horizontal forces/torques) and indirect (lower limb joint loading and/or time to complete a specific traction related movement) traction measures. Player studies typically involved high traction demand tasks such as sprinting or cutting and included both direct and indirect traction measures. Mechanical studies included both rotational and translational traction measures and a wide variety of mechanical test rig designs ranging from the simple FIFA rotational traction device[6] through to bespoke devices claiming more biofidelic set-ups. While most mechanical tests involved complete boots/outsoles, a few also described more controlled baseplates allowing different stud designs and configurations to be studied. For each source, the independent variable(s) and the strength of evidence for each independent variable affecting traction were recorded.

This process resulted in 53 unique literature sources (Tables 1 and 2). Some sources considered multiple independent variables and/or included both player and mechanical testing, which gave a total of 123 studies, where a specific

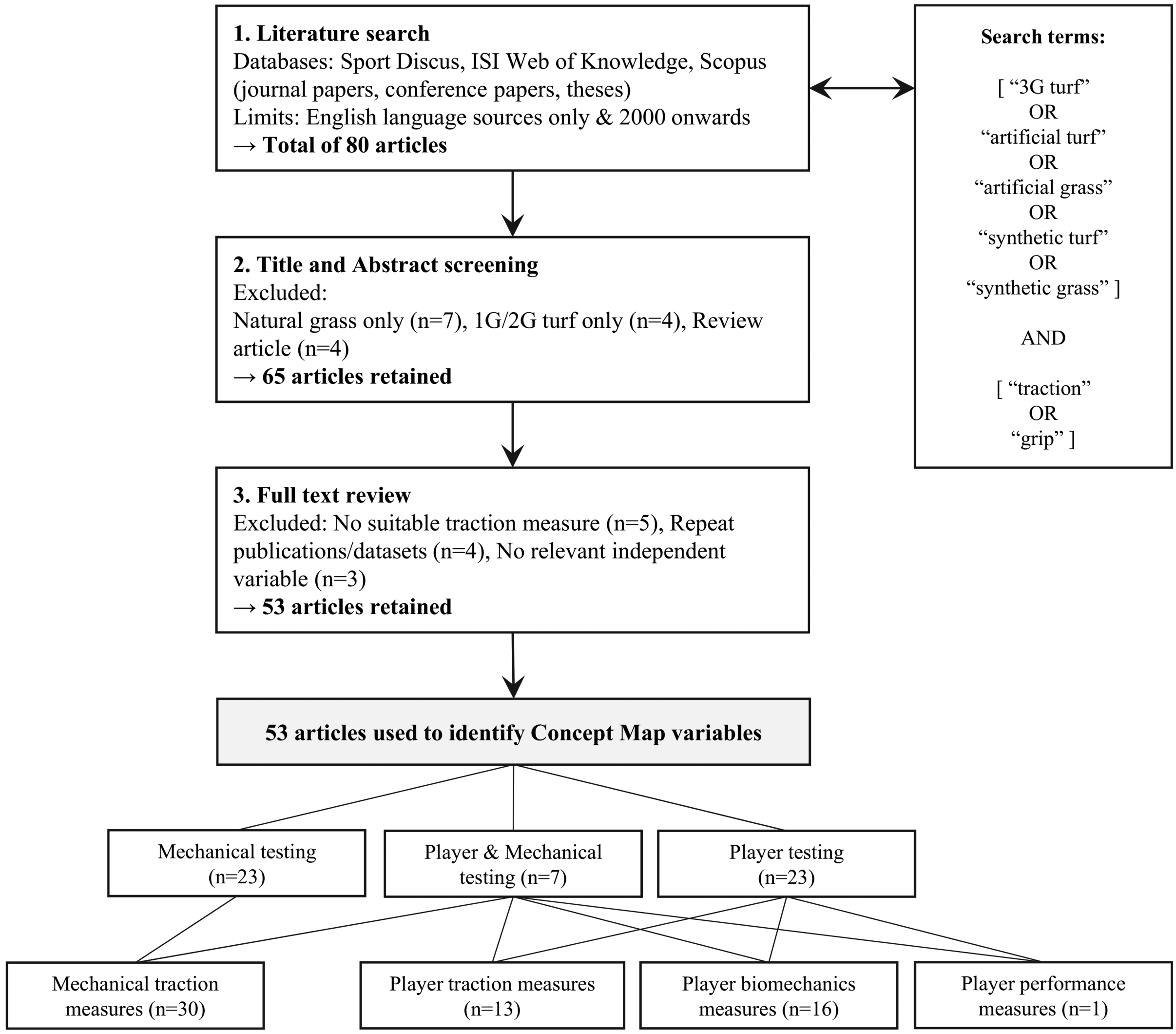

FIGURE 5 Summary of the systematic review process used to identify Concept Map variables

independent variable was investigated using either player or mechanical testing. Overall, there have been fewer player studies compared to mechanical (43 player vs 80 mechanical). This was particularly the case for surface related variables (8 player vs 37 mechanical), whereas, for the remaining, the split between player and mechanical was more even. Variables related to the boot and surface have been investigated most frequently (45 studies each) with the player (26 studies) and environment (7 studies) less so. However, for the boot, only 9 studies have focused on a specific variable, whereas 36 have compared multiple commercial/prototype boots for which several independent variables differed between experimental conditions. In general, the surface investigations have been more rigorous with 31 studies focused on a specific variable, and only 14 having compared multiple 3G turf surfaces where several independent variables differed between experimental conditions. Thus, of the 123 studies, 73 have been based on a controlled study of a single independent variable and the remaining 50 have combined multiple independent variables within the same study providing results that are more difficult to interpret from the perspective of advancing fundamental knowledge and understanding on traction.

