ORIGINAL ARTICLE

Investigating the effect of outsole configurations on rotational and translational traction using a mechanical prosthetic foot

Bahador Keshvari[1] · Long Lehoang[1] · Veit Senner[1]

Abstract

Studded football boots and their interaction with the pitch surface play a major role in generating traction and on the risk of injuries and performance. The aim of this study was to establish a methodological framework to predict a safe zone of traction for different specific football movements in natural preloads. We measured peak pressure distribution among 17 male football players in four specific football movements (cutting 135°, sprinting, turning, and penalty kick) on artificial turf using a baseline football boot with an insole pressure sensor. A mechanical prosthetic foot was adjusted to replicate similar peak pressure distribution based on these four movements. Traction was measured under three preloads: 400, 600, and 800 N. They were lower than those measured with the players to avoid damage to the mechanical test device. This procedure was conducted for seven different outsole configurations. Rotational and translational traction was estimated for high preloads (above 2000 N) using an artificial neural network. Our findings show pressure distribution is an important bridge between subjective measurement (field tests) and objective measurement (laboratory tests) for accurate traction measurement. Artificial neural networks can aid in finding the upper and lower ranges of traction in the natural preloads. Such findings could help footwear developers, trainers, players, and governing institutions to choose an appropriate football boot outsole according to the safe zone of traction established in this study.

Keywords Traction · Outsole configurations · Rotational traction · Translational traction

1 Introduction

Traction as the product of shear stresses resulting from the interaction between studded boots and playing surface [1] does not obey classical laws of friction. This means that any values measured are a combination of adhesion, cohesion and material hysteresis and therefore show a non-causal behavior, which in turn leads to a distribution of measured values [2]. Traction was consistently rated as a key consideration in selection of sports footwear after comfort and stability in 1998, and second only to comfort in 2006 [3, 4]. It was also reported that insufficient traction between studs and playing surfaces can affect performance in rapid change of direction, such as cutting or turning, or accelerating (decelerating) in sprinting (or kicking) [5–8]. Accordingly, insufficient traction is linked to risk of lower extremity injuries [9–11]. Insufficient traction can be defined as excessive traction which causes foot fixation, or as a poor traction (low amount) which causes slippage. However, the safe zone of traction (between performance and injuries) has been poorly investigated.

Traction can be subdivided into rotational and translational traction. In the words of Thomson et al. [12], translational traction "… is the horizontal force required to overcome resistance between the boot outsole (studs/cleats) and playing surface in a straight line". They also define that "… rotational traction is the rotational force required to release the studs through the playing surface in a rotational manner". In their study, these two types of traction were independently assessed. An increase in rotational traction led to a significant increase in transverse and frontal plane joint loading at the ankle and knee joints, while increases in translational traction led to increases in frontal plane joint loading at the ankle and knee joints [13].

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Since the early 1970s, numerous mechanical test devices have been developed for evaluating traction of studded boots [13–16]. However, there are limitations to these devices. For instance, to evaluate rotational or translational traction, it is necessary to map the pressure of specific football movements and replicate the desirable stance phase (initial, mid, or final) of those movements under laboratory conditions using a mechanical test device. If the pressure mapping in a laboratory test applying a mechanical prosthetic foot was not according to those of players' performing movements, the results could be unrealistic. However, a sub-requirement is to have a more realistic foot model to replicate the movement via the test device [17].

Other than a study by Grund et al. [17], pressure mapping from field tests (in football or other sports) has not been applied to mechanical tests in the laboratory. However, such pressure mapping is an important factor in calculating traction in a desired stance phase of specific football movements. It would, therefore, make sense to adjust the test device to achieve the desired pressure mapping. Also, with the exception of the mechanical prosthetic foot mentioned in the study by Grund et al. [17], as far as we are aware, no measurement considering a varus/valgus position of the shaft with respect to the foot has been reported in previous field tests, even though this is an important contributor to Anterior Cruciate Ligament (ACL) injuries. This study addresses this by rethinking the available apparatus to measure traction by simulating pressure distribution using a realistic foot model.

During field tests in football, Smith et al. [18] and Blackburn et al. [19] used implemented force plate technique to measure ground reaction forces. They determined that vertical ground reaction force regularly exceeded 2.5 BW (> 1500 N) although most of the abovementioned studies did not evaluate traction with preload exceeding 1500 N. This is likely due to mechanical problems that might occur while testing at higher preloads, which casts doubt on the validity of these studies. To predict translational and rotational traction in higher preloads, Kirk et al. [20] suggest using an artificial neural network (ANN) to evaluate the effect of boot and surface and the optimization of traction forces experienced by athletes, since traction forces do not in all probability follow a linear relationship with applied load. In summary, there is a gap in the literature that would guide the investigation of traction from field test to laboratory test, or in evaluating traction under realistic preloads. Therefore, the aim of this study is to establish a methodological framework within which to predict rotational and translational traction under a realistic preload. This would, in turn, facilitate the identification of a safe zone of traction to aid in the design of football boots.
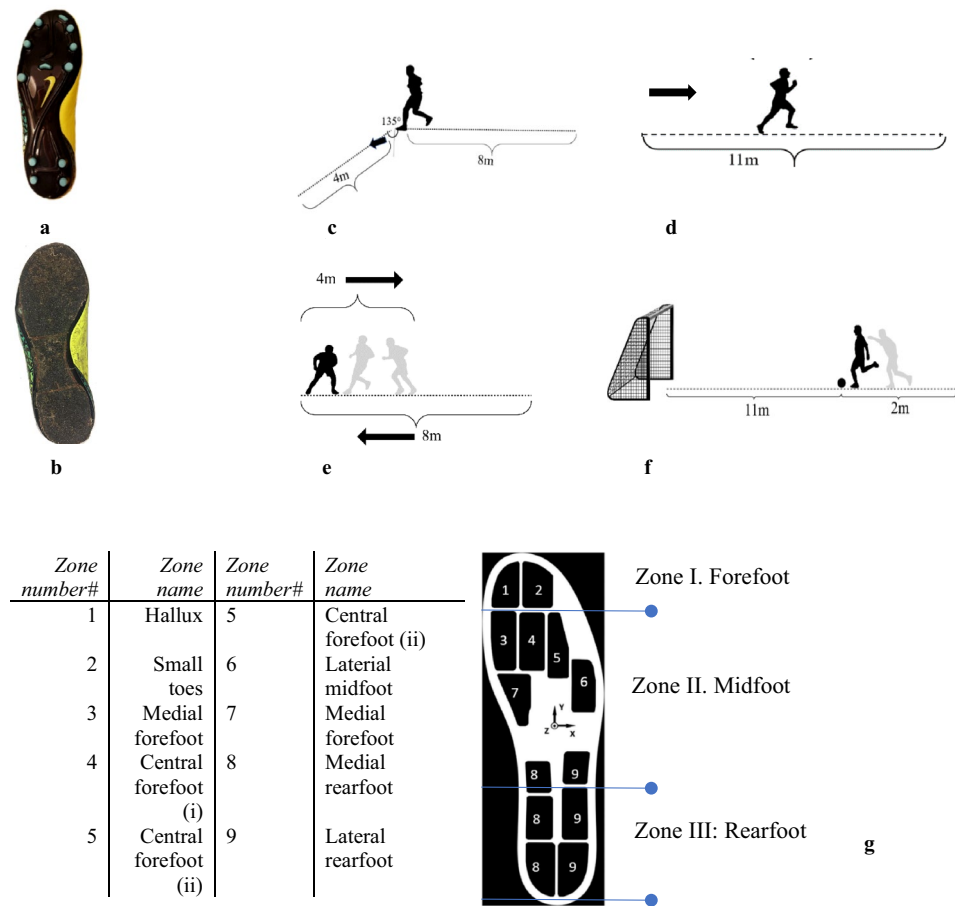
2 Methodology

