Measuring variation in vertical ground reaction force for football boot midsoles, playing surfaces and football specific movements

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Research Article

Keywords: Football boot, surface hardness, football movement, midsole cushioning, vertical ground reaction force

Posted Date: May 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1614221/v1

Abstract

Excessive repetitive impacts in football are linked to chronic and non-contact injuries. Number of factors (extrinsic and intrinsic) play roles on such injuries.

Purpose: Our study aimed to investigate the effect of midsoles, surfaces and specific football movements on peak vertical ground reaction force (VGRF).

Materials and Methods: The studs of two football boots, artificial turf boots (ATB) and natural grass boots (NGB), used in this study were removed, after which the soles were smoothed and covered with abrasive paper. 17 male subjects 26 (±6) years old, 181(±7) cm, 79 (±11) kg performed two specific football movements (cutting 135° and penalty kick) on artificial turf (AT) and natural grass (NG) with ATB and NGB. The cushioning characteristics of the two football boots and resilience modulus of the two surfaces NG and AT were measured with an impactor machine and light falling weight deflectometer.

Results: Peak VGRF was measured with insole measurement system for all possible conditions. Our findings determined that the ATB (softer midsole) generates greater VGRF (2.25BW) than the NGB (1.95BW) – an increase of 15%. In terms of the surface, the AT with higher resilience modulus results in higher VGRF. Moreover, the peak VGRF of the cutting movement (2.28BW) differed significantly compared to the penalty kick (1.99BW).

Conclusion: Our results indicate that in boot-surface interaction, the effect of midsole boot cushioning on VGRF is more tangible than surface resilience. However, this study motivates boot developers to design a football boot based on all three variables: midsole hardness, movements and surface hardness.

Introduction

Mechanical loading on a human locomotor system in *sport activities* can be defined as constructive or destructive [1]. Evidence for destruction comes from the response of bone cells, depending greatly on excessive repetitive impacts [2-5] with surface properties [6, 7], boot properties [8, 9], and movement types [3, 10]. This excessive destructive mechanical loading can cause micro or macro trauma and result in overuse injuries [1, 11, 12] which include around a quarter of all sport injuries [13].

A study of sport boots focusing on the midsole component revealed that highly cushioned running shoes increased the peak VGRF more than normal running shoes during running [14]. Nin et al. (2016) determined that forefoot peak VGRF in a 'soft shoe' was higher than in a 'hard shoe' during shot-block landing [15]. In contrast, other studies have revealed that there is no effect of highly cushioned midsole shoes and normal running shoes on VGRF peaks (impact and active peaks) [16, 17]. Previous research has produced mixed results concerning the effect of the midsole on ground reaction forces, thereby requiring more studies in order to reach a common consensus. However, to our knowledge, in some sports where the midsole is equipped with a studded outsole, the effect of midsole on peak VGRF has been poorly understood. In football, boots are broadly classified as natural grass boots (NGB) and artificial turf boots (ATB). These are different in stud configuration, which alters peak VGRF [5, 18] and peak pressure [19]. However, the boots in these studies are not only different in stud configuration, but midsole cushioning and other impact factors also vary. Since these studies cannot show that the differences occur due to midsole or outsole changes, more research is needed to investigate the effect of two midsole cushioning properties – on ATB and NGB – while taking account of the configuration and characteristics of the outsole. In addition, another feature of football boots, namely a 'good fit', which is a prerequisite for boot comfort [20], can be influenced by different construction of boots (upper shape, boot lace, heel flare, heel cup) [21]. Paying less attention to good fit while comparing midsole cushioning, makes the final results ambiguous as to whether significant biomechanical changes or no changes to midsole hardness influences comfort in terms of good fit [22]. It has been suggested that the comfort variable can be measured by different type of questionnaire, such as visual analogue scale (VAS) [23].

