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REVIEW

METHODS AND VARIABLES USED IN THE MEASUREMENT OF THE INTERACTION SPORTS FOOTWEAR AND SURFACE: A SCOPE REVIEW

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ABSTRACT

Introduction: The interaction forces between sports shoes and the contact surface are associated with both lower limb injury risks and performance enhancement. However, there is still disagreement about which loads and assessment methods are most suitable to explain this interaction. The lack of standardization hinders the development of safer and more effective shoes and limits consumers' ability to choose appropriate models.

Objectives: To identify the available models and methods used to characterize and measure variables explaining the interaction between sports shoes and their respective contact surfaces through a scoping review.

Methods: Studies were selected from 4 online databases. Inclusion criteria were experimental studies involving sports shoes and assessment methods of interaction with the respective surface, with no restrictions on language, date, or location. Data from all included articles were extracted and organized in a spreadsheet.

Results: A total of 44 studies were included. The methods were categorized into subgroups: those using only mechanical devices; mechanical devices and cadavers; humans; and humans with mechanical devices. The reviewed studies included data from 738 shoes or soles, 214 surfaces or conditions, and 791 participants, mostly focused on Football and American Football. For rotational loads, Torque and Peak Torque were the most used variables, while translational loads were primarily assessed using Horizontal and Vertical Components and Ground Reaction Forces.

Conclusions: Considering sport-specific demands alongside translational and rotational loads is essential for a consistent and meaningful evaluation of sports shoes and their interaction with playing surfaces.

KEYWORDS

Sports shoes, friction, surface interaction, rotational traction, biomechanical

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INTRODUCTION

The interaction between sports shoes and their respective contact surfaces with the ability to alter lower limb biomechanics has been the focus of study for decades[1–4]. Over the years, new technologies were applied in the development and construction of sports surfaces, concurrently with the migration of different types of natural floors, such as grass and wood, to synthetic surfaces, such as modern synthetic lawns and rubberized surfaces[5–8]. Progress has also been accompanied by footwear, with increasingly modern designs and materials made to meet the high level of performance demands while seeking to reduce the risk of lower limb injuries in athletes[4,9–11].

Sports injuries are a major concern for everyone involved in sports, whether athletes, technical professionals, health systems, brands, or institutions. According to the International Olympic Committee: Injury is tissue damage or other disturbance of normal physical function due to participation in sports, resulting from a rapid or repetitive transfer of kinetic energy[12] Although the causes of sports injuries in general are the result of complex nonlinear systems[13], the forces of the interaction between sports shoes and the surface are considered a risk factor for injuries[8,10,14,15]. High rates of rotational traction during sports gestures may be related to the occurrence of indirect contact and non-contact injuries in lower limbs[10].

The strengths of the interaction between sports shoes and the contact surface are related not only to the risk factor for injuries[10,15], but also to the perspective of performance in different motor gestures and sports modalities[16–19]. Regarding performance, some movements inherent to the practice of physical exercises, such as jumps[16,19], runs[15,19], lateral movements[20,21] and direction change maneuvers (DCM)[11,22], already were analysed from the perspective of footwear-surface interaction. Furthermore, the forces resulting from this interaction can alter the kinematic variables of the lower limbs and the motor strategy adopted by the athlete in the sporting gesture, directly impacting their performance[11,18,19,21–24].

However, there is disagreement about which loads involved and methods applied to obtain these forces would be better to explain this footwear surface interaction[8,22,25]. The literature differs in terms of evaluations using only mechanical devices[1,23,26,27], with human beings[15,16,21] or that combine both models[3,17,18,22,28]. Consequently, the analysed variables are also distinct both in relation to the nomenclature of physical quantities and their applicability[1,3,10,16,18,19,26]. Independently, it is known that the vertical and horizontal forces act directly during displacements and consequently in the footwear and surface interaction[15,25]. However, the magnitude of the resulting rotational loads reported in the literature seems to be influenced by the methods used to obtain them[10].

Although comfort and personal taste are important factors[4,8], the lack of accessible information regarding the interaction between footwear and surface regarding the risk of injuries and performance also hinders the choice of footwear by the final consumer. The lack of standardization and consensus regarding the comparison process between methods and variables also makes it difficult to make safer and more effective shoes. When performing a preliminary search for existing systematic or scope reviews, no studies were found that synthesized the methods and variables available in the literature. Therefore, the objective of the present study is to identify the available evidence models and their methods used to characterize and measure the variables that explain the interaction between sports shoes and their respective contact surface using a scoping review.

METHODS

This study is a scope review, followed the JBI methodology[29] and the items indicated by the PRISMA-ScR Checklist https://www.prisma-statement.org/scoping[30]. Unlike other models, scoping reviews are not intended to answer a specific question, not reporting a synthesized result of multiple references resulting from a well-established methodological process. These reviews are advocated when we want to map concepts and/or key words, verify the breadth of knowledge on a given topic in literature or guide future research projects[29]. In this sense, our initial intention was to map the methods used to characterize and measure the variables that explain the interaction between sports shoes and their respective contact surface, so that, in the future, it will be possible to point out possible standardizations that will help to obtain information in this area.

This review was not registered in PROSPERO, as the database accepts only systematic reviews with planned data synthesis and risk-of-bias assessment. Scoping reviews, by their exploratory and descriptive design, are not eligible for registration according to PROSPERO's policy

Search strategy

The acronym PEOT *(Table 1)* was used to elaborate the eligibility criteria. Studies published in the online databases PubMed, Embase, Scopus, and Scielo, without language, date, and geographic location restrictions up to May 2023, were selected. Studies involving only human beings without mentioning the use of sports shoes and who did not present data on the variables involved in the footwear/surface interaction.

PEOT	
Population	Sports shoes
Exposure	Assessment methods
Outcome	Sports shoe/surface interaction
Type of study	Observational or interventional

Table 1. *Inclusion Criteria according to the PEOT acronym.*

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The keys for the search strategy were defined based on the afore mentioned eligibility criteria, related to the population and exposure, since identifying the outcomes described in the literature was one of our objectives. The words were defined through the MeSH Terms (PubMed), their networks and their synonyms, as well as keywords from previously researched articles relevant to the topic, alternated with the Boolean operators “AND” and “OR”. Search strategies for all databases are available in *Table 2*.

Source of evidence screening and selection

The Mendeley Reference Manager software (Mendeley Ltd, 2023) version 2.82.0 was used to manage studies and references. Two reviewers with clinical and subject experience independently assessed the titles and abstracts of all articles identified in the searches. Those that did not present enough information in the title or abstract to be weighted were read in full. Duplicate articles were excluded. When there was no agreement between reviewers, the case was resolved by consensus or by an experienced third reviewer. Only the studies selected in the screening stage had their complete versions downloaded, for later reading in full and extracting the data.

Data extraction

Data were extracted from all articles included in the scope review and tabulated manually in a Microsoft Excel for Mac (Microsoft, 2022) version 16.66.1 spreadsheet in data graph format. Data graphics are commonly used in scoping reviews in their data extraction phase, offering the reader a descriptive compilation of the results according to the proposed objective and aiming to answer the review question[28]. The extracted information was Study (1st Author and year); Study Name (Title); Sample Size (n); Type of Sports Footwear; Evaluation method; Goal; Conditions tested; Attempts made/analysed (n); Analysed Variables; Results; Conclusion; Gaps in the study. The results were presented in a frame concept map format.

PEOT	Descriptors
POPULATION (Sports shoes)	Shoes **OR** Shoe **OR** “Sports Shoe” **OR** “Sports Shoes” **OR** “Sport Shoes” **OR** “Sport Shoes” **OR** “Athletic Shoe” **OR** “Athletic Shoes” **OR** footwear **OR** “athletic shoewear” **OR** “cleated shoe” **OR** shoewear **OR** cleats **OR** “soccer shoes” **OR** “soccer boots” **OR** “soccer cleats”
AND	
EXHIBITION (Type of surfaces)	Friction **OR** Floor and Floorcoverings **OR** Surface Properties **OR** Rotation **OR** “Floor and Floorcoverings” **OR** “Floorcoverings and Floors” **OR** Floorcoverings **OR** Floorcovering **OR** Carpets **OR** Carpet **OR** Floors **OR** Floor **OR** “Properties, Surface” **OR** “Property, Surface” **OR** “Surface Property” **OR** “Playing Surface” **OR** “Surface type”.