This variable identification process led to a list of 39 variables; 22 have been previously investigated and found to affect traction or traction related measures, 2 have been investigated and found not to affect traction or traction related measures, whereas 15 have not been directly investigated (Table 1). The two contradictory findings related to the surface variables of usage and maintenance where the single study conducted by Burillo et al[57] reported neither to affect rotational traction[6]; however, this was based on an interpitch study, where the interpitch variance in other surface variables may have been too high to identify any usage and/or maintenance effects on traction. Among those variables not previously investigated, the boot outsole features heavily (four variables) with previous boot studies having focused entirely on the studs. Player technique has not been studied but its contribution appears intuitive given that changes in the player kinematics and kinetics during ground contact affect variables such as normal stress and center of rotation and, therefore, traction forces. Performance infill shape has not been studied in isolation but has been a potential confounding factor in studies investigating different performance infill materials.[56,58] Carpet fibre material is the other surface variable not previously investigated but with the potential to affect outsole friction and shear resistance forces.

Only two variables that have been reported to affect traction or traction related measures were excluded from the list (Table 2); the presence of a shockpad[60] and the stabilizing infill (sand) net bulk density.[20,22] The mechanisms by which these variables might affect traction were not identified within these studies. Furthermore, other (laboratory-based) studies have found the presence of a shockpad to have no effect on traction forces.[20,59] The shockpad effects[60] were observed in situ as pitches aged and may have represented the indirect effects of the shockpad affecting the change in state of the performance infill layer over time which, in turn, affected the traction forces.[86]

Following on from variables generation, the structuring step involved grouping the 39 variables identified. This was based on which of the traction system contributing factors (player, boot, surface, and environment) they related to, with a secondary classification based on whether they could be considered constant for the duration of the interaction or dynamic. This led to the definition of nine groups of variables:

1-6: Player, Boot Design, 3G Turf Design, 3G Turf History, 3G Turf State, and Environment. The variables in each of these six groups remain constant throughout the interaction and relate to only one of the four contributing factors, ie, player, boot, surface, or environment. To recognize that 3G turf state can change over time due to aging, usage, and maintenance, the 3G Turf variables have been split into those related to the original surface design (3G Turf Design), those related to the surface history (3G Turf History), and the combination of these, which determines the current state of the surface (3G Turf State).

7-9: Player Dynamics, Player-Boot Dynamics, and Traction System Dynamics. The variables in each of these three groups are time dependent, ie, they can change during the boot-surface interaction. Of the four contributing factors, only the player can generate dynamic variables, eg, ground reaction forces. Player-Boot Dynamics are variables dependent on both the player and boot, eg, the number of studs in contact at a given instant. While Traction System Dynamics refers to variables that depend on Player-Boot Dynamics, 3G Turf State, and Environment variables, eg, the performance infill layer shear modulus.

The Concept Map representation step organized these nine groups of variables to visually reflect the top-to-bottom structure of real-player boot-surface interactions (Figure 6). The player groups were placed at the top of the Map, followed by the player-boot interface, the boot, the boot-surface interface, and the surface groups at the bottom. This resulted in a visually accessible representation of how each variable contributes to the generation of traction forces at the boot-surface interface.

Although application of the Concept Map is outside the scope of this study, potential applications were discussed as part of the variable identification and structuring processes. Most importantly, in terms of progressing scientific understanding on traction, the Concept Map provides a checklist of variables that should be reported in all studies investigating boot-surface traction on 3G turf. A weakness of the existing literature is that, while most of the Player, Player Dynamics, and Boot Design variables have been reported, variables in the Surface groups have often been excluded with several studies doing little more than reporting that a 3G turf surface was used. Given the diversity of 3G turfs available and the number of Surface Design, History and State variables that can affect traction (Figure 6 and Tables 1 and 2), it is critical for future studies to be more rigorous in reporting details of the surface(s) used if the outcomes are to contribute to advancing scientific understanding. The Concept Map can also help to direct future research by providing a useful summary of current evidence on the effect of each variable on traction. Notably, the Map has identified 15 variables that may affect traction but have yet to be directly investigated. Finally, as scientific understanding progresses and the Concept Map evolves, then the Map can also provide a useful tool for boot and surface designers by detailing the links between design features and their effect on traction; relevant to the fine-tuning of designs to achieve the desired traction response.

Limitations of the Concept Map should be recognized. The first is that variables indirectly affecting traction have been excluded. This was done to minimize the visual complexity of the Map without comprising future applications. The Map is intended to be a useful first iteration, with some evaluation through the three-step approach to variable identification and the discussions around utilization. As with every stage of the framework, it is expected that refinements will be needed as scientific understanding develops, potentially through the addition of further variables or allowing variables to be ranked based on their effect size.