Football teams are more likely to frequently switch between pitch surfaces during training or in match venues. Following the development of artificial turf in football, the demand for this surface in training and competition has increased. A 12-year study by Fujitaka et al. (2017) showed that switching football surfaces from natural grass to artificial turf increases the incidence of injuries [24]. Accordingly, Stiles et al. (2007) state that '[p]ast studies showed that the increased use of artificial surfaces in place of natural surfaces in sport has led to a higher prevalence of overuse injuries [26, 27]' [25]. However, current research comparing natural grass with artificial turf generally finds that there is no significant difference in injury incidence and severity [28-30]. McMurtry et al. (2019) assessed injury incidence to quantify risks in different playing surfaces and determined that surface cannot account for cumulative injury mechanisms such as medial tibial stress syndrome, chronic ankle sprains, and cartilage degeneration [31]. Reducing the magnitude of the external load (which affects internal structures) is one option for preventing overuse type injuries. External load can be affected by a variety of boundaries, including surface [32]. Girard et al. [2007] finds that 'harder surfaces (e.g. greenset)' compared to 'softer surfaces (e.g. clay)' increased plantar loading in specific movements [33]. McMurtry et al. (2019) revealed that in football, VGRF parameters differed between two surfaces: natural and artificial grass (there is no information available about compliant level of surfaces) [31]. However, their study included participants with prosthetic legs, which may exaggerate effect sizes in comparison to able-bodied participants. Other kinetic parameters such as peak pressure in concrete vs natural grass surfaces [34], peak pressure in natural grass vs artificial turf [6], and vertical peak acceleration in concrete vs woodchip [35] have determined that harder surfaces are correlated to the aforementioned kinetic parameters. In contrast, Weijie Fu et al. (2015) revealed that there is no difference in peak pressure in running movement comparing both concrete and grass surfaces, nor in peak acceleration. Inconsistency of past results prevents researchers reaching a consensus about the effect of surface stiffness on kinetic parameters in football, e.g. peak VGRF [36]. To measure peak VGRF, some studies, Simonsen et al (2000), Orloff et al. (2008), Katis et al. (2010), Blackburn et al. (2003) and Bencke et al. (2000), inserted force plates into the pitchto measure specific movements (i.e. cutting and kicking) [37- 41]. However, inserting force plates under a *natural* football pitch was criticized by Clarke et al. and Akins et al., who are of the opinion that this results in changing soil characteristics [42, 43]. Thus, to avoid such a change, some researchers have used in-boot measurement systems in different sports as an alternative to force plates [8, 44, 45]. The purpose of the present investigation was to characterize and to compare VGRF on two different midsoles, two surfaces and two specific football movements using an insole-measurement system. Three hypotheses were investigated:

1. Midsole conditions have a significant influence on VGRF
2. Surface conditions have a significant influence on VGRF
3. Different football-specific movements have a significant influence on VGRF

Materials And Methods

Participants

Seventeen male participants were recruited from football clubs (third and fourth Bundesliga) in Munich (Germany) and the surrounding area based on having had a minimum of 5 years' experience playing football but were excluded if they had had a lower extremity musculoskeletal injury within the past six months or a lower extremity reconstructive operation within the past three years. The mean age, height and weight were 26 (±6) years old, 181(±7) cm, 79 (±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 was conducted according to the ethical standards of the Helsinki Declaration [46].

Protocol

Two boots of different football classifications (see Table 1), *Adidas Neoride III* (ATB), *Nike Hypervenom, (NGB)* were chosen based on the high demand for these boots at the time of the experiment. Prior to the start of the study, a Type A shore durometer (Kern & Sohn GmbH, Germany) was used to determine the material hardness at the forefoot and rearfoot regions of the boots. Each reading was taken as the average of five measurements at one location following Sterzing et al. (2013) [47] (see Figure 1).

Table 1 *characteristics of the two boots used in the experiment*

	Shore hardness		*HT* (mm)*	*Mass (g)*	*FT** (mm)*
	Forefoot	*Heel*			
ATB	*58.3*	*53.25*	*200*	*320*	*100*
NGB	*82.78*	*72.98*	*100*	*238*	*50*

HT: Heel Thickness, FT**: Forefoot thickness*

To ensure the outsole were identical, the studs of both boots were flattened and smoothed with a belt-grinding Machine. Abrasive paper (grit size, 80) was then glued to the outsole of the boots (see Figure 2). The grit size was chosen in a pilot test among three participants and the main criteria was to avoid slippage while performing sprinting, kicking and cutting movements on natural grass and artificial turf.