Table 2. *Search strategy for Scielo, Embase and Scopus databases.*

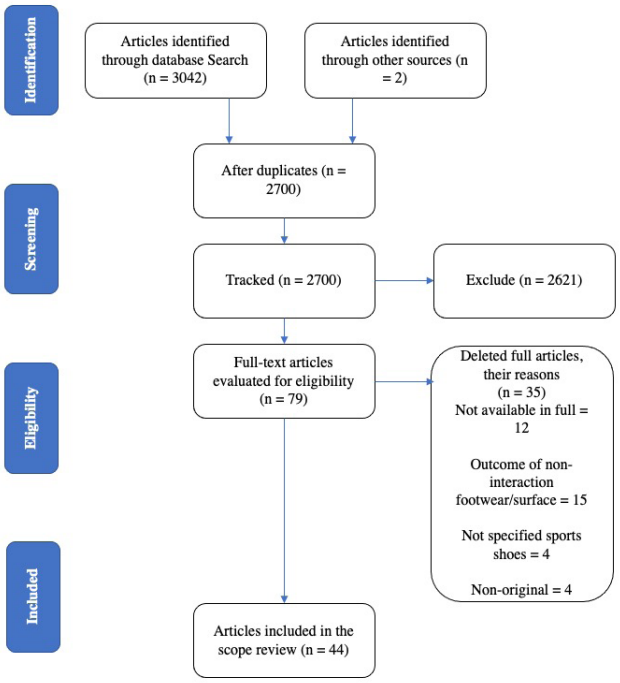


Figure 1. *Flow diagram of the process of including articles in the Scope Review.*

Methodological quality appraisal of included studies

In accordance with the methodological guidance for scoping reviews[31,32] a formal methodological quality assessment (risk of bias) of included studies was not conducted, since the main objective of this review is to map methods and variables rather than synthesise outcomes or evaluate intervention effects.

RESULTS

After searching the databases based on the search strategies, 3042 studies of potential interest were found, of which 1736 came from EMBASE, 642 from PubMed, 654 from Scopus and 2 works from their references, totalling 3044 articles. After excluding 344 duplicate works, all 2700 remaining titles and abstracts were read and from this universe 79 were read in full of 44 being included for the analysis of this scope review. The flow diagram *(Fig. 1)* presents a complete overview of the selection process for these articles with their reasons for exclusion.

Characteristics of the included studies

The works included in this review covered a period from 1974 to 2019, all in English, available online. Of these, 40 were characterized as experimental studies[1,3,6,7,10,15-18,21-24,26-28,33-58]; 2 systematic reviews, one with meta-analysis[10,19] and 2 technical notes[2,58]. In general, the studies aimed to analyses the shoe-surface interaction through biomechanical methods, varying the shoes and/or the surfaces or their conditions, applying

substances that modify the adherence or that increase the humidity of the floor.

The methods used to evaluate the footwear-surface interaction in the 40 experimental studies were divided into subgroups, those that used only a mechanical device[1,7,17,24,26,27,33–48,59]; those who opted for mechanical apparatus and corpses[49,52], those who preferred only human beings[6,15,16,53,56,60] and finally those who mixed human beings with a mechanical apparatus[3,5,21,22,27,50,54,55]. The experimental studies represent data from 738 shoes or soles, 214 surfaces or conditions and 791 individuals, with only one article analysing 555 individuals with their respective shoes[15,51]. The summary characteristics of the studies are presented in *Table 3*.

Sports

Predominantly, the analysed experimental studies included as their evaluation focus the sports shoes of the modalities that have DMM as inherent characteristics of their practice. Conceptually, MMD are decomposed into a phase of internal rotation with hip adduction together with knee abduction with the foot fixed to the ground[9] and when performed with variations in speed, they are fundamental for practices such as soccer, futsal, basketball, and handball[59,60]. In all, 15 studies use specific footwear for football (34%)[5,6,9,22,24,33,38,40,42,44,47-49,52,59], 10 for American football (23%)[1,24,27,35,42,43,49,50,63], 7 for tennis (16%)[7,18,26,41,54], 3 for basketball (7%)[21,34,47], 3 for running (7%)[15,16,59], 1 for ice skiing (2%)[17], 1 for bowling (2%)[55], 1 for golf (2%)[53], 1 for wrestling (2%)[46], 1 for squash (2%)[3], 1 for rugby (2%) [37] and 1 which characterizes footwear as athletic without specifications (2%)[28].

Evaluation condition

When analysing the footwear/surface interaction, the works that used a mechanical apparatus and those that analysed human beings also made use of one or more force sensors such as load cells or force platforms, or even a mixture of such instruments to capture of data. Also, 7 studies[18,21,22,28,52,53,56] used kinematics methods, with 3D motion capture cameras, associated with dynamometry, considering a more complete strategy for analysing the footwear/surface interaction. Only one author[7] analysed aspects related to sole temperature during interaction using thermocouples. The data acquisition frequency ranged from 50 Hz to 10000 Hz for load cells and from 120 Hz to 240 Hz for motion capture cameras.

Those studies that opted to use a mechanical testing device made use of compressive loads. Such loads were named in different ways, being described as normal load, compression load or vertical load, regardless of how they were called, all involved a load perpendicular to the ground that compressed the shoe on the surface and were expressed either in Newtons (N) in the interval between 67 N and 2000 N[5,7,9,22,24,26,27,33-46,49,52,59], or in kilograms (kg) between 11.35 kg and 72.4 kg[3,21,47], or in pounds (lbs) between 25 lbs and 150 lbs[1,50].

Regarding the positioning of the mold in the mechanical devices for the evaluations, some studies used a 20º angle of plantar flexion, justifying that this positioning was like the physiological standards[9,22,33]. The tests involving human beings were carried out respecting the anthropometric and individual characteristics of everyone[6,15,16,18,53,56]. Other aspects such as maximum displacement of the mold or individual, maximum loads, speed and acquisition window are described in *Table 3*.

Analyzed variables

The analysis of the sports footwear/surface interaction, predominantly, was expressed through the forces involved. Regardless of the methodology, the forces measured in rotational and/or translational situations were measured both in tests with mechanical devices and with those that used human beings. For the evaluation of loads in rotational situations, torque (Nm) and peak torque (Nm) were measured. Either through a direct measurement making use of the product of the force by its distance from the axis of rotation[1,9,15,21–24,26,27,33,34,36–40,45,47–49,52,53,59] or indirectly using linear regressions for measurements through kinematic aspects[18,21,22,51,53,56]. The following translational forces were measured separately or together with their peaks: in mechanical devices the horizontal and vertical components (N)[3,5,21,26,27,33,35,36,39,45,47,49,54,56] and in the evaluations with human beings the Ground Reaction Force (body mass; N; N/kg)[3,5,15,16,18,21,54–56].

In addition to the forces and their components, the interaction between the shoe and the surface was also expressed through traction or rotation coefficients that involved, respectively, the ratio of horizontal force to vertical force or torque to vertical for ce[1,3,5,15,17,19,21,28,33,41,42,46–48,49,51,53,55]. Relationships between forces/torques and their respective kinematic variables are also established. The rotational stiffness is obtained from the ratio between the values of torque and angular detachment (Nm/º)[24,28,37,38,43] of shear is obtained from the ratio between the values of force and linear displacement (N/mm)[26].

Some variables such as displacement (mm; º) [24,26,27,36,39,41,42], speed (m/s)[5,15,27,28,36,42], time (s)[7,27,50,55], impulse (Nm/s; N/s)[5,22,27], joint angles (º)[18] and temperature (ºC)[7] were also used, but in fewer studies.