2.1 Phase 1: field test

Seventeen male participants were recruited from football clubs of Regionalliga Bayern (the fourth tier of the German football league system). Most of these clubs were close to Munich (Germany). The participants had at least 5 years' experience playing football. They were excluded if they had had a lower extremity musculoskeletal injury within the past 6 months or a lower extremity reconstructive operation within the past 3 years. The mean (and standard deviation) age, height, and mass of 17 male participants was 26 ($\pm$ 6) years old, 181($\pm$ 7) cm, and 79 ($\pm$ 11) kg. Participants gave written, informed consent prior to the experiment. The consent form declares the confidentiality of the objectives, risks of the study, and protection of personal data through appropriate procedures for anonymization. In addition, the consent form assures participants they are free to withdraw from the research at any time without giving a reason and without penalty for not taking part. This research adhered to the ethical requirements of the host institution and was conducted according to the ethical standards of the Helsinki Declaration [21].

Three pairs of Nike Hypervenom Phinish FG (UK 9) soft ground football boots were used in this experiment. All the original studs of the boots were flattened and smoothed with a belt-grinder (see Fig. 1a, b). To ensure appropriate grip, the football outsoles were covered with a layer of sandpaper, each of different thicknesses (coarse rate: ISO 24 and ISO 50). The football surface used in this study (pilot test, field test and laboratory test) was 2-star AT (sand/rubber infill 100% polypropylene) used for 4 years. The surface construction consisted of 30 mm elastic base layer (DIN V18035/7). It was covered by fiber carpet with a pile length of 10 mm filled with sand (18 kg/m^2) and rubber (0.5–1.7 granulation diameter, 5 kg/m^2). The total length of the pile and carpet was 50 mm. Before the main field test, a pilot test was accomplished.

A pilot study was accomplished at the beginning of the experiment. Its purpose is to identify an appropriate sandpaper grip size for the main field test. Three participants were asked to accomplish two types of cutting movements (turning and cutting 45°) and sprinting. At the end of the test, they were asked to compare the boots based on their qualitative perception of traction on artificial turf (AT) and to report their perception of traction verbally. All three stated that the football boots covered with coarse ISO 24 - paper sand (Grit size = 80) provided sufficient traction to perform the required movements with appropriate grip and low risk of slippage.

Fig. 1 **a** Original outsole of the football boot, **b** the football boot with flatten outsole used in field test, **c** cutting movement 135°, **d** sprinting movement, **e** turning movement, **f** penalty kick, **g** different sections and zone of plantar

Zone number#	Zone name	Zone number#	Zone name
1	Hallux	5	Central forefoot (ii)
2	Small toes	6	Lateral midfoot
3	Medial forefoot	7	Medial forefoot
4	Central forefoot (i)	8	Medial rearfoot
5	Central forefoot (ii)	9	Lateral rearfoot

Zone I. Forefoot

Zone II. Midfoot

Zone III: Rearfoot

g

2.1.1 Field test

Participants were first asked to warm up for 15 min according to the FIFA 11 program [22]. Then they were asked to perform four movements: cutting 135°, sprinting, turning and penalty kick (see Fig. 1c–f). For each condition, participants performed three trials, the first and second trials were intended to allow players to become familiar with the boots and surfaces and adapt to an insole pressure sensor. The participants took up to 2 min' rest after each set of four movements. The pressure mapping data were only recorded in the third trial for use in the laboratory test. The purpose of using an insole pressure sensor was to acquire the peak pressure of four specific movements and then obtain the pressure map for those peak pressures. The Opengo insole (Moticon GmbH, Munich Germany) used in this experiment consisted of 13 capacitive pressure sensors. Over half of the insole area (52%) was covered by pressure sensors. The measurement range was specified from 0 to 40 N/cm^2 and also was computed at 50 Hz. To differentiate pressure in the plantar area, 13 insole sensors were divided into three sections (forefoot, midfoot, and rearfoot) and nine zones (Fig. 1g). In the cutting movement (135°), participants were asked to perform an 'open' technique, which involves the athlete using the foot

on the opposite side to the direction they want to turn. In this movement, the peak pressure on the foot which changed the direction was collected (see Fig. 1c). In sprinting, the peak pressure of a stance phase over 2 m in the middle of the path (random feet in this area) was gathered (see Fig. 1d), and in turning, the data from the main foot which changed the direction was recorded (see Fig. 1e). For the penalty kick, the data from the supporting foot were collected as the ball was kicked towards the goal frame (see Fig. 1f). In all movements, the measured foot was the preferred foot [23]. A Clegg hammer impactor 2.25 kg (SD Instrumentation Ltd) was used in the field test to evaluate the hardness of the surface. Three trials were performed on four designated strips of the playing surface on a football pitch (in a total of 12 trials). The mean hardness of experimental surface in the field test aided in replicating the same playing surface in the laboratory trials.

2.2 Phase 2: football boots

Five outsole configurations (see Fig. 2) were randomly chosen among 15 designs in our outsole-design data bank. In addition, two outsole E and H were chosen due to traditional usage of them in football competition and training:

Fig. 2 Outsole configurations of eight outsoles used in the Laboratory. *Outsole 'A' has sandpaper without studs*
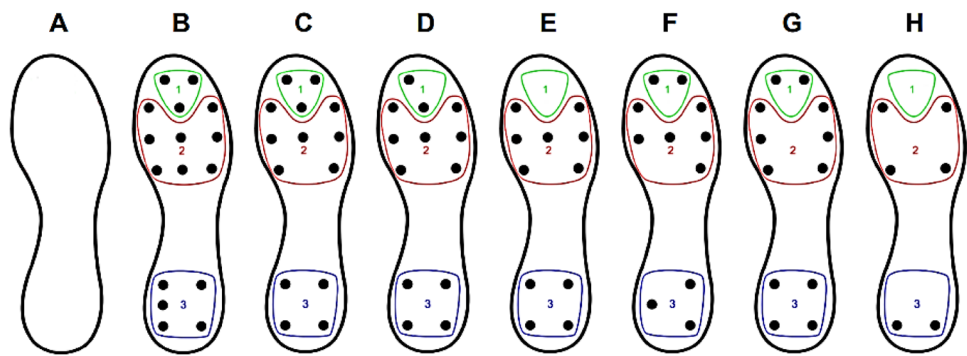
The football boot data bank was classified into three parts: (I) variety of outsole configurations (design of stud distribution), (II) stud length, and (III) surface area per stud. The data bank consisted of the photographed boots and the measurements. For this experiment, we focused only on the outsole configurations and stud lengths (see Fig. 3). The stud lengths derived from more than forty boots' studs over three plantar zones (forefoot, midfoot, and rearfoot) among all football boots in our database. The surface area was adopted from the football boot brand Adidas, model: Copa Mundial FG.