To distinguish the characteristics of the soles (resilience variable), a Light Falling Weight Deflectometer (LFWD) was used for every experimental test day on two common football pitches: artificial turf (sand/rubber infill, 100% Polypropylene) and Natural grass. The test determines the dynamic modulus of soil deformation in different ranges [48]. The LFWD consists of a steel loading plate with accelerometer sensor, a falling weight and an electronic measuring unit. The procedure involves dropping a 10kg weight freely from a height of 72cm, along the guide rod, to hit an installed dashpot unit in the middle of the steel loading plate. The loading plate has a diameter of 30cm and a thickness of 20mm and weighs 15kg [49]. The dynamic soil resilience modulus (Evd) is determined as the ability of a material to absorb energy when it is deformed elastically, and releases that energy upon unloading. It is a measure of material stiffness and provides a mean to analyse stiffness of materials under different conditions, such as density and stress level. It is measured in MN/m^2 (MPa) using the following equation 1 [50].

$$Evd = 1.5\, r \left(\frac{\sigma}{s}\right) \quad (1)$$

Where r=radius of the load plate, σ=stress under the load plate, s=mean settlement of the load plate. In our experiment, the dynamic soil resilience modulus of the artificial and natural surfaces was measured with the average of second and third drops of the four trials on a random spot on the experimental field.

Mechanical Midsole Characterization

A dynamic shock absorption test [51] was used for the measurement of cushioning properties. The pneumatic impactor device consists of a sphere with a 5cm diameter and total weight of 4.3kg. The machine operates by allowing the weight to fall onto the tested material from a defined height of 7mm. A single axis accelerometer sensor (range of −50g to 50g) was attached to the impactor in order to quantify the shock absorption with a measuring frequency of 5000Hz. The two locations on the boot midsoles tested by impactor were in the forefoot and heel, following Sterzing et al. (2013) (see figure 3) [47]. Twelve trials were conducted using the impactor but only trials two to ten were taken into the account.

Material of the Study: Insole Sensor Pressure

To measure vertical force and plantar pressure distribution, the insole pressure sensor system Opengo (Moticon GmbH, Munich Germany) was used in this experiment. Opengo consists of 13 capacitive pressure sensors, covering more than half of the insole area (52%). The peak pressure is specified from 0 to $40 Ncm^{-2}$ and also was computed at 50 Hz. No external devices or cables are needed to operate the system. In order to differentiate pressure in the plantar, 13 insole sensors were divided into 6 plantar sections. HxT=hallux and other toes, CFF=central forefoot, LMF=lateral midfoot, MMF=medial midfoot, LRF=lateral rearfoot and MRF=medial rearfoot.

Main Test

Pre-Test. In the beginning of experiment, all participants undertook a warm up program (*FIFA 11*) [52], with their own private (desired) boot. *Step 1*. Participants randomly chose a pair of boots, NTS or AGS, into which the insole- pressure sensors were inserted with an identical football socks. *Step 2.* They carried out two movements, cutting (135°) and penalty kick with two boots on one of the surfaces. For each condition, participants performed three trials, the first and second trial was to make players familiar with the boots and surfaces and the inserted insole, and the third trial was recorded and used for the measurement phase. *Step 3.* After performing the test on one of the surfaces (randomly), participants took up to two minutes rest and then followed the same procedure in step 2 but on another surface. As in *Step 2*, for each condition, participants performed three trials, the first and second to make players familiar with the boots and surfaces and the inserted insole, and the third recorded and used for the measurement phase.

In the cutting movement (135°), participants were asked to use 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 VGRF of the feet which changed the direction was collected. In another movement, the penalty kick, the data of the supporting foot was collected during their kicking the ball at goal (see Figure 4).

Furthermore, the discomfort level of the feet based on *footwear fit*, which can potentially be caused by pressure-related skin lesions on the edge of the feet was measured using Visual Analogue Scale (VAS, 100mm) after warm up. Poor fit (=high discomfort) is denoted by 0, and best fit (=low discomfort) by 100.

Methodology of Data Analysis

Data of the participants (n=17) on two surfaces, two boots and two movements (N=136) was analysed with a repeated measure ANOVA (2×2×2) with a confidence level=0.05. Effect size was used for all three variables expressed as Cohen’s d—0.2 denoting a minor effect, 0.5 denoting a moderate effect and 0.8 denoting a major effect [53].

DATA ANALYSIS

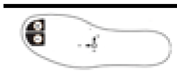
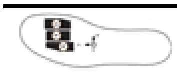
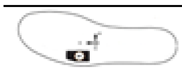
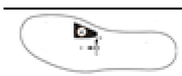
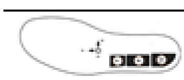
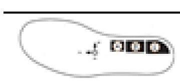
Comparing peak vertical force

The repeated measures ANOVA (2×2×2) determined that cutting vs penalty kick, natural grass vs artificial turf and finally artificial turf boot vs natural grass boot differed significantly (see Figure 5). According to the effect size, movement, boot midsole, and surface have a, respectively, 0.72, 0.78 and 0.28 higher effect on peak force. There was no significant interaction effect between variables ($P>0.05$).