Description of evaluation methods

Some authors developed mechanical devices[24,26,27,40,43,47,48,59] later used in their studies, while others opted for commercial devices[33,37,38,42], regardless of the choice of devices used presented a similar structural pattern. All are made up of an external frame made of resistant metal with a rod attached to the center, considered the axis of rotation, where a foot mold is fixed to one of its ends, so that the footwear, adapted to the mold, is in contact with the surface sample. At the other end of

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Author	Year	Sample size	Sport	Method	Variable	Description
Mechanical apparatus						
Thomson et al.[33]	2019	6 shoes; 5 surfaces	Soccer	Instrument: Load cell Acquisition frequency: Torsion 500Hz; BiAxial 7000Hz Normal Load: Rotation 580N; 300N translation Speed: Angular 90º/s; linear 200mm/s Displacement: Angular 90º Position: 20 degrees of plantar flexion	Peak horizontal force (N) Translational traction coefficient Torque (Nm) Peak Torque (Nm)	Surface tests repeated at 5 locations on a natural grass field, tested at 5 times. The shoes were grouped according to the type of sole. The interaction was measured using a portable S2T2 tester. Only the locks of the forefoot portion of the shoe in contact with the surface, which allowed rotation or else locked in a linear position to the axis for translation tests.
Moncalero et al.[17]	2017	6 shoes; 3 surfaces; 3 individuals	Ice Skiing	Instrument: Load cell	Coefficient of friction	A device in the automated sled model was used, where the floor is traversed under its own power at a constant speed with standardized samples. The device is capable of automatically calculating the variables of interest.
Morse et al.[34]	2016	1 shoe; 2 surface	Basketball	Instrument: Load cell Acquisition frequency: 100Hz Normal Load: 445N, 667N and 890N Speed: 1st/sec, 5th/sec, and 10th/sec Displacement: Angular 20º Test position: 0º, 45º and 90º	Torque (Nm)	The interaction was measured using a test device installed on the biaxial servo-hydraulic load frame, designed so that the entire sole was in contact with the surface (a portion of wooden court with a product that increases surface grip and without). . First, the desired axial load was applied, after which the surface was rotated.
Kent et al.[35]	2015	19 shoes; 2 surfaces	American football	Instrument: Load cell Acquisition frequency: 10000Hz Normal Load: 2800N Speed: 1.5m/s Maximum torque: 200Nm Acquisition window: Translation 200ms; Drop Test + Translation 100ms Drop Test: Mass 42kg; Drop height 67mm	Peak horizontal force (kN) Peak Torque (Nm) Peak vertical and horizontal forces in the combined drop and translation test (kN)	The interaction was measured using a test device (BEAST), a foot shape connected to a shaft that can move horizontally and vertically along an internal support structure. The inner frame is able to move within the heavy outer frame. The axis allows rotational, vertical and horizontal movement. Capable of measuring translational pull, rotational pull and combination of translational + drop test. Only the cleats of the forefoot portion of the shoes were used. The tests were carried out at the installation site of the natural and synthetic grass, each repetition was moved to a new portion within the lawn. For each surface a linear regression analysis was performed to test a relationship between forces.
Kent et al.[36]	2015	1 shoes; 8 surfaces	American football	Instrument: Load cell Acquisition frequency: 10000Hz Normal Load: 2800N Speed: 1.5m/s Maximum torque: 200Nm Acquisition window: Translation 200ms; Drop Test + Translation 100ms Drop Test: Mass 42kg; Drop height 67mm	Displacement (mm) (º) Horizontal (mm/s) and angular (º/s) speed Peak horizontal force (kN) Peak Torque (Nm) Peak vertical and horizontal forces in the combined drop and translation test (kN)	The interaction was measured using a test device (BEAST), a foot shape connected to a shaft that can move horizontally and vertically along an internal support structure. The inner frame is able to move within the heavy outer frame. The axis allows rotational, vertical and horizontal movement. Capable of measuring translational pull, rotational pull and combination of translational + drop test. Only the cleats of the forefoot portion of the shoes were used. The tests were carried out at the site of the natural and synthetic grass installations, each repetition was moved to a new portion within the lawn.
Ura et al.[7]	2015	1 shoe; 3 surfaces	Tennis	Instrument: Thermocouples and Load Cell Normal Load: 500N, 600N, 800N, 1100N, 1200N, 1400N, 1700N, 1800N 2000N Acquisition window: 3000ms	Temperature (ºC) Time(s) Temperature variation (ºC) / time (s) DCOF	A test device (University of Sheffield) was used to determine the behavior of the temperature distribution of the sole under different conditions during a simulated sliding movement. The second part involved simulating a repeated landslide and measuring how the temperature changed after several landslides. The third step involved a repeated glide over the surface for 15 min.
Ballal et al.[37]	2014	5 shoes; 1 surfaces	Rugby	Instrument: Load cell Acquisition frequency: 500Hz Normal Load: 1000N Speed: Angular 45º/s Displacement: Angular 140º Test position: 45º	Peak Torque (Nm) Angle of rotation (º) Rotational Stiffness (Nm/º)	A test device (MTS 858 Bionix) was used. The surface was fixed to the equipment through a wooden base. The tests were performed by applying a vertical force on the foot, performed under angular control until reaching a maximum angular rotation in both directions of rotation.
Galbusera et al.[38]	2013	3 shoes; 2 surfaces	Soccer	Instrument: Load cell Acquisition frequency: 500Hz Normal Load: 1000N Speed: Angular 45º/s Displacement: Angular 140º Test position: 0º and 45º	Peak Torque (Nm) Angle of rotation (º) Rotational Stiffness (Nm/º)	A test device (MTS 858 Bionix) was used. The surface was fixed to the equipment through a wooden base. The tests were performed by applying a vertical force on the foot, performed under angular control until reaching a maximum angular rotation in both directions of rotation and in the two positions of the test shape.
Clarke et al.[39]	2013	9 shoes; 1 surface	Tennis	Instrument: Load cell Acquisition frequency: 2000Hz Normal Load: 400-1000N Test position: 7° of eversion in the direction of movement	Traction force (N) Horizontal displacement (m) Torque (Nm) Dynamic traction (N)	A test device (University of Sheffield), controlled by force, was used. Forefoot portion of the sole of the footwear used. Application of a fixed normal force allowed only vertical movement. As the target normal force was reached, an increasing and controlled horizontal force was applied. Each test was performed on a different portion of the surface, simulating the sliding movement.
Clarke et al.[26]	2013	1 footwear; 5 surfaces	Tennis	Instrument: Load cell Acquisition frequency: 2000Hz Normal Load: 1000N Displacement: Linear 250mm Test position: 7º of eversion in the direction of movement; 90° from the forefoot region in the direction of movement.	Traction force (N) Horizontal displacement (m) Torque (Nm) Peak traction force (N) Dynamic traction (N) Initial stiffness (N/m)	A test device (University of Sheffield), controlled by force, has been developed. To analyze the tension developed as a shear force gradually increases. Application of a fixed normal force allowed only vertical movement. As the target normal force was reached, an increasing and controlled horizontal force was applied until sliding was initiated. Forefoot portion of the sole of the footwear used. Each test was performed on a different portion of the surface, simulating the sliding movement.