To do the laboratory test with the mechanical prosthetic foot (MPF), studs of a random football boot, the Adidas ACE 17.3 (size 42.5), were flatted and smoothed by the grinder. Then, 16 possible stud positions (see Fig. 4) were created with boreholes on the outsole and equipped with threaded bearings. Three types of conical-shaped studs of varying length and area were created for the three plantar zones (forefoot, middle, and heel) on the outsole (see Fig. 4b). These studs were Computerized Numerical Control machined (Fräsmaschine Deckel, FP 4A) in Polyoxymethylene (POM). They were used according to the seven outsole designs shown in Fig. 2. The outsole material was polyurethane.

### 2.3 Phase 3: laboratory test: mechanical prosthetic foot

To reduplicate field conditions in a laboratory setting, the following three steps were undertaken: first, we prepared football boots which could be varied with regard to different and desired stud configurations. Second, we provided an experimental surface matched closely to the impact peak acceleration from the Clegg Hammer test of the surface in our field test. Third, we adjusted the MPF in which the movements were replicated according to field test pressure mapping.

The MPF was designed as a pneumatic machine, which can pseudo-statically simulate motions leading to non-contact ACL injuries. The main components of the machine were the frame, the artificial leg and the pneumatic control

parts. The frame had two flexion frames mounted on it, which allowed setting up the flexion/extension and adduction/abduction angle of the artificial leg (Figs. 5, 6). The artificial leg comprised a vertical cylinder to statically apply loads (up to 1000 N) along the shaft, a pneumatic muscle (Muscle SIM, Festo AG & Co. KG, Esslingen, Deutschland, F_{Muscle} = Force responsible for rotational deflection) to induce rotation, and a 6-component load cell to record all six occurring force components (ATI-IA Omega160, Apex, NC, USA). The load cell was connected to an ATI Transducer Power Supply box (9105-PS-1). This box was then connected to a NI 9205 card (National instrument) which fits into a NI Crio. The Crio was then connected via Ethernet to the computer.

A specialized foot model used in this study [24]. It consisted of a metal skeleton which was molded in a foot shaped silicon casts with the length and width of 26 cm and 10.5 cm, respectively (see Fig. 6). To ensure the results reflected field test conditions as closely as possible, the machine also had a sophisticated foot and ankle model to simulate realistic plantar pressure distribution. To allow for linear traction measurements, a transversal table (Fig. 6g) was added, which can move the ground relative to the mechanical foot. The design was based on the linear table construction of the ski boot testing device concept presented by Knye et al. [25].

For our laboratory study, we provided surfaces with similar impact peak acceleration from Clegg Hammer to those used in the field test. The layered surface sample and the supporting steel block used in the laboratory experiment were 50×40 cm and 40×40 cm, respectively. The AT top layer was changed after 20 trials of each boot (e.g., a football boot at preload of 400 N in four movements, with each movement composed of 5 trials $= 4 \times 5 = 20$). The experimental surface was fixed to the supporting block with two clamps, one at the upper part and another at the lower part (Fig. 6i). The surface sample could either be moved forward or rearwards relative to the foot. For translational traction testing, the surface was vertically raised until it came into contact with the forefoot of the shoe and abovementioned normal loads were reached. After normal load was reached, the platform moved 200 mm anteriorly to the shoe at a speed
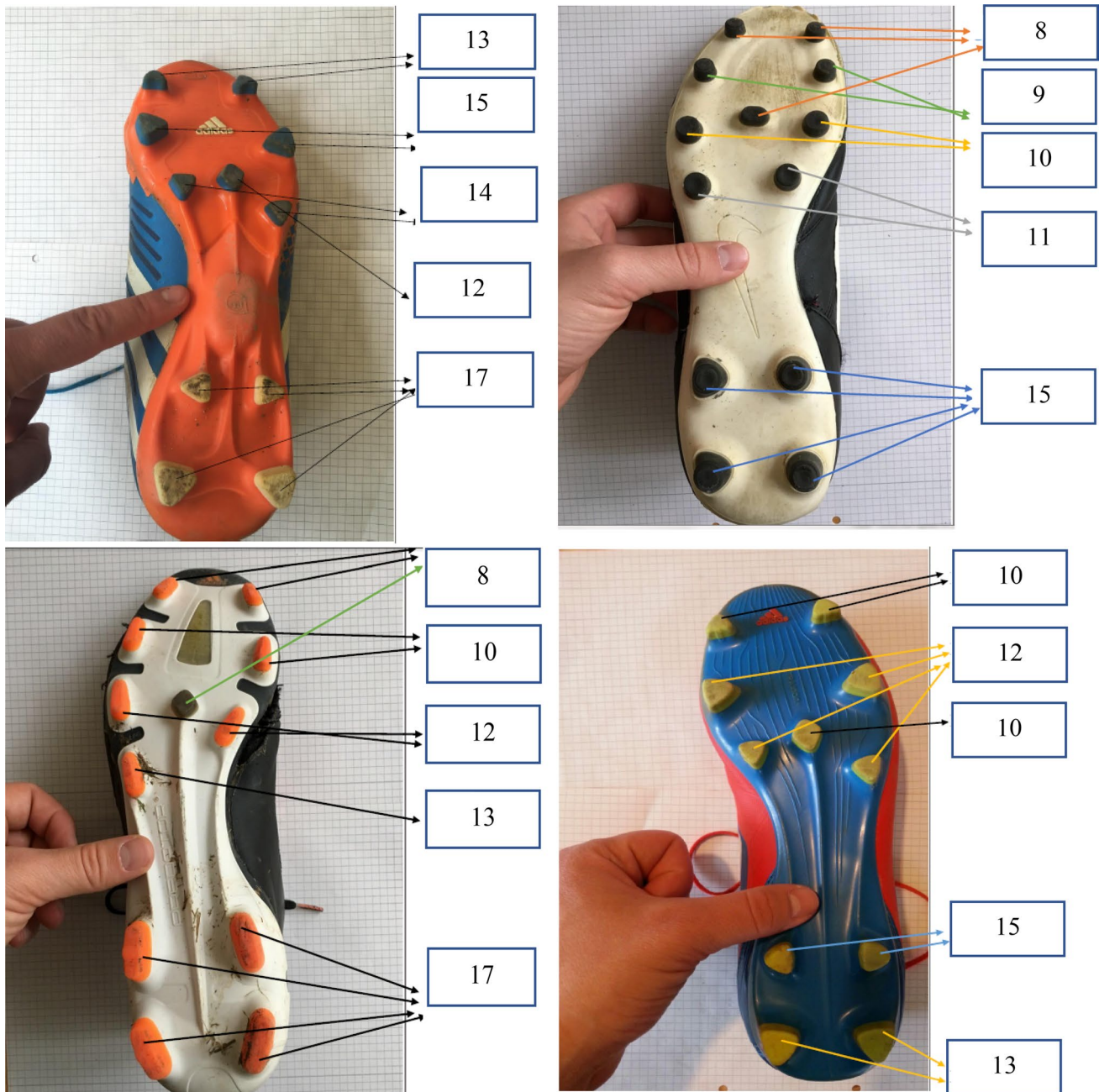
Fig. 3 Photographs of four outsoles of football boots measured their stud heights used in Data base (all dimension in mm)

of 0.2 m/s while the horizontal (F_y and F_x) forces were measured by the load cell during movement.