The effect of the two different boots, ATB and NGB, on natural grass and artificial turf are shown in detail for each movement in Figure 6. The boots in all four conditions differed significantly from each other. The artificial turf boot in all four conditions had a significantly higher peak VGRF than the natural grass boot.

However, peak VGRF on the two surfaces, NG and AT, only differed significantly when NGB was used. The supporting leg in the penalty kick had a higher peak VGRF on artificial turf in comparison to natural grass. To characterize pressure distribution, pressure mapping was classified into 6 sections (see Table 2). Peak pressure (average of both movement and surface) in ATB was significantly higher in the hallux, central forefoot and lateral heel. Accordingly, peak pressure in AT was significantly higher in the hallux, central forefoot and lateral midfoot. The comparison of peak pressure between the two movements determined that the peak pressure differed significantly in all sections except the medial forefoot. The central forefoot was affected by all three variables.

Table 2 Peak pressure (N/cm^2) of the plantar with respect to the three variables

	Movement		Surface		Boots		Effect size	SMEI[8]
Plantar mapping	C[2]	K[3]	AT[4]	NG[5]	ATB[6]	NGB[7]		
 HxT	7.99 0.13[5]	5.79 *** 0.39	7.21 0.22	6.58 * 0.30	7.06 0.24	6.73 * 0.23	M=0.7 Sr=0.27 Sh=0.24	M, Sr, Sh
 CFF	9.60 0.22	6.20 *** 0.50	8.46 0.25	7.34 *** 0.40	8.28 0.30	7.52 *** 0.31	M=0.74 Sr=0.42 Sh=0.59	M, Sr, Sh
 LMF	6.31 0.24	7.02 0.49	7.18 0.27	6.16 * 0.36	6.58 0.26	6.76 0.28	Sr = 0.34	Sr
 MMF	7.75 0.45	4.98 * 0.54	5.99 0.47	6.74 0.44	6.11 0.44	6.63 0.40	Sr= 0.19 M= 0.59 Sr×M=0.28	Sr , M Sr×M
 LR	2.01 0.17	4.66 *** 0.40	3.18 0.32	3.49 0.26	3.93 0.27	2.74 *** 0.28	M=0.8 Sh=0.73	M, Sh
 MR	2.36 0.17	3.96 *** 0.37	2.9 0.28	3.33 0.24	3.32 0.31	3 0.23	M=0.52	M

[S] standard error, [1] different percentage of vertical GRF in each group. [2] C=cutting. [3] K=penalty kick. [4] AT=artifical surface. [5] NG=natural grass .[6] ATB= artificial turf boot. [7] NGB= natural grass boot. [8] SMEI=significant main effect and /or interactions. [9] M=movement. [10] Sr=surface. [11] Sh=boot. *p-value < 0.05, ***p-value < 0.001

Soil hardness

The hardness of the natural and artificial surfaces was measured during the dynamic load plate test. The last two trials for each surface before the beginning of the experiment were collected. The mean and standard deviation of both surfaces' hardness over the five test days were 4.67 MPa (SD=0.02) and 2.95 MPa (SD=0.16), for AT and NG respectively. The Friedman non-parametric test revealed that there was a statistically significant difference between the two surfaces' dynamic soil resilience (E_{vd}), $\chi^2(1)=10$, $p=0.002$. Artificial turf was consistently harder than natural grass during the experiment.

Midsole cushioning

Peak acceleration and energy loss (hysteresis) of peak impact force were measured for fore- and rear-foot sections in the ATB and NGB (Table 3). Due to the thickness difference between the rear section of the two boots, there was a greater gap between in peak acceleration and energy loss in comparing to the forefoot of the boots. In general, peak acceleration and energy loss in the NGB boot was higher than in the ATB.

Table 3 Midsole thickness and peak acceleration from 7mm impactor drop

	Forefoot		Rearfoot	
	Peak AC[1]	Energy loss(J)	Peak AC	Energy loss(J)
ATB[2]	23.8 *(1.6)*	0.44(0.05)	11.2 (0.39)	0.31(0.08)
NGB[4]	28.35 (0.5)	0.57(0.039)	23.18(0.47)	0.44(0.038)

[1]=peak acceleration unit is g. [2]=artificial turf boot. [3] =standard deviation. [4] =natural grass boot.

Discomfort

The data of visual Analogue Scale (100mm) was analyzed with a non-parametric Friedman Test. The average discomfort for NGB and ATB, respectively, was 7.9 (Standard Error=0.58) and 7.1 (Standard Error=0.46). The results revealed that there was no significant difference of footwear fit between the two boots, $\chi^2(1)=1.66$, $p=0.197$.