Author	Year	Sample size	Sport	Method	Variable	Description
Kent et al.[27]	2012	1 shoe; 5 surfaces	American football	Instrument: Load cell Acquisition frequency: 10000Hz Normal Load: 2800N Speed: 1.5m/s Maximum torque: 200Nm Acquisition window: Translation 200ms; Drop Test + Translation 100ms	Horizontal (mm) and angular (º) offset Peak horizontal and angular displacement time (s) Speed (mm/s) (º/s) Horizontal Force (N) Vertical Force (N) Peak horizontal and vertical force (N) Impulse (N/s) (Nm/s) Torque (Nm)	A test device (BEAST) was developed, which consists of a foot shape connected to a shaft that can move horizontally and vertically along an internal support structure. The inner frame is able to move within the heavy outer frame. The axis allows rotational, vertical and horizontal movement. Capable of measuring translational pull, rotational pull and combination of translational + drop test. Only the cleats of the forefoot portion of the shoes were used. The tests were carried out at the site of the natural and synthetic grass installations, each repetition was moved to a new portion within the lawn.
Smeets et al.[40]	2012	2 shoes; 4 surface	Soccer	Instrument: Load cell Normal Load: 200N, 300N and 400N Offset: Angular 30º bidirectional Impact Test: 200N; Drop height 120mm	Torque (Nm) Peak Torque (Nm)	A mobile test device was developed to measure the interaction during a controlled rotational movement. A wooden frame was used to support the leg in an upright position. At the top a clamping device was attached allowing the application of a torque measured with a digital torque wrench. An increasing torque was applied, rotating the model. The entire sole of the shoe was in contact with the surface. Tests were performed in both directions of rotation. For each evaluation the device was moved.
Clarke et al.[41]	2011	1 shoe; 7 surfaces	Tennis	Instrument: Load cell Acquisition frequency: 200Hz Normal Load: 100-800N Speed: 0.1m/s	Translational traction coefficient Horizontal displacement (mm) Rigidity (N/mm x 10.5)	A test device (University of Sheffield), controlled by force, was used. Application of a fixed normal force allowed only vertical movement. As the target normal force was reached, an increasing and controlled horizontal force was applied until sliding was initiated. Portion of the sole of the shoe glued to the device.
Kuhlman et al.[42]	2009	4 shoes; 1 surface	American football	Instrument: Load cell Acquisition frequency: 250Hz Normal Load: 222N, 444N, 666N, 888N, 1110N, 1332N, 1554, 1776N. Speed: Max 0.1m/s Displacement: Angular 45º bidirectional; linear 20cm Test position: 0° in all movements	Static traction coefficient Dynamic traction coefficient Traction coefficient peak Horizontal displacement (cm) Horizontal speed (cm/s)	An automated mobile test device (Boise State TurfBuster) was used, which controls the translational and rotational movement with minimal operator interference. Characterized by an external frame, an internal frame and a dynamic movement frame driven by compressed gas, allowing vertical movement and rotation when applying normal loads to simulate lateral cutting movements. Device allowed angular adjustments of the shape of the foot 90º of internal and external rotation; 0-90º plantar flexion; 0-20º dorsiflexion; 0-30º inversion and eversion; with possible adjustments in 15º intervals. For each evaluation the device was moved.
Villwock et al.[23]	2008	10 Shoes; 9 surfaces	American football	Instrument: Load cell Acquisition frequency: 1000Hz Normal Load: 1000N Speed: 180º/s Acquisition window: 100-900ms after 3Nm. Test position: foot mid axis 14cm from the heel	Peak Torque (Nm)	A mobile test device was developed to measure interaction during a controlled rotational motion in accordance with ASTM. Featured with an aluminum frame that could be raised or lowered to the ground. The structure supported the lower limb, a suspended weight attached to a 0.25 m radius gear was used to produce a torque, with the center of rotation adjustable.
Villwock et al.[24]	2009	10 shoes; 4 surfaces	American football	Instrument: Load cell Acquisition frequency: 1000Hz Normal Load: 1000N Speed: 180º/s Acquisition window: 100-900ms after reaching 3Nm. Test position: axis fixed in the midfoot 14 cm from the heel	Torque (Nm) Peak Torque (Nm) Angular offset (º) Rotational Stiffness (Nm/º)	A mobile test device was developed to measure interaction during a controlled rotational motion in accordance with ASTM. Featured with an aluminum frame that could be raised or lowered to the ground. The structure supported the lower limb, a suspended weight attached to a 0.25 m radius gear was used to produce a torque, with the center of rotation adjustable.
Livesay et al.[43]	2006	2 shoes; 5 surfaces	Soccer	Instrument: Load cell Acquisition frequency: 500Hz Normal Load: 67N, 111N, 200N, 333N, 511N Displacement: Angular minimum 75º	Peak Torque (Nm) Rotational Stiffness (Nm/º)	A mobile test device was developed to measure the interaction during a rotational movement. Featured with a vertical shaft rigidly connected to the forefoot of the shoe and then used to generate a rotation, compressive load was applied by hanging weights on top of the vertical shaft. For each evaluation the device was moved.
Cawley et al.[45]	2003	9 shoes; 2 surfaces	American football	Instrument: Load cell Normal Load: 178N; 978N Test position: 0° in all movements	Translating force (lbs) Torque (inches/pounds)	A mobile test device was developed to measure the interaction during a translational and rotational movement with an internal rail movement that allowed translation and rotation along the axis. Device allowed angular adjustments of the shape of the foot 90º of internal and external rotation; 0-60º plantar flexion; 0-10º dorsiflexion; 0-25º inversion and eversion. A box was fixed where the test surface was affixed on top of the force platform inside the test device.
Newton et al.[46]	2002	3 shoes; 4 surfaces	Wrestling	Instrument: Load cell Normal Load: 100N	Static traction coefficient Dynamic traction coefficient	A device (Biodex) was used that gradually dragged the footwear with weight over the surface of the wrestling mat, a force platform measured the vertical and horizontal forces produced.
Heidt et al.[47]	1996	15 shoes; 2 surfaces	American football; Basketball	Instrument: Load cell Acquisition frequency: 50Hz Normal Load: 11.35Kg	Translation force (N) Torque (Nm) Peak translation force (N) Peak Torque (Nm) Translational traction coefficient	A test device was developed to measure the interaction during a rotational and translational movement. Featured with a vertical axis rigidly connected to the shoe last and then used to generate a rotational, compressive load was applied by hanging weights on top of the vertical axis. A box was fixed where the test surface was affixed inside the test device.
Torg et al.[44]	1996	5 shoes; 5 surfaces	American football; Basketball	Normal Load: 100 Pounds Displacement: Angular 60º Surface temperature: 52º, 60º, 78º, 92º, 110ºF	Translational traction coefficient Torque (Nm)	A test device was used to measure the interaction during a controlled rotational movement. A metal rod fixed to the shoe, a torque wrench was responsible for the rotation. The entire sole of the shoe was in contact with the surface. Tests were performed in both directions of rotation. For each evaluation the device was moved.
Andreasson et al.[59]	1986	25 shoes; 1 surfaces	Running; Tennis; Soccer	Instrument: Load cell Normal Load: 241N Speed: 1-5m/s	Torque (Nm)	A test device was developed to simultaneously measure frictional forces and torque, where the surface fixed to a disk that rotated bidirectionally through an electric motor fixed to an external structure with a foot mold positioned suspended from the disk.