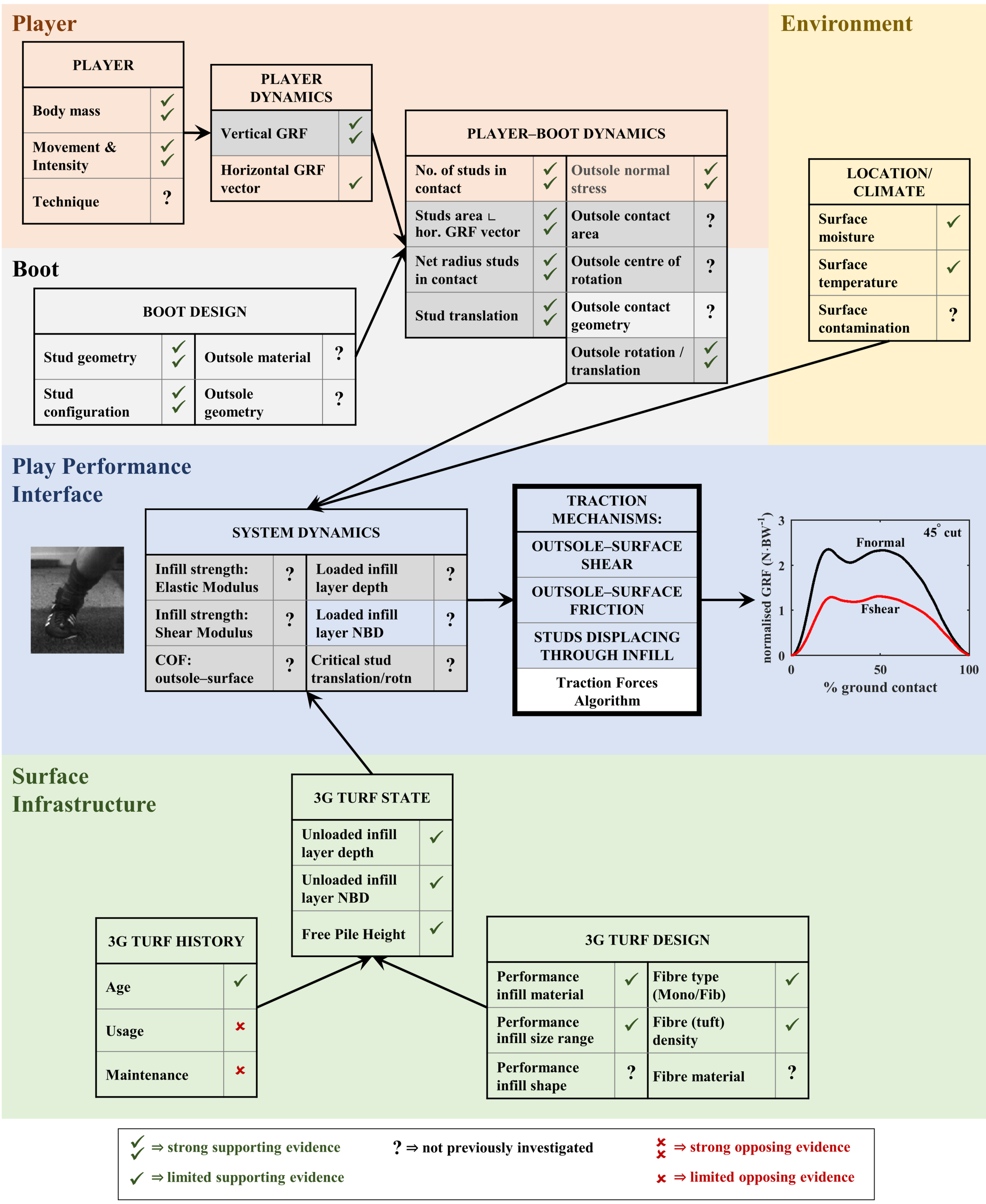

FIGURE 6 The Concept Map for 3G turf traction detailing the individual component and traction system variables affecting boot-surface traction. The gray shaded boxes represent that feature in the traction mechanisms equations (Equations (1)-(8)), the remaining were identified from the relevant existing literature or by the authors based on the hypothesized traction mechanisms. Also indicated is the weight of existing evidence for the effect of each variable. For simplicity, direct links are provided only between the groups of variables. NBD = net bulk density of the performance infill layer[20]

4 | RESEARCH ROADMAP

Stage three of the framework is the development of a Research Roadmap providing a structured pathway to building scientific understanding of boot-surface interactions on 3G turf surfaces (Figure 7). The Roadmap is split into three steps progressing from a focus on the individual traction mechanisms, through simple mechanical traction systems, to more complex mechanical systems and real-player boot-surface interactions. The first step focuses on understanding the traction mechanisms hypothesized within this paper. From a traction systems perspective this represents the lowest complexity; however, from a research perspective, there are substantial challenges particularly in the development of mechanical tests and measurement systems to capture the response of the performance infill layer to the displacing