Discussion

The findings of our study show that three independent variables, i.e., midsole, surface and movement, significantly influence peak vertical ground reaction force. The first part of our findings determined that in the artificial turf boot, the softer midsole generates greater VGRF (2.25BW) than the natural grass boot (1.95BW) – an increase of 15%. This is in line with Hreljac (1998) [54], who showed that VGRF in the soft midsole (1.59BW) is greater than a hard midsole (1.36BW) during landing in a tennis shoe – an increase of 14%. Our results are in line with Nin et al. (2016), who determined that forefoot peak VGRF in a soft boot was higher than in a hard boot during shot-block landing in basketball [15]. Our findings also support those of Kulmala et al. (2018), who determined that VGRF in a high-cushioned midsole boot (2.91BW) was significantly greater than in a low-cushioned boot (2.85BW) [14]. The strength relationship between this independent variable and VGRF was shown with the effect size of 0.78, which was close to a major size effect. The results of our study indicate that wearing soft midsole boots can result in increasing VGRF peaks.

In addition, by changing the NGB to ATB for both surfaces, the VGRF also increased in both movements (see Figure 5). A possible interpretation is that players need an optimum traction coefficient – rotational traction for cutting, and translational traction for kicking – to perform the movement successfully. Since the midsole of the ATB had higher cushioning and lower shore hardness than the NGB, participants generated greater VGRF through the ATB midsole to reach the sufficient traction coefficient, required for minimizing the slippage risk. According to the results for peak pressure, shown in Table 2, the central forefoot is the main contributor to peak pressure in both movements. This result also coincides with and is supported by that of Hennig and Thorsten (2010), who determined that peak pressure is greater in the central forefoot for different football boot models [55].

The perceived discomfort of these two boots' fit did not differ significantly. The discomfort factor rated in VAS was 7.9 (Standard Error=0.58) and 7.1(Standard Error=0.46) for ATB and NGB, respectively. Therefore, this boot attribution cannot be argued to have had any effect on kinetic parameters such as VGRF. We believe that boot discomfort (fit) should be assessed in all research with the related questionnaire in order to establish the potential effect of this variable on biomechanical parameters.

Another finding of our study was that the natural grass with lower resilience modulus (softer ground) results in lower VGRF than artificial turf. Since peak acceleration is correlated to peak VGRF [56-59], our study corresponds to the results of [35] and [60], who showed harder surface can increase peak acceleration. Additional analysis of plantar pressure determined that peak pressure in harder surface (AT) was significantly higher than NG (in certain sections such as HxT, CCF and LMF). These results are in line with Tessutti et al. (2012) and Ford et al. (2006), who revealed that the softer surface shows lower peak pressure. In our study, switching between surfaces from natural grass to artificial turf found a significant increase of VGRF (4%) [61, 6]. Changing football surfaces can occur within football programs, e.g. training or competition. These excessive and repetitive impact forces can cause tissue damage [23], resulting from poor adaptation due to the players' lack of perception of surface resilience [63, 64]. Therefore, further research should also investigate the relationship between perception of switches between playing/training surfaces and overuse injuries.-

In our study, the peak VGRF of two movements, cutting and penalty kick, were investigated with insole pressure sensors (Moticon, OpenGo). The peak VGRF of the cutting movement (2.28BW) differed significantly from penalty kick (1.99BW). As far as we know, this study is the first to compare peak VGRF of both two movements by insole pressure sensor. According to the findings of Blackburn et al. (2003), the VGRF in cutting movements (in football) is equal to 2.5BW (n=8) [40] whereas Bencke et al. (2000) found that the VGRF in cutting (in Handball) is 2.8BW (sample rate of 1000Hz) [41]. In another study, Simonsen et al [37], determined the peak VGRF with the sample rate of 500Hz is 2.78BW (n=6) [37]. In kicking movements, Orloff et al. (2008) and Katis et al. (2010) determined that VGRF can reach up to 2.25 BW [38, 39]. A comparison between cutting and penalty kick movements in these studies revealed that the VGRF of the cutting movement was *greater* than the kicking movement. Accordingly, our study shows that the VGRF of the two movements differ significantly. The diverse values of VGRF in our study and these previous studies (especially in cutting) may be due to a number of intrinsic and extrinsic factors, such as different techniques used to perform the movements, type of surfaces and boots, the number of test subjects, and finally the use of different measurement tools, especially with a different sample rate. Besides the advantages of using insole sensor measurements, such as high reliability, the limitation of insole pressure sensors is that they provide a lower force and latency in force kinetics compared to the force plate during fast motions [41].