Author	Year	Sample size	Sport	Method	Variable	Description
Torg et al.[48]	1974	12 shoes; 8 surfaces	American football	Normal Load: 25. to 150 Pounds Displacement: Angular 60º and 90º	Translational traction coefficient Torque (Nm)	A test device was used to measure the interaction during a controlled rotational movement. A metal rod fixed to the shoe; a torque wrench was responsible for the rotation. The entire sole of the shoe was in contact with the surface. Tests were performed in both directions of rotation. For each evaluation the device was moved.
Mechanical apparatus and corpses						
Wei et al.[52]	2012	4 shoes; 12 lower limbs	Soccer	Instrument: Load cell; 3D motion capture cameras Normal Load: 1500N Pre-torque: 2Nm internal rotation Initial torque: 60Nm at 1 Hz Displacement: Angular 30º Pre-torque: 2Nm internal rotation	Rotational Stiffness (Nm/º) Translation and rotation of the talus (°) Torque (Nm) Intersection angle of the torque/º curves	A test device was used to measure the interaction during a controlled foot external rotation movement. For each pair of shoes, one foot was using a rigid model and the other a flexible one fixed in a form. The limb is positioned turned 180º, with the foot upwards and the tip of the tibia downwards, and the rotation is driven by automated mechanisms.
Drakos et al.[49]	2010	2 shoes; 8 lower limbs	Soccer; American football	Instrument: Load cell Normal Load: 500N Initial torque: 1.5Nm Displacement: Angular 90º	Vertical Force (N) Torque (Nm) Power peak (N) Peak Torque (Nm)	A test device was used to measure the interaction during a controlled bilateral rotation movement. Each cadaverous lower limb was potted and tested. The device included an external metal structure with a metal cube attached superiorly to the center for fixing the lower limbs and applying loads in the traction and translation tests. In the lower, central potion, there was a box where the desired surface for testing was fixed., a force platform rises. With a system of pulleys a weight was attached externally to the machine which, when released, generated the rotation movement.
Humans						
Vidal et al.[15]	2019	1 shoe; 1 surface; 20 subject	Run	Instrument: Load cell Acquisition frequency: 500Hz	Ground Reaction Force (GRF) Horizontal Force (N) Vertical Force (N) Peak Required Coefficient of Friction (RCOF) Speed (m/s) Step length (m) Step duration (sec)	Each participant can warm up for 5 minutes. A self-selectable cadence run was requested, a run imposed at 180bpm and a walk imposed at 140bpm first in barefoot conditions and then with shoes on. All were instructed to step with the right foot on the first force platform and with the left foot on the second, these platforms were covered with a surface suitable for running.
Malisoux et al.[16]	2017	2 shoes; 4 surfaces; 21 subjects	Run	Instrument: Load cell Acquisition frequency: 1000Hz	Ground Reaction Force (GRF) Horizontal Force (N.kg-1) Vertical Force (N.kg-1) Average vertical loading rate (N.s-1.kg-1) Vertical instantaneous loading rate (N.s-1.kg-1)	A 5-10min warm-up was allowed. Maximal jump movements were investigated with ankle and knee movement extended with the shortest possible contact time, and multiple jumps with two consecutive jumps preceded by a knee flexion of approximately 90º. Each participant had a training period. The jump was considered valid if each foot landed on one of the force platforms covered by sports surfaces.
Bennet et al.[56]	2015	3 shoes; 1 surface; 14 subject	American football	Instrument: Load cell; 3D motion capture cameras Acquisition frequency: 120Hz Displacement: 7.6-8.2m	Peak Vertical Force Knee angle peak Torque (Nm/kg) Ground Reaction Force (GRF)	A 5-minute warm-up was allowed. Investigated a movement of change of direction at 90º with support on one leg followed by a maximum acceleration for 3m and another coming from a run and a sudden change of direction at 180º on top of a force platform covered by synthetic grass inside the laboratory.
Damm et al.[18]	2013	2 shoes; 2 surfaces; 8 subject	Tennis	Instrument: Load cell; 3D motion capture cameras Acquisition frequency: 960Hz and 120Hz Speed: Run 4m/s;	Ground Reaction Force (GRF) Peak Vertical Loading Rate (Body Weight/sec) Horizontal Force (N) Vertical Force (N) Coefficient of friction Joint angles (°)	The lateral jump movement with the right foot on the ground and a free running forehand at a distance of 6m from the force platform were analyzed. The athletes were instructed to perform the maneuver on the force platform. Encouraging the sliding movement on the gravel.
McGhie and Ettema[6]	2013	3 Shoes; 3 surfaces; 22 subject	Soccer	Instrument: Load cell Acquisition frequency: 1000Hz	Vertical Force Peak Vertical Force Ground Reaction Force (GRF) Impact absorption (N/kg)	A 10-minute warm-up was allowed. A running movement in a straight line with rapid deceleration of up to two steps when touching the force platform and a running movement with a 90º change of direction to the left were investigated, with the right foot reaching the demarcated area.
Worsfold et al.[53]	2008	3 shoes; 1 surface; 24 subject	Golf	Instrument: Load cell; analog video camera Acquisition frequency: 1000Hz and 200Hz	Torque (Nm) Peak Torque (Nm)	The tests were carried out in an outdoor field. Players were asked to play straight shots, in their own motor gesture. The force platforms were covered with natural grass, similar to that of the field.
Humans and mechanical apparatus						
Wannop et al.[22]	2019	1 shoe; 12 surface; 16 subject	Soccer	Instrument: Load cell; 3D motion capture cameras Acquisition frequency: 1000Hz and 2400Hz; 240Hz Normal Load: 650N Displacement: Angular 25º Speed: 75º/s Test position: 20° ankle plantar flexion	Torque (Nm) Peak Torque (Nm) Impulse (N/s) (Nm/s)	A robotic device consisting of a mobile platform placed inside a steel structure was used. Portions of the tested surfaces were fixed on this mobile test platform with a foot mold fixed by a rod and rotated by the device in order to simulate the movement of changing direction. For each test, a different location on the surface was used. After the mechanical tests, three surfaces were selected and the athletes were asked to perform a 90º change of direction movement on the force platform and with maximum effort in a laboratory environment.
Carré et al.[54]	2014	1 shoe; 3 surfaces; 12 subject	Tennis	Instrument: Load cell Acquisition frequency: 960Hz and 2000Hz Displacement: 250mm	Ground Reaction Force (GRF) Horizontal Force (N) Vertical Force (N) Coefficient of friction used	The athletes were asked to perform the sports gestures on a force platform. Then a test device (University of Sheffield), controlled by force, was developed. To analyze the tension developed as a shear force gradually increases. Application of a fixed normal force allowed only vertical movement. As the target normal force was reached, an increasing and controlled horizontal force was applied until sliding was initiated.

Author	Year	Sample size	Sport	Method	Variable	Description
Wannop et al.[9]	2013	555 shoes; 3 surfaces; 555 subject	Soccer	Instrument: Load cell Acquisition frequency: 2000Hz Normal Load: 580N Speed: Linear 0.2m/s; angular 90º/s Test position: 20° ankle plantar flexion	Peak Torque (Nm) Translational traction coefficient	The mechanical evaluation device consisted of a foot mounted under a movable platform with a load cell used to measure the resistance to force movement of the platform. For the translation tests, the shoe was dragged across the lawn by a motor. For the rotation tests, the other movements were locked allowing rotation up the axis of the forefoot of the shoe. The hunted of all individuals were collected after a training session and subjected to a battery of mechanical tests, after which epidemiological data of injuries were collected and a correlation was performed.
Wannop et al.[28]	2010	2 shoes; 1 surface; 13 subject	Not specified	Instrument: Load cell; 3D motion capture cameras Acquisition frequency (Hz): 240; 1000; 2400 Normal load: 750N Speed: Linear 0.1m/s; angular 75º/s Displacement: Individuals 30m Test position: 20° of plantar flexion	Translational traction coefficient Torque (Nm) Impulse (Nm/s) Speed (m/s)	A robotic device consisting of a mobile platform with a surface sample placed inside a steel frame was used to measure the interaction during a controlled foot rotation movement. The athletes were asked to perform a V cut movement (running forward and changing direction 45º) with their right foot and with a force platform installed in the center of a track
Müller et al.[5]	2010	4 shoes; 1 surface; 25 subject	Soccer	Instrument: Load cell Acquisition frequency: 1000Hz Normal load: 750N Displacement: Individuals 26m and 6m Speed: 0.3m/s	Ground Reaction Force (GRF) Horizontal Force (N) Vertical Force (N) Dynamic friction coefficient Speed (m/s)	The athletes were asked to perform the running movements in alternate directions (zigzag) and in a straight line with the highest possible speed. Individuals were also asked to perform specific activities of the modality, such as acceleration, change of direction at 45º to both sides and change of direction at 180º on a force platform covered by a grass. The mechanical analyzes were quantified by a testing device on a mobile horizontal sled system with the sole in full contact with the ground.
Pedroza et al.[55]	2010	5 shoes; 1 surface; 30 subject	Bowling	Instrument: Load cell	Coefficient of friction Coefficient of static friction Horizontal Strength (% of body weight) Vertical Strength (% of body weight) Time(s)	Athletes were asked to perform change of direction movements that resembled the movement of change of direction after touching the force platform with the right foot in three steps, change of direction laterally after contact with the force platform and a mixture of previous movements on different surfaces. Mechanical analyzes were performed with a small device (TORTUS) that rolled over the surface while capturing the data.
Nigg et al.[21]	2009	1 shoe; 5 surfaces; 21 subject	Basketball	Instrument: Load cell; 3D motion capture cameras Acquisition frequency: 2400Hz; 120fps Normal Load: 12.5kg	Torque (Nm) Coefficient of static friction Dynamic coefficient of friction Vertical Force (N) Horizontal Force (N)	Two movements were investigated: approaching from the left side of the analysis area, jumping, landing with the right foot and immediately returning to the initial position; entered the test area and changed direction at 45º with the right foot in submaximal effort. The test device consisted of a heavy sled attached to a sports shoe with the samples attached to a force platform, as the sled was pulled the shoe was dragged across the surface. For rotational attrition, a participant was asked to stand on his forefoot and perform a 180º turn up the surface on the force platform.
Chapman et al.[3]	1991	4 shoes; 6 surfaces; 1 subject	Squash	Instrument: Load cell Acquisition frequency: 200Hz Normal Load: 28Kg; 50.5Kg; 72.4Kg Analysis time: 2s	Vertical Force (N) Horizontal Force (N) Coefficient of friction	A wooden platform was fixed to a plaster foot to apply the vertical load and an increasing horizontal force was manually applied by a cable around the heel of the mold that displaced the device horizontally up the floor that was on top of a force platform. An athlete was asked to perform modality-specific movements in all ground conditions on a force platform wearing the mechanical test shoe.
Stanitski et al.[50]	1974	4 shoes; 1 surface; 6 subject	American football	Normal Load: 25 Pounds Displacement: Individuals 40 yards and 30 yards	Time(s) Coefficient of friction	The athletes were asked to perform straight and zigzag movements. For the analysis of the shoe-surface interaction, a drag test was used, with the application of a uniformly distributed vertical load on a shoe with a pre-calibrated spring scale to measure the amount of force needed to move the shoe, tested in different areas. from Camp.