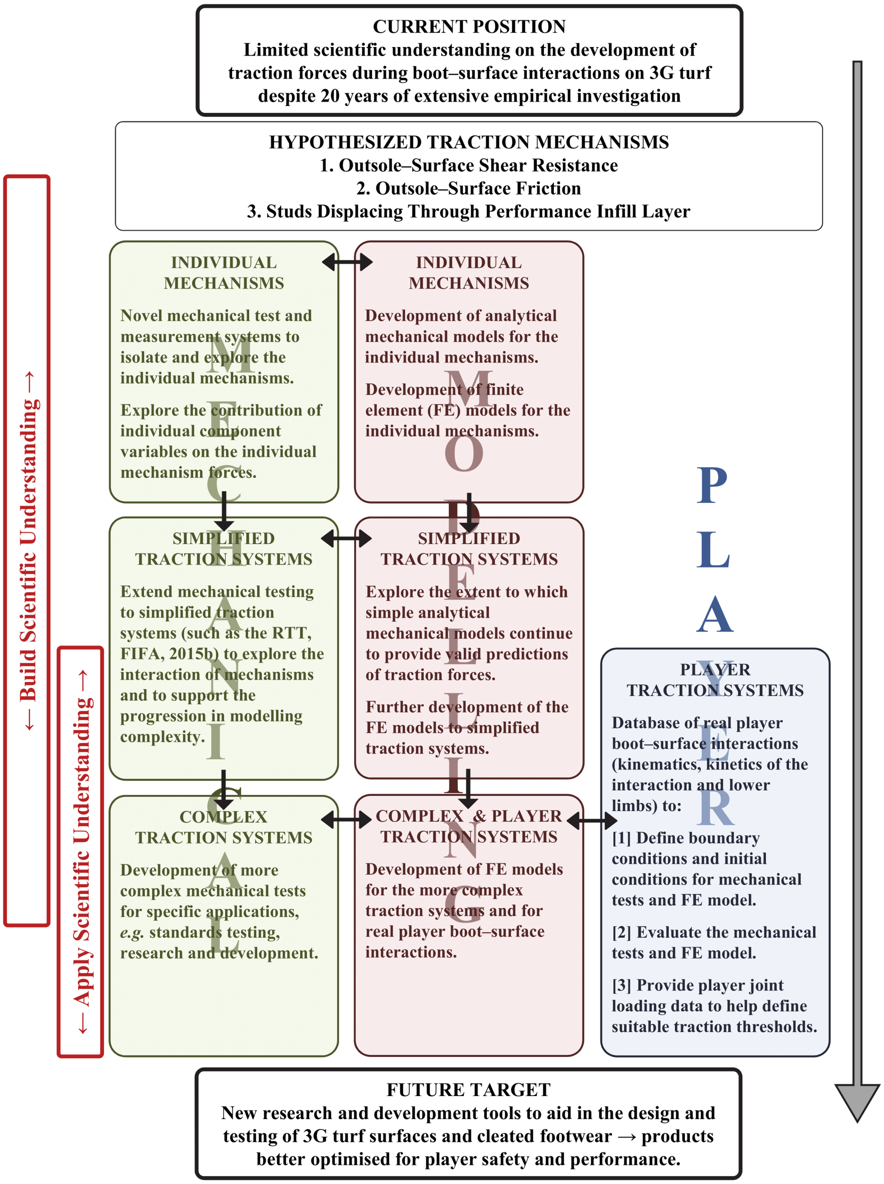

FIGURE 7 The Research Roadmap to help guide future studies aimed toward building scientific understanding on boot-surface traction through a mechanistic approach

stud(s). Although motion analysis methods exist for indirectly tracking stud movement during the contact phase,[87,88] tracking of the fine particulate performance infill has yet to be reported. The second step progresses from the individual mechanisms to focus on simple (mechanical) traction systems, eg, fixed normal stress and contact area applied by the outsole,[6] to further understanding on the mechanisms and their interaction. Thereafter, the third step involves progressively more complex traction systems and real-player boot-surface interactions to provide further scientific understanding that builds on that gained in the earlier steps. The outcomes from this final step are expected to lead to the development of novel tools for designing and testing 3G turf surfaces and studded footwear.

Throughout the three steps, three parallel and interlinked research methods are included; mechanical testing, modeling, and player testing. The mechanical testing is expected to provide much of the early understanding as a relevant means to explore the individual mechanisms and build complexity of the traction system in a controlled stepwise manner. Furthermore, it is expected that mechanical testing will remain the benchmark for the testing of surfaces for governing body approval, eg,[6] due to the advantages it provides over player-based testing. Modeling runs in parallel with the mechanical testing throughout (analytical and numerical). In the early steps, this may lend support to the challenges in physically measuring the response of the performance infill layer to displacing stud(s). In the latter steps, the application of finite element modeling within the design process for 3G turf and studded footwear represents a valuable tool for more efficiently assessing different materials, geometries, and traction scenarios. The player testing is suggested to commence when traction systems become the focus and is needed to support both the mechanical and modeling developments, eg, providing relevant boundary conditions and as an evaluation tool.

The proposed Roadmap provides a structured and logical means of building scientific understanding of the traction forces developed during boot-surface interactions. Its fundamental importance and uniqueness is in the ability to not only identify the key traction measures relevant to player safety and performance but also the mechanisms and variables that have the greatest effect on these measures. For example, the currently hypothesized mechanisms indicate that peak force/torque is likely dominated by stud displacement resistance due to the large displacements typically involved; however, the early stiffness response (as originally suggested by Livesay et al[26]) is likely to be more evenly balanced between outsole and studs contributions. Finally, it should be reinforced that the standardized reporting of traction systems investigated (based on the variables presented in the Concept Map) runs throughout the Roadmap, allowing the outcomes from each study to be used by others engaged in this framework.

5 | DISCUSSION

A framework for advancing scientific understanding on boot-surface traction for 3G turf based on a novel mechanistic approach has been presented. The underlying significance of this framework is the on-going need to minimize injury risk associated with boot-surface traction combined with the limited success of the current empirical approach. It is proposed that advancing scientific understanding of the mechanisms underpinning the generation of traction forces provides a more direct solution to achieving safer boots and surfaces. The first stage hypothesized the mechanisms that contribute to the development of traction forces and the associated analytical mechanical equations as informed by existing literature and the authors' experience. Three mechanisms were identified as outsole-surface friction, outsole-performance infill layer shear resistance, and stud-performance infill layer displacing resistance. The second stage used the equations and the existing literature to develop a Concept Map detailing the hierarchy of variables that influence the traction forces developed. Evidence currently exists for 22 of the 39 variables to affect traction, a further 15 have not been directly investigated, and only two have weak evidence to suggest that they do not affect traction. The third stage involved the development of a Research Roadmap to assist in the design and direction of future studies on traction aiming to advance scientific understanding. Overall, the framework has the potential to provide a more efficient route to designing traction systems for reduced injury risk (or increased performance) and to developing improved traction testing methods and standards for 3G turf.

The hypothesized traction mechanisms partly reflected those described in previous studies for natural grass surfaces. However, it has been suggested that crumbed rubber, commonly used as the performance infill for 3G turf surfaces, responds to loading very differently in the zone around the stud compared to soil due to differences in fundamental material properties such as compressibility and elasticity.[80] Based on what is known regarding the material properties of crumbed rubber and indirect experimental observations, it was hypothesized that the performance infill compresses and displaces with the stud, creating a local high-density performance infill zone that builds up in front of each stud. As the stud displacement continues, this local high-density performance infill zone grows, reaching a steady-state volume at some critical stud displacement dependent on the normal stress applied to the surface through the outsole. However, it should be noted that direct experimental evidence supporting this mechanism is currently lacking, at least in part due to the challenge in tracking the performance infill material beneath the outsole.