The Pedar Mobile system (Novel GmbH, Munich) was used to collect plantar pressure distribution in the laboratory test. The system consisted of two flexible insoles (each containing 99 sensors in a matrix design) and a portable data logger for data storage. The sampling frequency was 50 Hz. The insole pressure sensor was inserted in the baseline boot to replicate plantar pressure distribution for the cutting movement with a preload of 400 N. To attain

this plantar mapping, the MPF was adjusted based on abduction, adduction and flexion extension, as shown previously in Fig. 3. After replicating the pressure mapping of the field test in this laboratory condition, the baseline boot was replaced with other boot outsole configurations. Next, translational and rotational tractions were measured for the other seven boots. Each condition was tested in 5 trials. A similar procedure was followed for preloads of 600 N and 800 N. In all trials, the center of pressure was kept
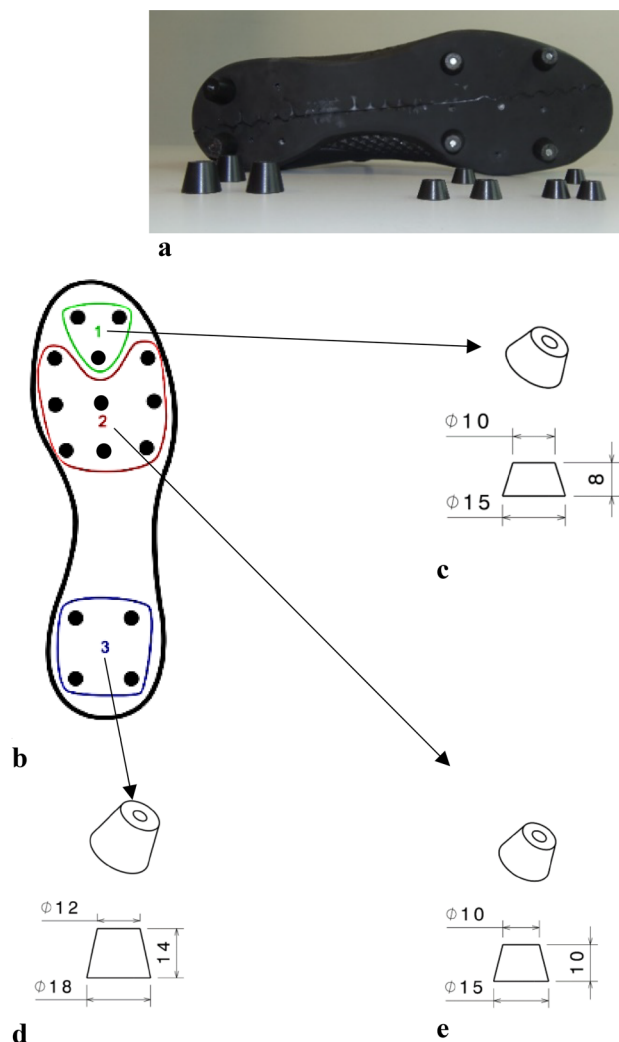
Fig. 4 **a** Photograph of three types of studs and the boot used in the laboratory test, **b** studs used in the out sole in three sections 1 = fore-foot, 2 = midfoot 3 = rearfoot, **c** stud geometry in forefoot in mm, **d** stud geometry of midfoot in mm, **e** stud geometry in rearfoot in mm (all dimensions are in millimeters)

constant per movement while applying preloads of 400 N, 600 N and 800 N (the location shown in the Fig. 8a–d).

The foot model used in our study was still different from an actual foot. In our attempt to reach a preload of 1500 N, it was observed that the traditional insole sensors (Moticon and Pedar) were partially damaged. The reason for this damage and inability to reach higher loads than 1500 N using the insole sensor is as follows: MPF is a pseudo-static machine requiring a higher contact time to reach peak pressure (than real movement) and the desired preload. In reality, in a football movement such as cutting, contact time is very short, roughly 200 ms at a velocity of 2.5 m/s. To increase the preload using MPF, an increase of surface interaction contact time is necessary, which risks damaging insole senor. Some mechanical limitations were observed when the

preload exceeded 1500 N. For example, upper ankle movements such as in cutting or turning resulted in deformities in pressure distribution. Therefore, we set the preload below 1000 N (400, 800, and 1000 N) to allow a safe margin for accurate pressure distribution, which helped us to confidently predict translational and rotational tractions in the load higher than 1500 N.

2.4 Phase 4: artificial neural network (ANN)

Neural networks were implemented in Python using the Tensor Flow framework and libraries such as Keras, NumPy and Pandas. Translational and rotational traction data were separated. Inputs to the ANNs were stud pattern, type of movement (sprinting/kicking for translational traction, and cutting/turning for rotational traction) and load (400, 600, and 800 N). To input the stud pattern, all 16 stud positions were numbered from 1 to 16 (see Fig. 7). If one position had studs attached, it was designated 1, otherwise 0. For both translational and rotational traction, 10 neural networks were implemented. In general, the ANNs consisted of one input layer with 18 inputs, 2 hidden layers and one output node, only varying in the number of nodes in their hidden layers. The activation functions were ReLU (Rectified Linear Unit) in the hidden layers and linear in the output. The order of data was randomized and split into a training/validation ratio of 80:20. Weights and biases were initialized randomly.

Randomization of data and random initialization of weights and biases were executed only once to establish baseline values and kept constant for all ANNs. This ensured better reproducibility, as different randomized values can lead to different results. Loss function was the mean squared error. The Adam optimizer was used to update weights and biases. In contrast to stochastic gradient descent (SGD), where the learning rate is constant, Adam is an algorithm that adapts the learning rate to different parameters. Training was stopped when the validation loss did not decrease further after 1000 iterations. Preloads which were estimated in the ANN are as follows: in cutting 135° = 2600 N, in sprinting = 3300 N, in turning = 1700 N and in penalty kick = 2600 N. The mean of preloads was 2550 N. These data were extracted from the literature [26–29] for cutting, sprinting and penalty kick. For the turning movement, the load was measured using the Moticon insole sensor pressure [30] in our study.