Table 3. *Characteristics of the experimental studies included in the scope review.*

the rod, a load perpendicular to the ground compresses the shoe on the desired surface, using iron washers or electric or hydraulic compressors. One or more load cells capture the force values at a pre-established distance from the axis of rotation, while the rotation or translation movement is performed.

Figure 2 presents the image of all the mechanical devices for analysis of the footwear surface interaction found in this review. Two ways of triggering the movement were found in the literature, those robotically automated or the manuals influenced by researchers. Both translational and rotational movement analyzes were performed with the devices, some had a locking system that allowed or disallowed a certain movement along the axis or other changes in configuration to allow or block a certain movement. Translational analyzes were also performed by dragging the shoe across the surface while force pickup was recorded[46]. Still, some devices[27,33,35,36,42] had wheels to be taken to the test surface, aiming at "in loco" analysis, allowing several points to be evaluated avoiding surface wear, while the others needed a surface sample fixed to a rigid structure in the form of a box or disc and then attached to the apparatus[1,7,22,26,28,34,37,38,43,47,49,52,59].

The evaluations that included human beings involved one or two force platforms covered by the surface of the respective modality analyzed, only 7 studies[18,21,22,28,52,53,56] used kinematics systems to capture movements in two or three dimensions. Subjects have between 5-10 minutes of warm-up and task familiarization. The requested movements were described as changes in direction between 30, 45, 90 and 180º, involving sudden deceleration, at self-selected or submaximal

speeds. Jumps were also explored, both single-legged and maximum jumps. A descriptive compilation of the experimental methodologies of the included authors is described in *Table 3*.

Other studies

Only 4 studies not described as experimental were included in the current scoping review, of these 2 were classified as technical notes[2,58], 1 systematic review[19] and 1 systematic review with meta-analysis[10].

Nigg[2] and Valiant[58], in their technical notes, explain that friction can be subdivided into translational and rotational and should ideally be evaluated together to describe the mechanical characteristics of the shoe surface interaction. The translational coefficient of friction can be found in the ratio of the force tangent to the plane to the force perpendicular to the plane, with test procedures using pendulums concomitant with a prosthetic foot and others that involved sliding a sports shoe under a surface. Rotational friction, on the other hand, can be measured through torque in relation to a defined axis of rotation, using equipment with specific sports shoes for certain floors. Still, for both translation and rotation, he suggested involving subjects performing the motor activities of the modality in question. The tests must be carried out with the appropriate footwear and material for the desired interaction, close to the real values of the forces involved. Although assessments with subjects are essential, they can be influenced by the unique way that subjects interact with the surface.

Both analyzed revisions had specific footwear for Football[19] and Rugby[10,19] as a population, characterized with studs of different materials, quantities, and arrangement on the sole. As an outcome, they

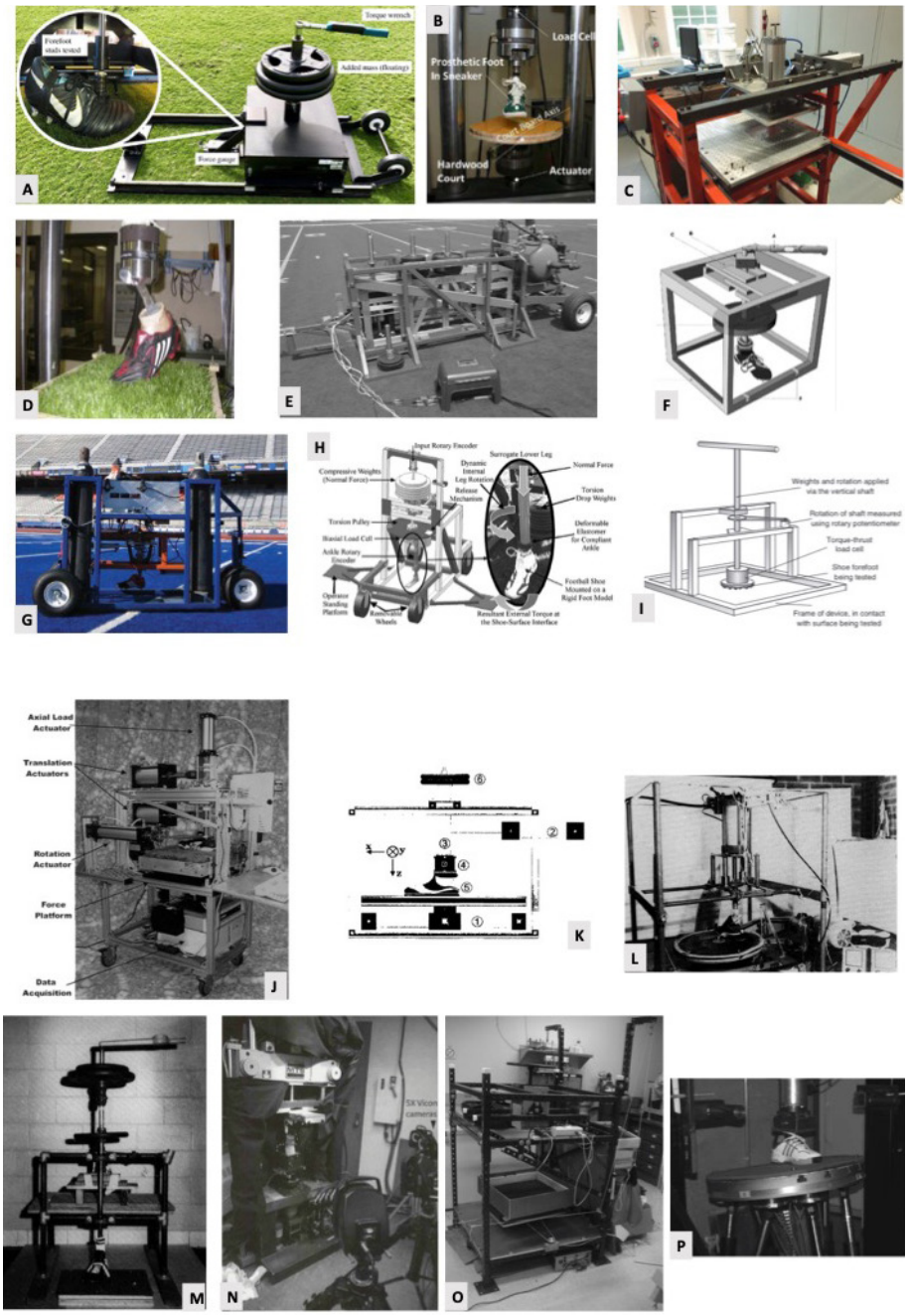


Figure 2. *Mechanical devices for analysis of footwear/surface interaction. A) S2T2, Exeter Research USA; B) Equipment Morse et al.[34]; C) UoS Shoe Traction Rig; D) MTS 858 Bionix servo hydraulic testing machine, MTS USA.; E) BEAST; F) Equipment Smeets et al.[40]; G) Boise State University TurfBuster; H) Equipment Villwock et al.[24]; I) Equipment Livesay et al.[43]; J) Equipment Cawley et al.[45]; K) Equipment Heidt et al.[47]; L) Equipment Andreasson et al.[59]; M) Equipment Torg et al.[48]; N) Equipment Wei et al.[52]; O) Equipment Drakos et al.[49]; P) Equipment Wannop et al.[9]*

evaluated the risk of injury and performance, in addition to factors that can alter the traction of the shoe surface interaction. In total, the studies covered 23 and 9 studies between the years 2000 to 2016 and 1946 to 2014, respectively, experimental, published in English, summarizing the variables and methodologies found. However, the focus of these reviews was to analyze the relationship between the type of footwear and its properties with the incidence and prevalence of injuries or with sports performance, not limiting itself to explaining how such an interaction could be measured or what is the best way for such evaluations.