This study suggests that boot developers should pay more attention to the midsole of boots when designing outsole configuration. However, the optimum design is likely to be when all three variables (midsole hardness, movements and surface hardness) are taken into the account by *weighting* them according to the effect size – as shown in our study – in order to further improve the design of studded football boots.

Conclusion

The aim of this study was to investigate the effect of three independent variables: midsole cushioning, surface hardness and different movement types using a pressure measurement system. The findings determined that the ATB (with softer midsole) generates greater VGRF (2.25BW) than the NGB (1.95BW). However, switching between surfaces from natural grass to artificial turf (greater hardness) was observed to have a significant increase of VGRF (4%). And finally, the peak VGRF of the cutting movement (2.28BW) differed significantly from the penalty kick (1.99BW). This study provides useful data for boot developers to *weight* these three independent variables in order to further improve the design of studded football boots.

Abbreviations

VGRF	Vertical ground reaction force	LFWD	Light falling weight deflectometer
ATB	Artificial turf boots	NG	Natural grass
NGB	Natural grass boot	HXT	Hallux and other toes
CFF	Central forefoot	LMF	Lateral midfoot
MMF	Medial midfoot	LRF	Lateral rearfoot
MRF	Medial rearfoot	AT	Artificial turf
F	Forefoot	H	Heel
VAS	Visual analogue scale		

Declarations

Cconflict of interest

The authors declare that they have no competing interests.

Consent to publish

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

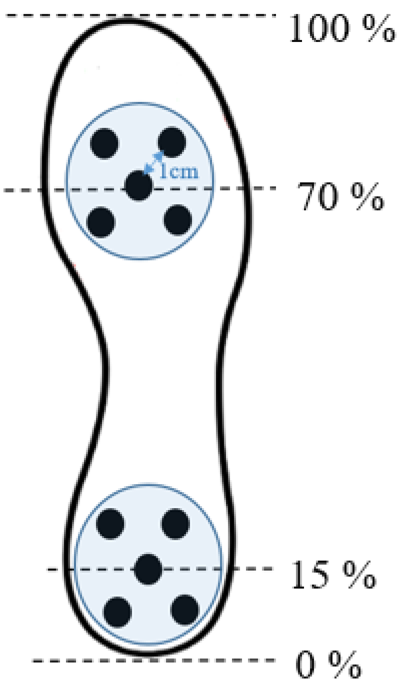
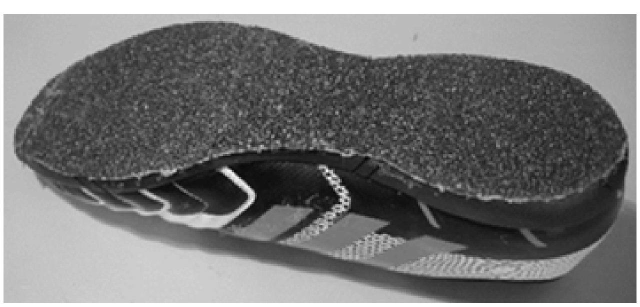


Figure 1

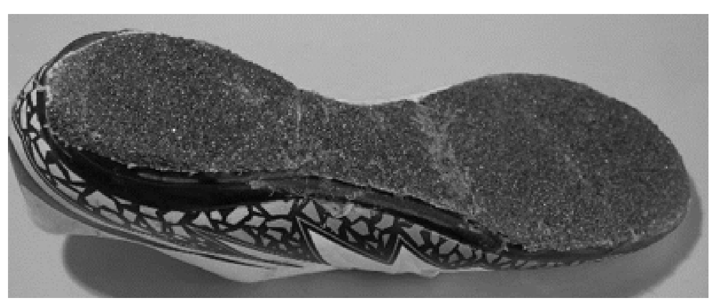
Shore hardness measurement locations using shore durometer

2a ATB before flattening

2b NGB before flattening



2c ATB(after flattening)



2d NGB (after flattening)

Figure 2

two football boots before and after flattening (ATB=artificial turf boot, NGB=natural grass boot)