3 Results

The plantar pressure distributions measured per movement in the field test were sub-classified into three different sections (see Fig. 8). The peak pressure was normalized (%) for each movement for all 17 participants. Three areas are
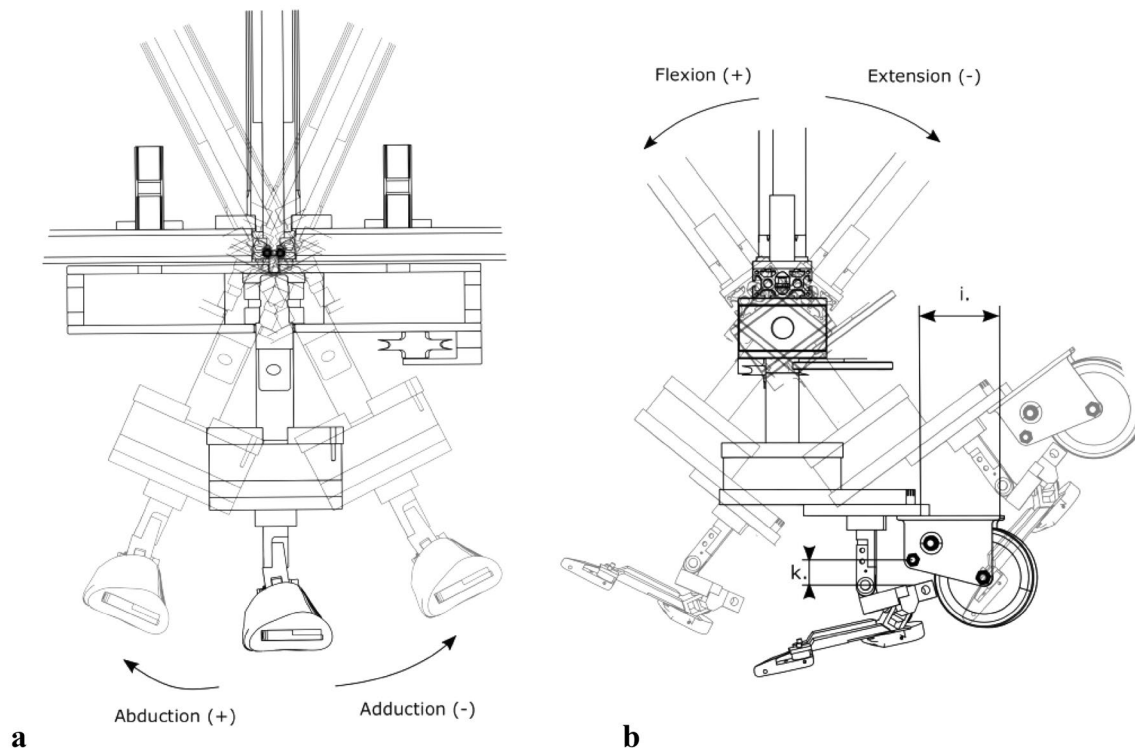
Fig. 5 Two degrees of freedom for adjusting movements **a** abduction/adduction and **b** flexion extension. This adjustments aid in to reach to appropriate pressure distribution per each movements (cutting, kicking, sprinting and turning)

common to all movements: the medial forefoot, central forefoot and hallux. Pressure mapping in the laboratory test was followed according to normalized data (Fig. 8) in preloads of 400, 600, and 800 N.

In the field test, the hardness of surface was equal to 155 g (4.9 = SD) and in the laboratory it was equal to 155.3 (3.4 = SD). The ANNs ran based on overall 480 measurements (8 boots, 3 preloads, 4 movements: each conditions include five trials). 12 measurements were excluded after Grubbs' test for outliers. The three best performances based on validation error were chosen for translational and rotational traction (see Tables 1, 2).

Rotational (Nm and translational traction coefficient were predicted in the preload of 2550 N based on the mean results of the three best performances of the ANN (Tables 1, 2). These results are sorted in Table 3 for TTC from highest to lowest, while the data from rotational traction (cutting and turning) are sorted from lowest to highest. Higher rotational tractions were attributed to 'foot fixation' and knee injuries whereas low translational traction was related to risk of slippage [10, 11, 31–33]. Therefore, the upper ranges of both RT and TT in Table 3 are related to the abovementioned injuries and, in addition, such a sorting can facilitate understanding the selection of a 'safe zone', which will be explained in the Discussion below.

The mean translational traction coefficient among all seven boots in sprinting was 0.10 and in kicking 0.11. The mean rotational traction in cutting was 36.23 and in turning 15.62. Based on the ANN predictions, the highest translational traction coefficient in both sprinting and kicking was for stud pattern C while in rotational traction, stud patterns G and C are lowest.

4 Discussion

This study established a methodological framework within which to predict traction (rotational and translational) with a mean preload of 2550 N. Such a method should help to recognize a safe zone for different outsole configurations in specific football movements. #. Pressure mappings of four specific football movements were measured in the field test and analyzed by normalized peak pressure. Peak pressure in all four movements was highest in the midfoot of the plantar. The sprinting movement had the highest midfoot peak pressure (60.80%) while the turning movement had the lowest, with 46.40%.

The lowest pressure in all three plantar sections of all four movements was on the heel in sprinting, with only 4.9%. Turning and kicking movements
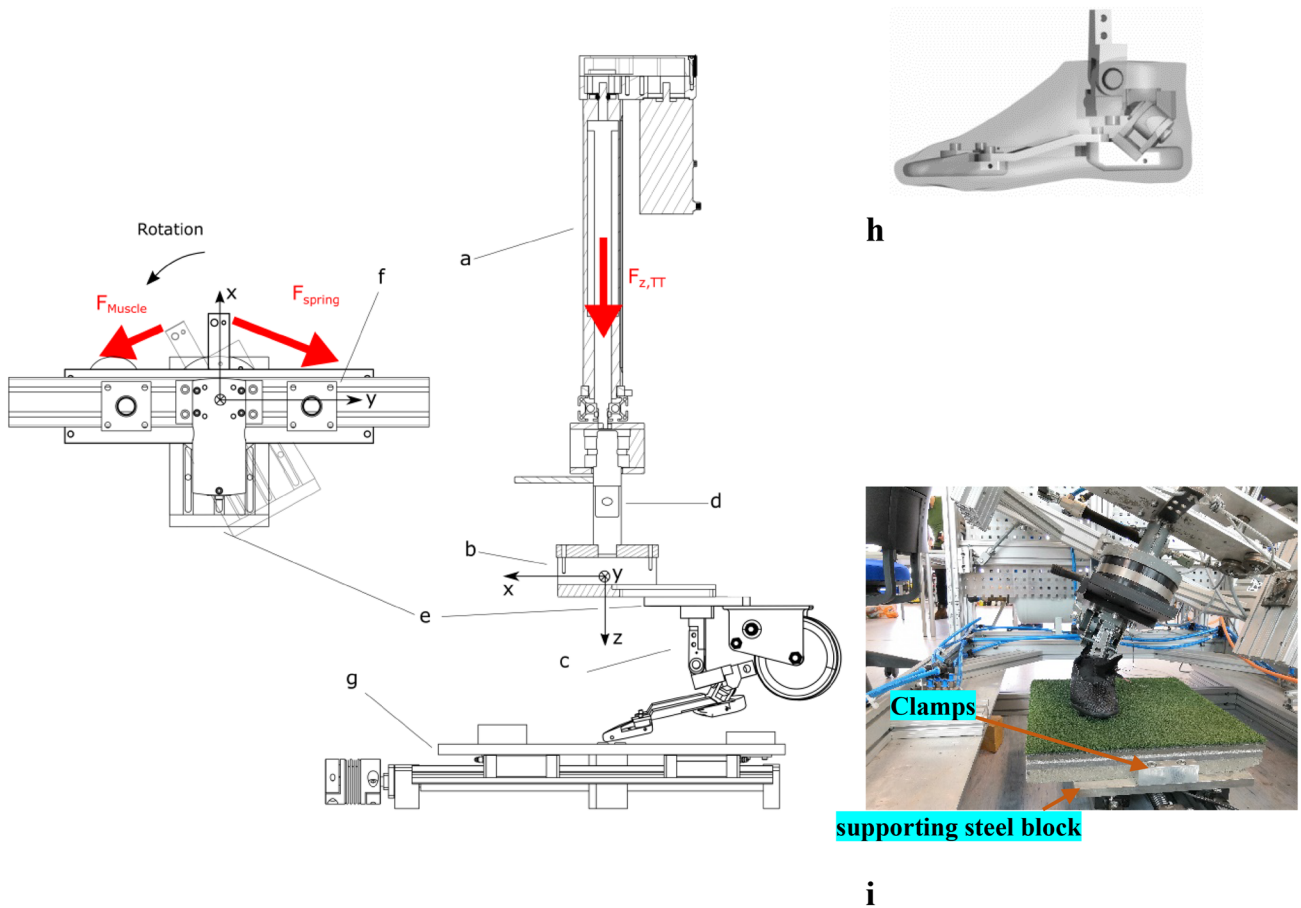
Fig. 6 Diagram showing the MPF in detail **a** electromechanical cylinder, **b** load cell, **c** traction foot model, **d** rotational axis, **e** rotational axis displacement Mosul, **f** parallel guide, **g** transversal table. Forces: F_{Shaft}—load to recreate ground reaction force, F_{Muscle}—force respon-sible for rotational deflection, F_{Spring}—rotational restoring force, **h** foot model with silicon cover, **i** MPF while replicating 135° cutting movement after adjustment with appropriate pressure distribution