The development of the traction mechanisms and related Concept Map required some simplifying assumptions. For example, the vertical forces generated by a player will depend on the surface response to vertical loading; this has been neglected on the assumption that these effects are likely to be smaller than those of the identified Player variables. In addition, the response of the performance infill layer to displacing studs has only qualitatively described the situation where the high-density zones from multiple studs interact or extend beyond the confined outsole area into a lower density performance infill region. However, these simplifications do not reduce the scope or applicability of the framework, which should be considered as a flexible and evolving tool, particularly with respect to the traction mechanisms. The intent of this paper is to provide a robust and applicable starting point for the framework and encourage scientific understanding to be built through this mechanistic approach.

Traction during boot-surface interactions on 3G turf has been widely investigated over the last 20 years. A total of 53 unique sources were used within the development of the Concept Map containing 123 independent variables. Around 40% have been empirical and focused of benchmarking multiple boots and/or surfaces in which many variables differed between experimental conditions making it difficult to generate any meaningful conclusions. This approach has presumably been driven by the large commercial interest associated with studded footwear development. The remaining 60% was also empirical but more controlled in terms of focusing on a single variable with normal load (or, more correctly, normal stress), movement type, stud geometry, and surface wetness being the most commonly investigated. The majority were focused on assessing the effect of a given variable (or variables) on measures of traction force/torque, with little focus on the mechanisms that control this force/torque, at best including some comments within the discussion but without any follow up. In general, these studies have provided clearer evidence for the Player and Boot Design related variables affecting traction; evidence regarding the Surface Design/History/State and Environment variables has been more mixed. This may indicate that the Surface Design/History/State and Environment variables have a lesser effect on traction, certainly within the ranges investigated. However, this statement should be treated with caution given the current lack of knowledge on the most relevant measure of traction. The early stiffness response (ie, the rate of change of shear force/torque with displacement) has recently been argued to be more relevant to players and may have significant outsole and stud contributions. Peak force/torque continues to be more widely used, however, and occurs at a much greater displacement where the stud contribution dominates; representing a possible reason why boot related variables have generally been found to have greater influence than surface related variables.

Although this paper has focused on the development of the framework, it is relevant to discuss how the framework might be applied. To demonstrate the potential insights gained from the proposed framework, the normal stress applied to the surface affects both the shear and elastic moduli of the performance infill layer. Defining how these vary with normal stress appears important to understanding the traction system response. Several Surface Design/History/State variables also affect these values and a better understanding of this would enhance the surface design process. In terms of Boot related variables, outsole-surface friction is relevant in defining the extent of surface shear prior to sliding; reducing this may represent a means to attenuate the initial high stiffness response experienced by players. Furthermore, the mechanisms suggest that, once the shear forces exceed the outsole-surface friction, stud geometry and configuration dominate the boot contribution to traction. Notably, while the player can control the extent of outsole and stud interaction, these represent only one of many factors affecting the shear and elastic moduli of the performance infill layer.

The framework can be considered particularly timely given recent investigations into public health associated with the use of crumbed SBR from recycled tyres as the performance infill for 3G turf pitches.[89] At present, it remains the infill of choice due to the reduced cost compared to nonrecycled products; however, new regulations may drive the need to look for alternatives. With none readily available at a similar cost, this may open the door to performance infill selection being based on factors other than cost and, potentially, the scope to use infills to achieve specific traction responses, eg, to minimize injury risk or to better match the traction response of high-quality natural grass. The framework can provide a strong basis for identifying performance infill materials targeted toward specific traction responses. A similar argument applies to situations where cost may not be the primary factor driving performance infill selection, such as at the top level of professional football (and rugby). Crumbed SBR is still commonly used in these situations, presumably due to the current lack of understanding as to what a safer or better performing alternative might be.

The framework proposes a step change in how traction is investigated. The focus on building scientific understanding through the mechanisms that contribute to the generation of traction forces appears a logical approach toward the design of safer boots and surfaces, particularly given the limited progress achieved through the empiricism of the last 20 years. However, there are challenges to exploring some the hypothesized mechanisms due to current limitations related to measuring the response of the performance infill layer to the outsole and studs. Thus, much research is needed to simply confirm or corroborate what has been proposed within this paper before more advanced understanding can be sought. Regardless, traction related injuries remain a significant burden (in both time loss and cost) and the current empirical approach to improving this situation has met with, at best, limited success. When combined with the on-going development of new surfaces and boots, it appears that a more scientifically rigorous approach to studying traction is needed; to this end, the proposed mechanistic approach represents a novel and much needed solution.

6 | CONCLUSIONS

The traction forces generated during studded boot-surface interactions on 3G turf surfaces affect player performance and injury risk. The prevalent empirical approach to studying traction has met with limited success in the development of safer surfaces and boots, with traction related injuries remaining an on-going concern.

This perspective article has proposed a novel mechanistic approach to generate the scientific understanding needed to support the design of safer 3G turf surfaces and boots. A three-stage conceptual framework has been developed, representing the first attempt to deconstruct boot-surface interactions and hypothesize the science behind the mobilization of traction forces. This framework has indicated that initial research should focus on better understanding the science behind the three hypothesized traction mechanisms; in particular, how the confined and compressed crumbed rubber and reinforcing carpet fibres that form the performance infill layer respond to the displacing studs. Thereafter, scientific understanding should be built through increasing the complexity of the traction systems studied in a stepwise manner progressing toward real-player boot-surface interactions. Adoption of this framework has significant potential not only within the development of safer surfaces and boots but also toward improved mechanical tests to assess surface safety.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Steph Forrester, Conceptualization-Equal, Formal analysis-Equal, Investigation-Lead, Writing-original draft-Lead, Writing-review & editing-Lead; Paul Fleming, Conceptualization-Equal, Formal analysis-Equal, Investigation-Supporting, Writing-original draft-Supporting, Writing-review & editing-Supporting.