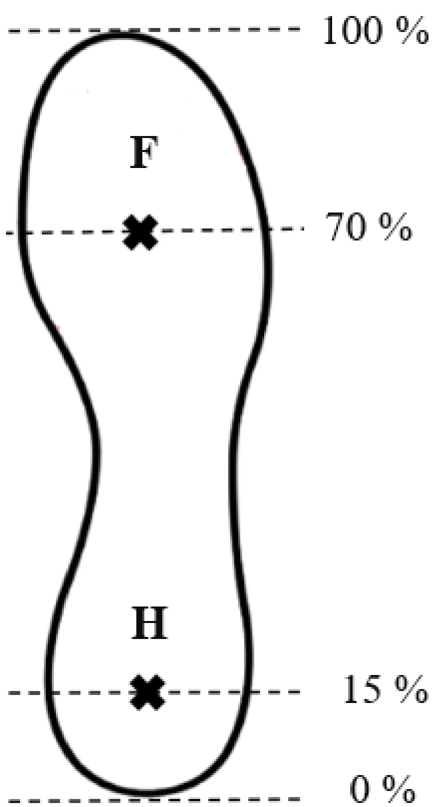
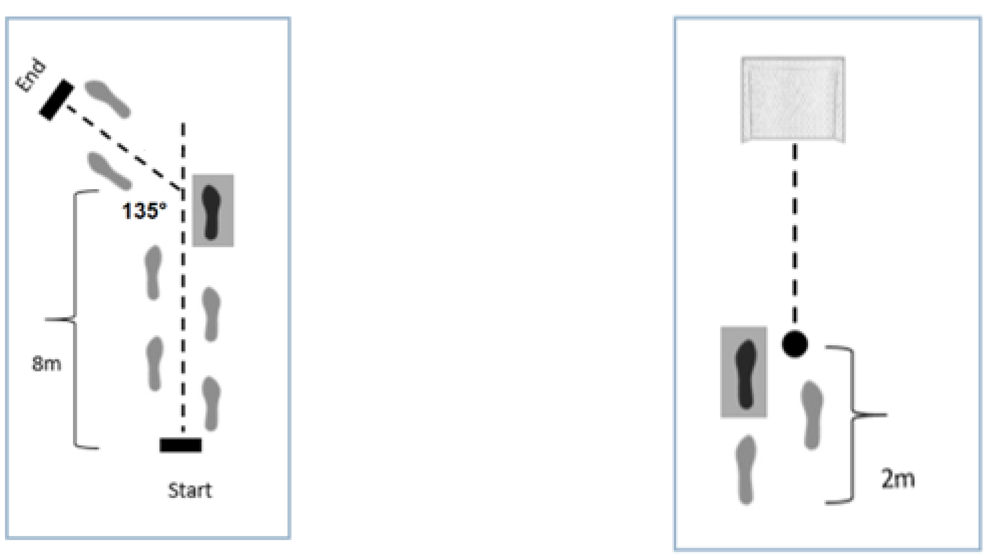


Figure 3

Schematic of impact test (F = forefoot, H = Heel)



4a. Cutting 135° movements

4b. Penalty kick

Figure 4

Schematic of two movements (measurement foot in black)

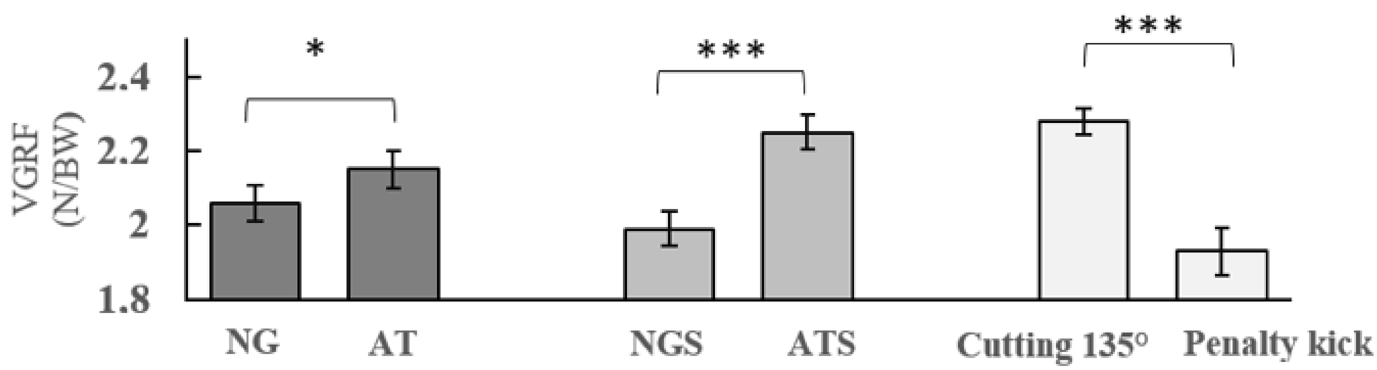


Figure 5

the peak force on different surfaces (NG and AT), different boots (NGB and ATB) and two movements (*=p<0.05, ***=p<0.001, AT= artificial turf, NG=natural grass, NGB=natural grass boot, ATB=artificial turf boot)