Fig. 7 **a** Numbering of stud positions and **b** structure of artificial neural network with two hidden layers. Input layers include studs (0 and 1), movements (translational traction and rotational traction), and preload
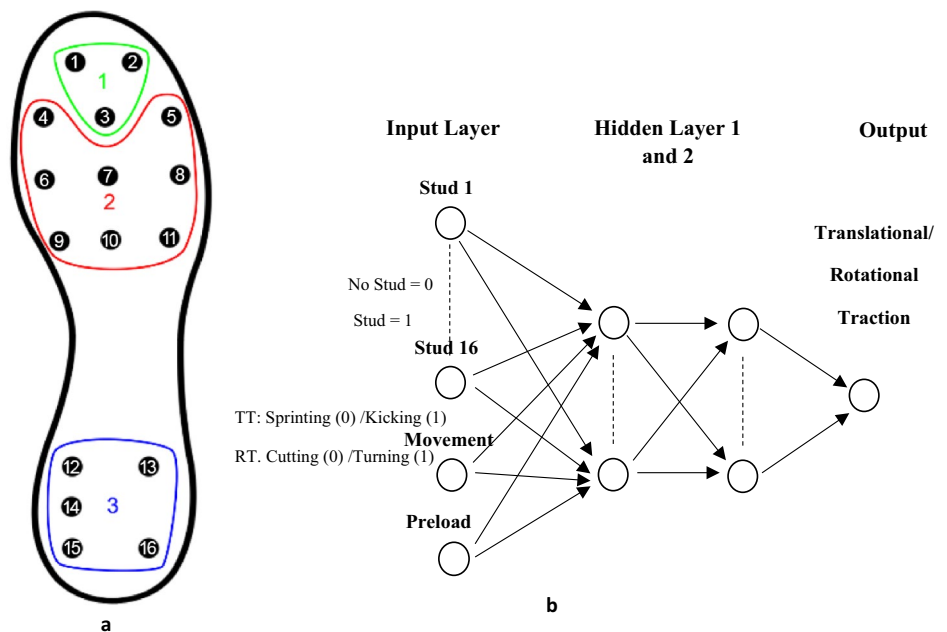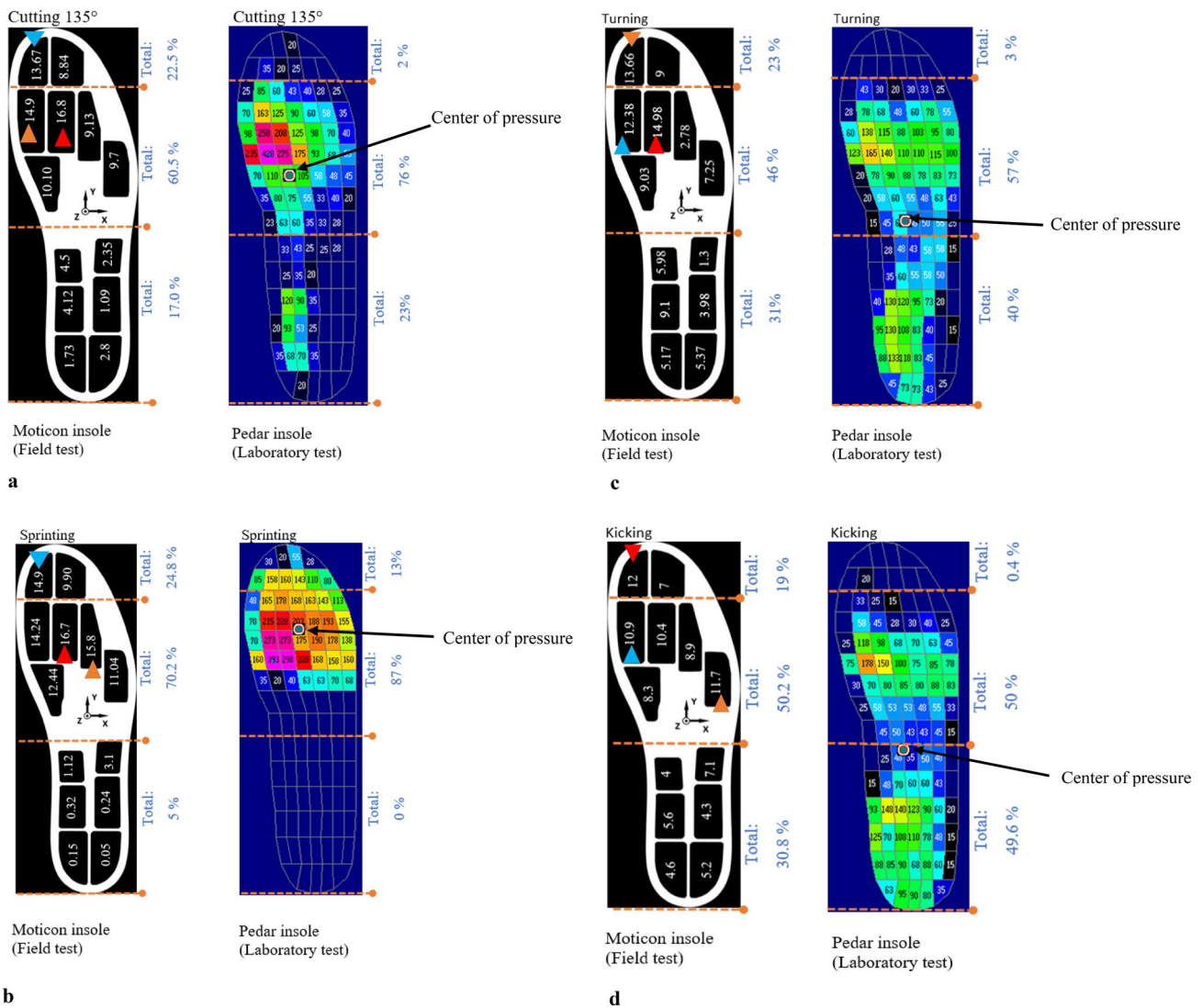
Fig. 8 a–d Data of pressure mapping of Moticon (in the left side) were normalized (%) for each movement and shown in three sections: three first peak sections of pressure in plantar are colored as highest with red color, second highest with orange, and third highest with blue color. Data of pressure mapping of Pedar insole (in right side) were normalized for each movement (%) and shown in three sections: the plantar pressure of football boot used in laboratory test by Pedar insole in maximum preload 800 N (Unit is in kPa). The location of centers of pressure is shown per movement in the laboratory experiment while using Pedar system (Color figure online)