DISCUSSION

This scoping review aimed to map and describe the predominant methodological approaches used to evaluate the interaction between sports footwear and their corresponding contact surfaces, as well as to identify the key variables involved. From the synthesis of the 44 included studies, four primary methodological categories were identified: (i) mechanical apparatus; (ii) mechanical apparatus combined with cadaveric models; (iii) human-based testing; and (iv) hybrid approaches integrating mechanical and human protocols.

This classification not only provides insight into the historical evolution of experimental designs within this field but also highlights the persistent lack of methodological standardization in the investigation of footwear surface dynamics. The observed heterogeneity reflects the inherently multidisciplinary nature of the topic, which encompasses biomechanics, materials engineering, ergonomics, and sports sciences. Despite this diversity, few studies offered a critical rationale for their chosen methodology. The selection of devices, surface types, or loading parameters often appeared pragmatic rather than theoretically grounded. This gap underscores the need for a unified conceptual framework like those adopted in other biomechanics subfields, (gait analysis or EMG normalization procedures) to enable more meaningful comparisons across studies.

Mechanical apparatus approaches

Mechanical apparatus provide a high degree of experimental control and repeatability, enabling researchers to isolate mechanical variables such as torque, coefficient of friction and rotational stiffness[24,28,37,43,48,64]. Typical rigs share common design elements: an axis or rod with a fixed foot/sole mold, a perpendicular compressive load, and force transducers positioned at standardized offsets from the axis of rotation[1,10,26–28,33]. Such systems are invaluable for fundamental tribological characterization and for testing the mechanical consequences of sole geometry, stud arrangement, or material composition under tightly constrained conditions[25].

However, these devices have intrinsic limitations, first, they often fail to reproduce the complexity of human movement: dynamic neuromuscular modulation, joint kinematics, and variable contact mechanics that occur during on-field maneuvers are absent in purely mechanical tests[9,19]. Second, the selection of “physiological” loads and angular velocities is inconsistent across studies. While several authors explicitly used compression forces and velocities intended to approximate athlete-generated loads, reported values varied widely (e.g., compressive loads expressed between ~67 N and 2000 N or 11.35–72.4 kg in different papers)[1,2,5,24,26,28,33,36–38,43,47,49,64], and measurement frequencies ranged from 50 Hz to 10000 Hz for load cells. This heterogeneity undermines comparability and complicates the translation of laboratory derived metrics to in injury risk or performance outcomes.

To increase translational relevance, mechanical studies should adopt standardized calibration procedures and pre-defined loading regimes anchored in in field measures of athlete kinetics. Where possible, device-based tests should be informed by human derived ranges of compressive force, angular velocity and contact geometry. In addition, mechanical rigs can be highly valuable for mechanistic validation (e.g., establishing how sole pattern changes rotational stiffness) provided that the limitations of ecological validity are explicitly acknowledged.

Among the identified approaches, mechanical testing devices provide the advantage of reproducibility and isolation of specific physical parameters (e.g., torque, coefficient of friction, or ground reaction forces). These devices, however, frequently lack ecological validity. The application of physiological loads and realistic velocities well as highlighted by the literature[2,5,33], this is essential to simulate in-sport conditions. The challenge lies in balancing experimental control with real-world relevance.

Mechanical apparatus combined with cadaveric models

Combining mechanical apparatuses with cadaveric specimens has been used to probe tissue-level responses to shoe–surface forces and to explore injury mechanisms with a level of anatomical realism not achievable with rigid molds alone[49,52]. Cadaveric models offer unique opportunities to quantify ligamentous strain, joint kinematics under applied torques, and structural failure limits, providing insights that can be complementary to both mechanical and human studies[49]. Such studies have been particularly relevant for understanding non-contact anterior cruciate ligament (ACL) injury mechanisms, as rotational stiffness and talar translation values obtained from cadaveric simulations have been associated with the limits of ligament tolerance observed in clinical and in vivo investigations.

Nonetheless, cadaveric research faces practical constraints and caveats that must temper interpretation. The absence of neuromuscular control, differences in tissue hydration and mechanical properties post-mortem, and the ethical and logistical challenges of obtaining

large sample sizes all limit external validity. Furthermore, cadaveric approaches are most informative when used to validate mechanical thresholds that are subsequently explored in live-subject or epidemiological studies. Cadaveric findings are particularly relevant to injury biomechanics (e.g., ACL strain under rotational moments), and their interpretive value increases when cross-referenced with clinical data and in vivo kinematic analyses.

Human based testing

Human based testing provides the most ecologically valid framework for examining the interaction between sports footwear and the surface, since it captures the integrated outcome of mechanical, neuromuscular, and perceptual factors. Unlike purely mechanical setups, human trials allow observation of how athletes dynamically adapt to traction demands through muscle activation, proprioceptive control, and task-specific movement strategies. Within the studies included in this review, human-based protocols typically employed one or more force platforms — often covered by the playing surface of interest — to record ground reaction forces (GRF) during movements such as cutting maneuvers (30°, 45°, 90°, or 180°), sudden decelerations, and single- or double-leg jumps. Some investigations combined kinetic data with 2D or 3D motion capture and, in a smaller subset, with surface electromyography (EMG), thereby enabling a multi-dimensional assessment of the shoe surface interaction[6,15,16,53,56,60].

Despite these methodological advantages, human testing introduces substantial inter-individual variability. Factors such as anthropometry, strength levels, limb dominance, prior injuries, fatigue, and technical skill can all influence the recorded traction and loading profiles[6,15]. Although many studies attempted to standardize warm-up and familiarization procedures, reporting of participant characteristics was frequently incomplete[6,15,16]. This omission limits the ability to contextualize observed differences and hinders the generalization of results across populations. The same applies to procedural details: few studies clearly described the calibration of force plates, the synchronization of kinetic and kinematic systems, or the analytical procedures used to compute derived variables such as rotational stiffness and traction coefficients. Greater transparency in these methodological aspects is essential for reproducibility and for comparison between laboratories.

Recent biomechanical research supports the notion that the mechanical interaction between footwear and surface is inseparable from neuromuscular control[65]. Proprioceptive feedback and motor variability dynamically modulate how forces are transmitted and absorbed at the foot–surface interface[65,66]. Frizziero et al.[66](2023) demonstrated that variations in proprioceptive stability across the menstrual cycle may elevate injury risk in female athletes, reinforcing the need to consider physiological states when interpreting traction outcomes. Similarly, Kulis et al. and Padulo[65,67] (2023) have shown that kinematic precision and movement variability are sensitive to external conditions, such as training load and surface stiffness, which in turn shape the functional interaction between the athlete and the ground. These insights indicate that future human based protocols should integrate neuromuscular and kinematic monitoring to capture the full spectrum of factors influencing shoe surface mechanics. Overall, the current evidence underscores the importance of designing human based studies that combine controlled testing conditions with ecological validity. Standardized descriptions of participant characteristics (sex, age, competition level, training background), movement tasks, environmental conditions, and signal processing parameters (sampling rates, filter settings, event detection methods) are critical to enhance reproducibility. Moreover, incorporating EMG and motion analysis alongside kinetic measures offers a more complete and realistic understanding of the footwear–surface interface, bridging laboratory assessments and real sport performance.

Hybrid approach

Hybrid methodologies that integrate mechanical testing with human-based trials have emerged as an effective strategy to bridge the gap between experimental control and ecological validity. These approaches allow researchers to first define mechanical boundaries—such as torque thresholds, compressive loads, and friction coefficients—under tightly controlled laboratory conditions, and then validate these findings in human movement contexts.

Several studies included in this review adopted such integrative designs, combining mechanical rigs and human trials to explore the footwear–surface interaction in dynamic scenarios[3,5,9,21,22,49,50,53,54]. For example, Wannop et al.[9] compared torque profiles obtained through mechanical devices with in-field rotational forces measured from over 500 football athletes, revealing consistency in rotational traction behavior across testing scales. Similarly, Müller et al.[5] and Bennet et al.[56] used hybrid setups to relate mechanical stiffness parameters to in vivo joint loading during cutting maneuvers, demonstrating that higher mechanical rotational resistance was reflected in increased knee moments during human trials. Damm et al.[60] and Pedroza et al.[55] also exemplified this dual approach, aligning the coefficients of translational and rotational traction derived mechanically with performance metrics and stability outcomes in tennis and bowling tasks, respectively.