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REFERENCES

1. Forrester SE, Tsui F. Spatial and temporal analysis of surface hardness across a third-generation artificial turf pitch over a year. *Proc Inst Mech Eng P J Sports Eng Technol*. 2014;228(3):213-220.
2. James IT. Advancing natural turf to meet tomorrow's challenges. *Proc Inst Mech Eng P J Sports Eng Technol*. 2011;225(3):115-129.
3. Blackburn S. *The Biomechanical Interaction Between Sports Players and Artificial Turf for the Development of a Validated Artificial Turf Testing Rig* [doctoral dissertation]. Glasgow, Scotland: University of Strathclyde; 2012.
4. Sterzing T, Müller C, Hennig EM, Milani TL. Actual and perceived running performance in soccer shoes: a series of eight studies. *Footwear Science*. 2009;1(1):5-17.
5. Silva DCF, Santos R, Vilas-Boas JP, Macedo R, Montes AM, Sousa ASP. Influence of cleats-surface interaction on the performance and risk of injury in soccer: a systematic review. *Appl Bionics Biomech*. 2017;1305479.
6. Fédération Internationale de Football Association (FIFA). FIFA quality concept: handbook of test methods. 2015. http://quality.fifa.com/en/Football-Turf/. Accessed January 1, 2019.
7. Fujikake K, Yamamoto T, Takemura M. A comparison of the mechanical characteristics of natural turf and artificial turf football pitches. *Football Science*. 2007;4:1-8.
8. Forrester S, Montgomery J, Fleming P. Modelling traction forces during studded boot–surface interactions. In: Proceedings of the 42nd Annual Meeting of the American Society of Biomechanics; 2018; Rochester, MN.
9. Valiant GA. Traction characteristics of outsoles for use on artificial playing surfaces. In: *Natural and Artificial Playing Fields: Characteristics and Safety Features*. West Conshohocken, PA: ASTM International; 1990:61-68.
10. Worobets J, Wannop JW. Influence of basketball shoe mass, outsole traction, and forefoot bending stiffness on three athletic movements. *Sports Biomechanics*. 2015;14(3):351-360.
11. Luo G, Stefanyshyn D. Identification of critical traction values for maximum athletic performance. *Footwear Science*. 2011;3(3):127-138.
12. Barry B, Milburn P. Tribology, friction and traction: understanding shoe-surface interaction. *Footwear Science*. 2013;5(3):137-145.
13. Potthast W. Motion differences in goal kicking on natural and artificial soccer turf systems. *Footwear Science*. 2010;2(1):29-35.
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 Technology*. 2010;3(1):5-12.
15. Serensits TJ, McNitt AS. Comparison of rotational traction of athletic footwear on varying playing surfaces using different normal loads. *Appl Turfgrass Sci*. 2014;11(1).
16. Kent R, Forman JL, Crandall J, Lessley D. The mechanical interactions between an American football cleat and playing surfaces *in-situ* at loads and rates generated by elite athletes: a comparison of playing surface. *Sports Biomechanics*. 2015;14(1):1-17.
17. Kent R, Forman JL, Lessley D, Crandall J. The mechanics of American football cleats on natural grass and infill-type artificial playing surfaces with loads relevant to elite athletes. *Sports Biomechanics*. 2015;14(2):246-257.
18. Severn KA, Fleming PR, Clarke JD, Carré MJ. Science of synthetic turf surfaces: investigating traction behaviour. *Proc Inst Mech Eng P J Sports Eng Technol*. 2011;225(3):147-158.