Table 1 The three best performing neural networks in translational traction

Hidden layer 1[a]	Hidden layer 2[a]	Training iterations	Training loss	validation loss	Training error (%)	Validation error (%)
20	10	4569	2.1×10^{-3}	1.6×10^{-3}	13.7	9.9
12	6	6522	1.6×10^{-3}	1.8×10^{-3}	11.9	11.1
18	5	5547	8×10^{-3}	1.9×10^{-3}	8.3	11.1

[a]Number of nods in hidden layer

determined that plantar pressure was distributed more evenly in comparison to sprinting and cutting movements. The difference between the highest and lowest peak pressure values of three plantar sections in turning was (46% − 23%) = 23.0% and in kicking was (50.20% − 30.80%) = 19.4. However, such differences

Table 2 The three best performing neural networks in rotational traction

Hidden layer 1[a]	Hidden layer 2[a]	Training iterations	Training loss	validation loss	Training error (%)	Validation error (%)
20	20	5257	1.9	1.4	9.3	7.0
10	10	4757	2.1	1.9	10.3	8.0
20	18	5574	1.32	2.8	7.8	8.1

[a]Number of nods in hidden layer

Table 3 Neural networks' mean predicted tractions of all stud patterns

Rank	Sprinting		Kicking		Cutting		Turning	
	Pattern	TTC	Pattern	TTC	Pattern	RT (Nm)	Pattern	RT (Nm)
1	C	0.14	C	0.14	G	35.22	G	14.62
2	B	0.13	B	0.13	C	35.39	C	14.80
3	G	0.13	G	0.12	B	35.60	B	15.00
4	F	0.12	F	0.12	E	35.60	E	15.00
5	H	0.10	H	0.10	D	35.90	D	15.25
6	D	0.09	D	0.08	F	37.90	F	17.30
7	E	0.08	E	0.08	H	38.00	H	17.40

TTC translational traction coefficient, *RT* rotational traction (Nm)

were large in sprinting, $(70.2\% - 5\%) = 65.2\%$ and in cutting, $(60.5\% - 17\%) = 43.5\%$.

Our findings determined that the peak pressure in all four movements had some common areas, such as the central forefoot, medial forefoot and hallux. In the cutting (135°) movement, our results showed that for central forefoot I. medial forefoot and hallux contributed more than other plantar areas in generating peak pressure. This finding is in line with those of Teymouri et al. [32]. Moreover, our results also determined that in cutting (135°), peak pressure in the medial heel was greater than in the lateral heel. This finding is also in line with Teymouri et al. [32] and Eils et al. [33].

In sprinting, the medial forefoot and hallux showed the highest peak pressure in comparison to other areas of the plantar (this is in line with Eils et al. [33]). In the turning movement, the pressure distribution tended to shift to the medial sections (Hallux, medial midfoot and medial heel). In turning movement, the central forefoot I showed higher peak pressure. Finally, in kicking, the peak pressure was highest in the hallux, central and medial forefoot (this is in line with Teymouri et al. [33]). In the kicking movement, the lateral heel showed greater peak pressure than the medial heel, which is in line with findings of Eils et al. [34]. It should be added that plantar pressure measurements cannot take account of all players or their various individual techniques and movements. Moticon insole has been used in sport field [34, 35] and clinical experiments [36, 37] to measure pressure mapping, temporal parameters and peak vertical force. Some studies show that force impulses were lower using Moticon insole when compared to AMTI [38], although the

insole sensor (Moticon) revealed moderate–excellent reliability (0.61–0.90) [30, 39]. Since our study focused on pressure distribution, specifically, peak pressure, we have compared our results with past studies which used Pedar as gold standard system [32–34]. As explained in the first paragraph of this discussion, the peak pressure data obtained by Moticon in four movements are in line with those of past studies [32–34]. This finding may be useful for other researchers interested in replicating this methodological framework in that they can be flexible in choosing between Moticon and Pedar insoles.

The MPF was adjusted according to the pressure mapping obtained in the field test. By measuring rotational (turning and cutting 135°) and translational traction (sprinting and penalty kick) in three preloads (400, 600, and 800 N), the three best performances of the ANNs were selected. The result of rotational traction with an estimated preload of 2600 N in cutting (135°) determined that the rotational traction lay in the range of 35–38 Nm. This predicted traction range can be defined in the range of high risk of injuries according to Wannop et al. [11]. However, the result of rotational traction with an estimated preload of 1700 N in the turning movement lay in rotational traction (14–17 Nm). This entails low risk of injuries, as determined by Wannop et al. [11]. It has been mentioned that higher rotational traction causes foot fixation related to injuries such as ACL [11, 40].

According to our results among seven boots, high rotational tractions are specific to outsoles H and F. On the other hand, the risk of slippage due to low RT should be

considered. Outsole G and outsole C had the lowest rotational traction. To reduce these two injuries and find the desirable range of rotational traction, our findings determined that the *safe zone* is to be found between outsoles B, E and D for rotational traction. Accordingly, in translational traction, an excessive increase of studs in the forefoot and midfoot area causes excessive translational traction. In translational traction, the range of seven outsoles' translational tractions was 0.08–0.14. Outsoles C and B increased traction to nearly 0.14.

The low translational traction coefficient in our study in comparison to other studies, such as [41, 42], can be seen from different perspectives. The penetration behavior of studded outsoles was influenced by the type of surface, i.e., AT or natural grass (NG). Penetration on AT causes instability and lower depth [43, 44]. The friction coefficient of AT and its interaction with POM studs varies between 0.16 and 0.65 [45]. In one of the pin-on-disk tribometer tests, POM had a friction coefficient of about 0.4 at a velocity of 200 mm per second on carbon steel [46]. In general, the low friction between the studs and turf could be another reason for the generation of lower traction in comparison to the abovementioned studies. In summary, low penetration of studs on AT, and the low friction coefficient of AT and POM studs could result in low translational traction.