This multi-tiered strategy enhances the interpretability of traction data: mechanical characterization defines the physical envelope of shoe–surface interactions, while human trials reveal how athletes adapt neuromuscularly to those conditions. By embedding motion capture and electromyography into hybrid pipelines, researchers can identify how traction-induced mechanical constraints

translate into neuromuscular recruitment patterns, postural control strategies, and joint loading variability. However, the current literature reveals substantial heterogeneity in how hybrid protocols are implemented and reported. Studies often differ in terms of load calibration procedures, movement tasks, and signal synchronization between systems. Few explicitly describe how mechanical parameters (e.g., torque–angle slopes, compression loads) are scaled to human forces, limiting replication and cross-study comparison. Establishing consensus reporting guidelines—defining minimum descriptions of device parameters, environmental conditions, participant demographics, and data-processing pipelines—would represent an essential step toward methodological standardization. Ultimately, hybrid approaches provide a promising pathway to unify the mechanical precision of laboratory testing with the biological realism of human motion analysis. When effectively integrated, they allow researchers to move beyond isolated mechanical outcomes and toward a systems-level understanding of footwear–surface interaction, injury mechanisms, and performance adaptation.

Methodological approach

The methodological diversity observed across the reviewed studies underscores the complexity of accurately characterizing footwear–surface interaction. The precision of measurement systems directly determines the reliability and interpretability of outcomes. Studies employing motion capture or instrumented platforms should ensure synchronization between mechanical and kinematic data streams, as asynchronous sampling can distort derived variables such as torque or traction coefficients. Kulis et al. (2023)[65] demonstrated that high-resolution kinematic analysis can detect subtle oscillations in sway among elite dance sport competitors—minute variations that reveal hidden biomechanical instabilities. The same principle applies to footwear–surface interaction, where small angular discrepancies or displacement errors can meaningfully alter torque estimations and misrepresent the mechanical behavior of the interface. Similarly, Padulo et al. (2023) emphasized that variations in external load alter gait variability, suggesting that experimental setups must replicate realistic compressive and rotational loads. Overly rigid or static laboratory simulations, while controlled, may fail to reproduce the complex dynamic loads athletes experience during cutting, landing, or acceleration tasks. Therefore, ecological fidelity—including realistic compression levels, angular velocities, and frictional properties—should be a central design principle in both mechanical and human-based testing.

Environmental variables further complicate methodological consistency. Temperature, humidity, surface compaction, and material degradation substantially affect traction outcomes, yet are seldom standardized across studies. The filling density of synthetic turf, grass fiber height, or the polymer composition of infill materials significantly modify both rotational and translational coefficients[24,32,41]. In addition, synthetic and natural surfaces exhibit distinct temperature–friction profiles, particularly under wet or dusty conditions[38,53]. The lack of environmental control or reporting introduces a critical source of heterogeneity that limits cross-study comparability. Therefore, documenting surface history and environmental state before and during testing should be considered an essential methodological criterion.

Future research

Future research must expand beyond purely mechanical descriptions to encompass the physiological and neuromuscular dimensions of footwear–surface interaction. For instance, EMG and muscle function profiling could enhance understanding of how neuromuscular control adapts to different traction environments, fatigue states, or surface types.

A significant observation in this scoping review is the disciplinary bias toward football and American football, which although justified by their injury incidence limits the generalizability of findings. Few studies have addressed footwear–surface interaction in handball, volleyball, or other indoor sports, despite their frequent inclusion of pivoting, jumping, and cutting actions[61]. Moreover, the near absence of research involving female athletes represents a methodological gap of both scientific and ethical relevance. Frizziero et al. (2023)[66] demonstrated cyclical fluctuations in proprioceptive control during the menstrual cycle, linking them to altered injury risk—a finding that reinforces the importance of sex-specific analyses in footwear research. Expanding the methodological framework to encompass gender, sport modality, and surface type interactions will be fundamental to developing inclusive, sport-specific testing standards.

One of the principal challenges identified in this review is the absence of standardized reporting and quality control across experimental designs. Many studies omitted essential methodological details, such as calibration routines, sensor uncertainty, or synchronization protocols between mechanical and kinematic systems. This lack of transparency hinders replication and impedes meta-analytic synthesis. Establishing shared reporting frameworks—analogous to CONSORT or PRISMA, but tailored for biomechanical and mechanical testing—would substantially elevate methodological consistency in the field. In footwear–surface biomechanics, this means balancing experimental precision with ecological validity—a challenge that future consensus efforts must explicitly address. The heterogeneity of current approaches calls for the development of an integrated, multi-layered testing framework. Such a framework should combine:

- Mechanically controlled tests, calibrated using physiologically relevant compressive and rotational loads;

- Human-based trials, integrating motion capture, force platforms, and EMG to assess adaptive neuromuscular strategies;
- Environmental monitoring systems, ensuring temperature, humidity, and surface compaction are recorded and controlled;
- Cross-laboratory calibration protocols, enabling comparability and reproducibility.

This integrative model would not only unify methodologies but also facilitate meta-analytic pooling once standardization is achieved. Furthermore, adopting open-access repositories for raw biomechanical and mechanical data—akin to practices in other scientific domains—could revolutionize transparency in sports biomechanics. Such repositories would accelerate discovery of optimal shoe–surface–environment combinations, promoting both performance enhancement and injury prevention.

Limitations

This scoping review, while comprehensive in scope and systematic in its procedures, presents certain methodological limitations that must be acknowledged.

First, the choice of a scoping review design inherently limits the analytical depth and inferential capacity of the findings. By definition, scoping reviews aim to map the existing literature and identify knowledge gaps, not to quantify effect sizes or assess causal relationships. Therefore, this review did not perform a formal risk-of-bias or quality assessment of the included studies. This decision follows international methodological guidance[30], which specifies that such appraisals are not required when the objective is descriptive mapping rather than evidence synthesis. While this approach ensures broad coverage, it also means that conclusions regarding the strength or quality of individual evidence cannot be drawn.

Second, the heterogeneity of the extracted data imposed a descriptive synthesis rather than a quantitative one. Because the included studies reported highly variable designs, measurement protocols, and outcome definitions, it was not possible to perform meta-analytical comparisons or compute standardized effect measures. As a result, this review provides a conceptual and methodological synthesis, focusing on patterns, trends, and gaps rather than statistical aggregation. This limitation reflects the current fragmentation of the field rather than a weakness of the review itself.

Third, although the search strategy was broad and rigorous, it may not have captured all potentially relevant studies. The review included major scientific databases (PubMed, Scopus, EMBASE) and secondary reference searches, but gray literature—such as technical reports, dissertations, or industry testing documents—was not systematically searched. Consequently, certain applied or proprietary methods used in industrial settings may be underrepresented. Nonetheless, the inclusion of over four decades of peer-reviewed data ensures a robust representation of academic research trends.

Another limitation concerns the focus and boundaries of the review scope. This work was intentionally restricted to studies addressing mechanical and biomechanical interactions between footwear and sports surfaces, excluding broader domains such as metabolic cost, comfort perception, or material engineering of shoe components. These topics, while related, were beyond the aims of this review. Future scoping or systematic reviews could integrate these complementary aspects to provide a more holistic understanding of footwear–surface interaction. Additionally, language and publication bias cannot be fully excluded. Although no language filters were applied during the search, only studies available in English were ultimately included, as full-text translations were not feasible within the review timeframe. This may have led to the exclusion of relevant non-English works, particularly from regions with strong footwear research traditions outside the Anglophone literature.

Finally, this review was not preregistered in PROSPERO, as that database does not currently accept scoping review protocols. Nonetheless, all methodological steps including database selection, search strategy, inclusion criteria, and data extraction procedures were predefined and explicitly reported in accordance with PRISMA-ScR guidelines, ensuring methodological transparency and reproducibility.

CONCLUSION

The current scope review highlighted the diversity of methodology when evaluating the footwear contact surface interaction, highlighting techniques that involved mechanical devices, human beings, cadavers or even a mixture of such procedures. The importance of an analysis involving translational and rotational aspects is essential for a complete explanation of the loads involved, showing that both horizontal forces and torque are important for describing the interaction.

The application of conditions close to specific sports realities is fundamental for the analyses. Although high-quality research is needed in this field, there appears to be consistent evidence that how interaction is measured can impact loading results. The consideration of the particularities and demands of each sport modality simultaneously with the existing loads in translational and rotational situations must be indispensable factors for a consistent approach in the evaluation of sports shoes and their respective surfaces.

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