19. Severn KA, Fleming PR, Dixon N. Science of synthetic turf surfaces: player–surface interactions. *Sports Technology*. 2010;3(1):13-25.
20. Severn K. *Player Surface Interactions: Traction on Artificial Turf* [doctoral dissertation]. Loughborough, UK: Civil Engineering, Loughborough University; 2010.
21. Webb CH. Mechanical Traction Behaviour of Artificial Turf [doctoral dissertation]. Loughborough, UK: Civil Engineering, Loughborough University; 2016.
22. Sánchez-Sánchez J, García-Unanue J, Gallardo AM, Gallardo L, Hexaire P, Felipe JL. Effect of structural components, mechanical wear and environmental conditions on the player–surface interaction on artificial turf football pitches. *Mater Des*. 2018;140:172-178.
23. Kuhlman S, Sabick M, Pfeiffer R, Cooper B, Forhan J. Effect of loading condition on the traction coefficient between shoes and artificial turf surfaces. *Proc Inst Mech Eng P J Sports Eng Technol*. 2010;224(2):155-165.
24. Wannop JW, Stefanyshyn DJ. The effect of normal load, speed and moisture on footwear traction. *Footwear Science*. 2012;4(1):37-43.
25. Smeets K, Jacobs P, Hertogs R, et al. Torsional injuries of the lower limb: an analysis of the frictional torque between different types of football turf and the shoe outsole. *Br J Sports Med*. 2012;46(15):1078-1083.
26. Livesay GA, Reda DR, Nauman EA. Peak torque and rotational stiffness developed at the shoe-surface interface: the effect of shoe type and playing surface. *Am J Sports Med*. 2006;34(3):415-422.
27. Müller C, Sterzing T, Lake M, Milani TL. Different stud configurations cause movement adaptations during a soccer turning movement. *Footwear Science*. 2010;2(1):21-28.
28. Müller C, Sterzing T, Milani T. Stud length and stud geometry of soccer boots influence running performance on third generation artificial turf. ISBS-Conference Proceedings Archive. 2009.
29. Clarke JD, Carré MJ. Improving the performance of soccer boots on artificial and natural soccer surfaces. *Procedia Engineering*. 2010;2(2):2775-2781.
30. De Clercq D, Debuyck G, Gerlo J, Rambour S, Segers V, Van Caekenberghe I. Cutting performance wearing different studded soccer shoes on dry and wet artificial turf. *Footwear Science*. 2014;6(2):81-87.
31. Ekstrand J, Nigg BM. Surface-related injuries in soccer. *Sports Medicine*. 1989;8(1):56-62.
32. Lambson RB, Barnhill BS, Higgins RW. Football cleat design and its effect on anterior cruciate ligament injuries: a three-year prospective study. *Am J Sports Med*. 1996;24(2):155-159.
33. Durá JV, Hoyos JV, Martinez A, Lozano L. The influence of friction on sports surfaces in turning movements. *Sports Engineering*. 1999;2:97-102.
34. McGhie D, Ettema G. Biomechanical analysis of traction at the shoe-surface interface on third-generation artificial turf. *Sports Engineering*. 2013;16(2):71-80.
35. Ekstrand J, Hägglund M, Fuller CW. Comparison of injuries sustained on artificial turf and grass by male and female elite football players. *Scand J Med Sci Sports*. 2011;21(6):824-832.
36. Rahnama N, Manning LK. Mechanisms and characteristics of injuries in youth soccer. In: *Science and Football V: The Proceedings of the Fifth World Congress on Sports Science and Football*. London, UK: Routledge; 2005.
37. Ball DJ. Risks of injury - an overview. In: Harries M, Malatchie G, Williams C, King J, eds. *ABC of Sports Medicine*. London, UK: BMJ Books; 2000:88-91.
38. Heidt RS Jr, Dormer SG, Cawley PW, Scranton PE Jr, Losse G, Howard M. Differences in friction and torsional resistance in athletic shoe-turf surface interfaces. *Am J Sports Med*. 1996;24(6):834-842.
39. Milburn PD, Barry EB. Shoe-surface interaction and the reduction of injury in rugby union. *Sports Medicine*. 1998;25(5):319-327.
40. Wannop JW, Luo G, Stefanyshyn DJ. Footwear traction and lower extremity noncontact injury. *Med Sci Sports Exerc*. 2013;45:2137-2143.
41. Porter DA, Schon LC. *Baxter's The Foot and Ankle in Sport*. Philadelphia, PA: Elsevier Health Sciences; 2007.
42. Myklebust G, Maehlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports*. 1998;8(3):149-153.
43. Myklebust G, Maehlum S, Engebretsen L, Strand T, Solheim E. Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scand J Med Sci Sports*. 1997;7(5):289-292.
44. Wannop JW, Worobets JT, Stefanyshyn DJ. Footwear traction and lower extremity joint loading. *Am J Sports Med*. 2010;38(6):1221-1228.
45. Nigg BM, Yeadon MR. Biomechanical aspects of playing surfaces. *J Sports Sci*. 1987;5(2):117-145.
46. Thomson A, Whiteley R, Bleakley C. Higher shoe-surface interaction is associated with doubling of lower extremity injury risk in football codes: a systematic review and meta-analysis. *Br J Sports Med*. 2015;49(19):1245-1252.
47. Hershman EB, Anderson R, Bergfeld JA, et al. An analysis of specific lower extremity injury rates on grass and FieldTurf playing surfaces in National Football League Games: 2000-2009 seasons. *Am J Sports Med*. 2012;40(10):2200-2205.
48. Brock E, Zhang S, Milner C, Liu X, Brosnan JT, Sorochan JC. Effects of two football stud configurations on biomechanical characteristics of single-leg landing and cutting movements on infilled synthetic turf. *Sports Biomechanics*. 2014;13(4):362-379.
49. Bennett HJ, Brock E, Brosnan JT, Sorochan JC, Zhang S. Effects of two football stud types on knee and ankle kinetics of single-leg land-cut and 180 cut movements on infilled synthetic turf. *J Appl Biomech*. 2015;31(5):309-317.
50. Strutzenberger G, Cao H-M, Koussev J, Potthast W, Irwin G. Effect of turf on the cutting movement of female football players. *J Sport Health Sci*. 2014;3(4):314-319.
51. Kaila R. Influence of modern studded and bladed soccer boots and sidestep cutting on knee loading during match play conditions. *Am J Sports Med*. 2007;35(9):1528-1536.
52. Wong P, Chamari K, Mao DW, Wisløff U, Hong Y. Higher plantar pressure on the medial side in four soccer-related movements. *Br J Sports Med*. 2007;41(2):93-100.
53. Galbusera F, Tornese DZ, Anasetti F, et al. Does soccer cleat design influence the rotational interaction with the playing surface? *Sports Biomechanics*. 2013;12(3):293-301.