In general terms, higher translational traction coefficient can affect joint loading, although the perceived grip and perception of running can be increased [47, 48]. On the other hand, low translational traction will contribute to slippage risk. This indicates that it would be advisable to avoid outsoles with upper ranges (outsoles C and B) and lower ranges (outsoles D and E) of translational traction due to the mentioned risk of injuries. Therefore, outsoles G, F, and H can produce a *safe zone-translational traction*, where the payoff risk between joint loading and slippage is optimized. Our study suggests another approach that can also be used to find the optimal outsole configuration. Obviously, low translational and rotational traction can cause injuries from slippage. To avoid such a risk, we suggest determining the mean of translational and rotational traction per movements. In sprinting, the mean translational coefficient was 0.10 corresponding to outsole H. In kicking, the mean translational coefficient was 0.11 corresponding to outsole F and H. In cutting and turning, the mean rotational traction was 36.23 Nm and 15.62 Nm, respectively. According to these ranges, the theoretical safe outsole in respect of traction (where traction is close to the mean) was outsole D. This outsole might therefore mitigate the risk of injuries since it lies within the identified safe zone of rotational and translational traction. However, this would need to be determined in further work.

Our study provides a methodological framework that determined a traction 'safe zone' within our database of loads and conditions (see Table 3). The mechanical prosthetic foot played a significant role in generating rotational and translational tractions in this study. However, there are some limitations regarding replication of those four movements from field test to laboratory test using this apparatus:

1. FIFA has defined appropriate and acceptable hardness for *NG* in a range between 40 and 100 g. but not for AT [49]. The AT is generally harder than NG, especially when it comes to outdoor surfaces, and has a duration of 4 years usage [50]. Logically, some maintenance can be applied to NG, in that its hardness can be maintained or improved over time, which does not apply to AT. The surface used in this study was an AT with a hardness of 155 g. An advantage of such AT in comparison to NG is that it has fewer deformations due to environmental changes on different days of experiments. Since the football boots used in the field test were stud free, excessive changes of environment may influence slippage risk on the outdoor AT. Our priority was to minimize surface variations caused by extrinsic variables in both field and laboratory tests. Another advantage of using AT in our study is that it allowed us to measure traction which may cause risk of injuries among adolescent players [51]. Lastly, using AT in our methodology should help other researchers to facilitate the replication of this experiment in a flexible manner.

2. The plantar pressure distribution of four movements replicated with the MPF was not identical to the field test in the forefoot section. The pressure mapping of hallux, and other toes were not replicated similarly to the pressure mapping obtained in the field test. To fulfill the pressure desirable pressure mapping of the field test in the laboratory test, the foot model should have dorsiflexion/plantar flexion and toe extension. These degrees of freedom would be helpful in replicating movements more accurately to reach the desired plantar pressure distributions.

Since stud length plays a significant role in stud penetration and consequently in rotational and translational traction [52], our approach was to use three different heights of studs in the forefoot, midfoot, and rearfoot sections as per available boots on the market. These mean heights were derived from our data bank. Using a mean of stud lengths from different football boot manufacturers can aid in minimizing bias in producing stud length. Such a measurement helps to clearly classify stud length for three different sections. Future study should investigate the mean of surface areas of all available studs on the outsole to identify the optimal surface area per stud for each section (forefoot, midfoot, and rearfoot) (Table 4).

Table 4 Rotational and linear traction of the laboratory test

Pre-load (N)	Outsole design	Rotational traction (Nm)		Translation traction coefficient		Rotational traction (Nm)		Translation traction coefficient	
		Cutting	SD	Sprinting	SD	Turning	SD	Kicking	SD
400	B	20.55[a]	1.23	0.42	0.03	7.05	1.21	0.21	0.02
600		21.91	0.64	0.37	0.04	6.22	1.71	0.23	0.02
800		21.31	0.65	0.33	0.00	7.18	0.58	0.24	0.02
400	C	18.90	1.07	0.38	0.04	6.26	1.13	0.30	0.02
600		20.49	0.52	0.36	0.01	6.10	0.30	0.27	0.00
800		21.17	1.68	0.30	0.01	8.47	1.26	0.26	0.01
400	D	19.32	0.64	0.34	0.02	6.29	1.21	0.24	0.03
600		22.55	0.44	0.24	0.03	6.38	0.82	0.24	0.02
800		22.87	1.48	0.25	0.02	7.19	0.70	0.24	0.01
400	E	19.87	1.24	0.27	0.00	5.29	1.35	0.26	0.01
600		21.77	0.18	0.28	0.01	7.52	1.29	0.25	0.02
800		20.48	2.45	0.25	0.01	8.05	0.66	0.26	0.02
400	F	21.83	1.49	0.39	0.02	6.73	0.80	0.23	0.02
600		24.31	0.53	0.33	0.04	8.38	0.90	0.26	0.01
800		24.14	1.16	0.27	0.02	10.28	1.20	0.24	0.00
400	G	17.64	1.01	0.34	0.01	5.52	1.19	0.29	0.01
600		19.76	0.33	0.32	0.01	7.32	0.62	0.29	0.01
800		21.47	1.98	0.29	0.01	8.08	0.44	0.28	0.00
400	H	17.82	0.49	0.30	0.02	9.21	1.99	0.26	0.01
600		21.63	1.64	0.30	0.01	9.50	1.33	0.29	0.02
800		24.87	1.04	0.26	0.00	12.18	0.71	0.26	0.01

[a]Mean of five trials

The future mechanical prosthetic foot should be able to endure higher preloads (at least 2500 N). This more robust foot would offer the possibility of validating the results of our study. This should be noted that data of tractions (translational and rotational) in higher preloads presented here should be used in cautious due to the gap between inputs preload (400 N, 600 N and 800 N), and estimated output preloads (exceeding 2500 N). In future studies, two modifications will be considered: (I) modifying the foot model to make it behave more like an actual foot while interacting with the surface (changing the design and materials). (II) Introducing a hydraulic pressure sensor in place of the used pressure insole. This modification would aid in increasing reliability and reducing the cost. Validation of our data at a preload higher than 2500 N can be applied in a future study, where the abovementioned limitations have been minimized. In addition, future research should also consider various outsole configuration to define upper and lower ranges of traction. Since players are equipped with sensory perception and can adapt to some acute traction changes

understanding perceived traction in a field test and comparing this with our mechanical testing machine can aid in defining such a safe zone in more accurate way and also wider range.

5 Conclusion

We have sought in this study to establish a robust methodological framework within which to identify an optimum zone of translational and rotational traction. Data from the field test were replicated in a laboratory test using a mechanical prosthetic foot with preloads below 1000 N. An artificial neural network was used to predict translational and rotational traction of different studded outsole configurations in realistic preloads of specific football movements: cutting 135°, sprinting, turning, and penalty kick. Rotational traction

related to the cutting 135° ranged from 35 to 37 Nm and rotational traction related to turning movement ranged from 14 to 17 Nm. The translational traction coefficient for both sprinting and penalty kick was in the range of 0.08–0.13. We hope that the results of this study may assist other researchers and sports professionals in estimating the risk of injuries for different stud configurations.

Declarations

Conflict of interest The author declares that he has no conflict of interest.

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