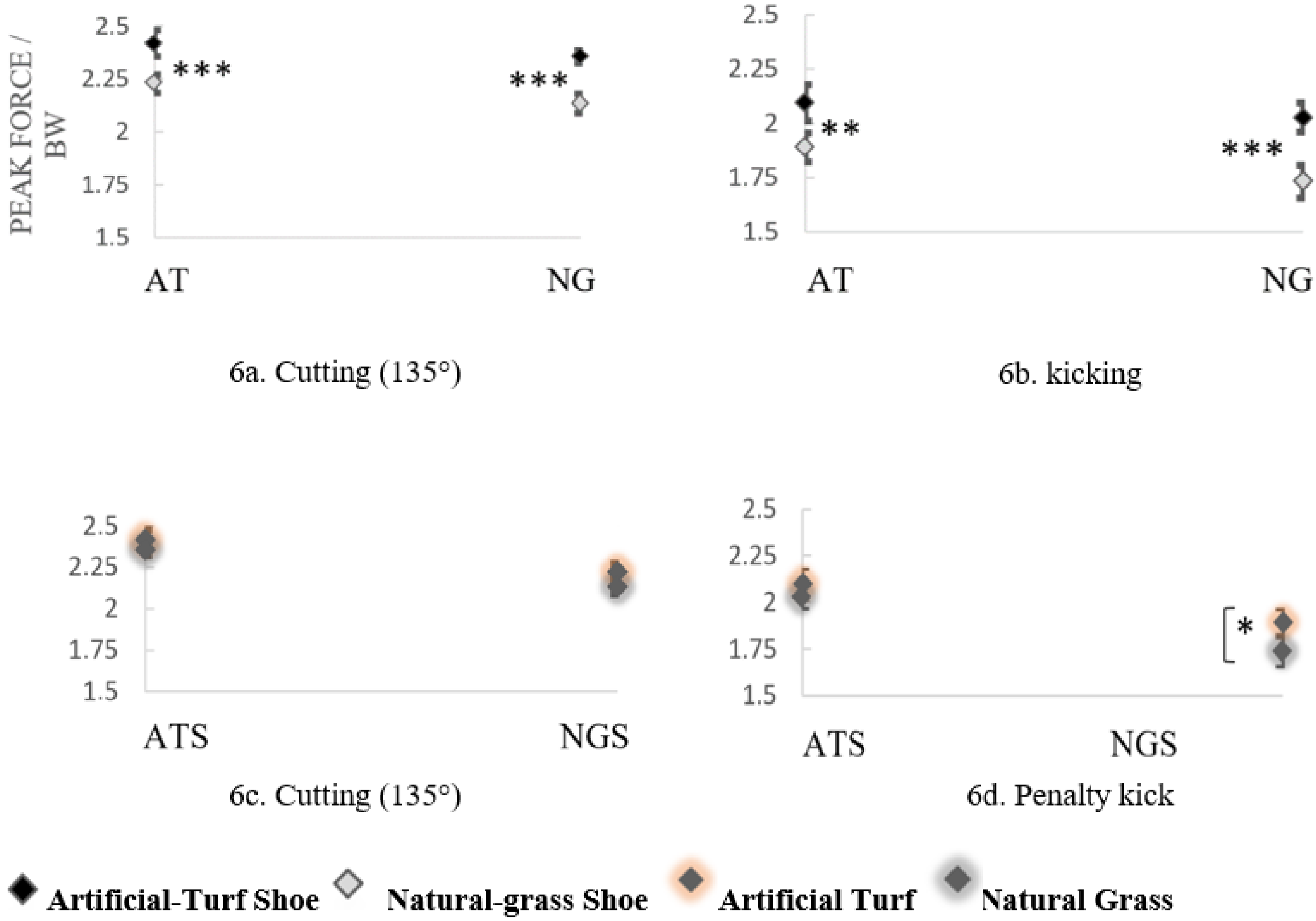


Figure 6

Comparing peak force in different conditions (p-value < 0.05=*, p-value < 0.01= **, p-value < 0.001 =***)