54. McGhie D, Ettema G. On the 'trench effect' theory: a biomechanical analysis of the relationship between traction and shoe orientation on third-generation artificial turf. *Footwear Science*. 2014;6(1):41-50.
55. Villwock MR, Meyer EG, Powell JW, Fouty AJ, Haut RC. Football playing surface and shoe design affect rotational traction. *Am J Sports Med*. 2009;37(3):518-525.
56. Zanetti EM, Bignardi C, Franceschini G, Audenino AL. Amateur football pitches: mechanical properties of the natural ground and of different artificial turf infills and their biomechanical implications. *J Sports Sci*. 2013;31(7):767-778.
57. Burillo P, Gallardo L, Felipe JL, Gallardo AM. Mechanical assessment of artificial turf football pitches: the consequences of no quality certification. *Sci Res Essays*. 2012;7(28):2457-2465.
58. Villwock MR, Meyer EG, Powell JW, Fouty AJ, Haut RC. The effects of various infills, fibre structures, and shoe designs on generating rotational traction on an artificial surface. *Proc Inst Mech Eng P J Sports Eng Technol*. 2009;223(1):11-19.
59. El Kati R. *Effect of Mechanical Behaviour of Artificial Turf on Player-Surface Interaction in Soccer* [doctoral dissertation]. Loughborough, UK: Civil Engineering, Loughborough University; 2012.
60. Sánchez-Sánchez J, García-Unanue J, Jiménez-Reyes P, et al. Influence of the mechanical properties of third-generation artificial turf systems on soccer players' physiological and physical performance and their perceptions. *PLOS ONE*. 2014;9(10):e111368.
61. Wannop JW, Luo G, Stefanyshyn DJ. Footwear traction at different areas on artificial and natural grass fields. *Sports Engineering*. 2012;15(2):111-116.
62. Mo X. A study on the influence of the change of football artificial turf's particle filling density on sports biomechanics characteristics. *Acta Technica*. 2017;62:235-246.
63. Charalambous L, von Lieres und Wilkau HC, Potthast W, Irwin G. The effects of artificial surface temperature on mechanical properties and player kinematics during landing and acceleration. *J Sport Health Sci*. 2016;5(3):355-360.
64. Silva DCF, Santos R, Vilas-Boas JP, Macedo R, Montes A, Sousa ASP. The influence of different soccer cleat type on kinetic, kinematic and neuromuscular ankle variables in artificial turf. *Footwear Science*. 2017;9(1):21-31.
65. Wannop JW, Stefanyshyn DJ. The effect of translational and rotational traction on lower extremity joint loading. *J Sports Sci*. 2016;34(7):613-620.
66. Sun D, Gu YD, Fekete G, Fernandez J. Effects of different soccer boots on biomechanical characteristics of cutting movement on artificial turf. *J Biomim Biomater Biomed Eng*. 2016;27:24.
67. Schrier NM, Wannop JW, Lewinson RT, Worobets J, Stefanyshyn D. Shoe traction and surface compliance affect performance of soccer-related movements. *Footwear Science*. 2014;6(2):69-80.
68. Driscoll H, Kirk B, Koerger H, Haake S. Influence of outsole design on centre of rotation during turning movements. *Procedia Engineering*. 2012;34:301-306.
69. Müller C, Sterzing T, Lange J, Milani TL. Comprehensive evaluation of player-surface interaction on artificial soccer turf. *Sports Biomechanics*. 2010;9(3):193-205.
70. Sterzing T, Müller C, Schwanitz S, Odenwald S, Milani TL. Discrepancies between mechanical and biomechanical measurements of soccer shoe traction on artificial turf. ISBS-Conference Proceedings Archive. 2008.
71. Stefanyshyn DJ, Lee J-S, Park S-K. The influence of soccer cleat design on resultant joint moments. *Footwear Science*. 2010;2(1):13-19.
72. Sterzing T, Müller C, Milani TL. Traction on artificial turf: development of a soccer shoe outsole. *Footwear Science*. 2010;2(1):37-49.
73. Queen RM, Charnock BL, Garrett WE, Hardaker WM, Sims EL, Moorman CT. A comparison of cleat types during two football-specific tasks on FieldTurf. *Br J Sports Med*. 2008;42(4):278-284.
74. Gehring D, Rott F, Stapelfeldt B, Gollhofer A. Effect of soccer shoe cleats on knee joint loads. *Int J Sports Med*. 2007;28(12):1030-1034.
75. Kirk RF, Noble ISG, Mitchell T, Rolf C, Haake SJ, Carré MJ. High-speed observations of football-boot-surface interactions of players in their natural environment. *Sports Engineering*. 2007;10(3):129-144.
76. Drakos MC, Hillstrom H, Voos JE, et al. The effect of the shoe-surface interface in the development of anterior cruciate ligament strain. *J Biomech Eng*. 2010;132(1):011003.
77. Wannop JW, Luo G, Stefanyshyn D. Wear influences footwear traction properties in Canadian high school football. *Footwear Science*. 2009;1(3):121-127.
78. Shorten M, Hudson B, Himmelsbach J. Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. In: Proceedings of the XIX International Congress of Biomechanics; 2003; Dunedin, New Zealand.
79. Lake M, Underdown T. Traction and lower limb motion during rapid turning on different football turf surfaces. *Footwear Science*. 2011;3(1):S92-S93.
80. Fleming P. Artificial turf systems for sport surfaces: current knowledge and research needs. *Proc Inst Mech Eng P J Sports Eng Technol*. 2011;225(2):43-63.
81. Kirk RF. *Traction of Association Football Boots* [doctoral dissertation]. Sheffield, UK: University of Sheffield, Department of Mechanical Engineering; 2008.
82. Clarke JD, Carré MJ. The influence of gravimetric moisture content on studded shoe-surface interactions in soccer. *Sports Engineering*. 2017;20(2):121-132.
83. Tay SP, Fleming PR, Hu X, Forrester S. Skin friction related behaviour of artificial turf systems. *J Sports Sci*. 2017;35(15):1500-1507.
84. Miller AT, Allen PK. Graspit!: a versatile simulator for grasp analysis. *Proc ASME Dyn Syst Control Div*. 2000;2:1251-1258.
85. Trochim WMK. An introduction to concept mapping for planning and evaluation. *Eval Program Plan*. 1989;12(1):1-16.
86. Sharma P, Fleming P, Forrester S, Gunn J. Maintenance of artificial turf–putting research into practice. *Procedia Engineering*. 2016;147:830-835.

87. Driscoll H, Kelley J, Kirk B, Koerger H, Haake S. Measurement of studded shoe–surface interaction metrics during in situ performance analysis. *Sports Engineering*. 2015;18(2):105-113.
88. Ferrandino M, Forrester S, Fleming P. The player surface interaction of rugby players with 3G artificial turf during rugby specific movements. *Procedia Engineering*. 2015;112:308-313.
89. European Chemical Agency (ECHA). Recycled rubber infill causes a very low level of concern. 2017. https://echa.europa.eu/-/recycled-rubber-infill-causes-a-very-low-level-of-concern. Accessed February 28, 2019.

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