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Plantar pressures in male adolescent soccer players and its associations with bone geometry and strength

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Plantar pressures in male adolescent footballers and its associations with bone geometry and strength

We would like to thank all the reviewers and the editor for their time reviewing our manuscript. All the comments performed by the reviewers have been considered and have undoubtedly improved the manuscript quality. To make it easier for the reviewers to detect the changes performed, we have applied the strikeout font in red for deletions and highlighted the additions in yellow.

Comment 1

General comment (originality, scientific accuracy, strengths and/or weaknesses): Overall, the topic is of interest, the data are meaningful, and the authors reported a significant difference in bone mineral content between high school athletes who typically generate high foot maximum pressures vs. those who generate low foot maximum pressures when performing various football (soccer) related tasks. However, the Discussion needs to be rewritten to focus on the results of the study.

Response: Thank you very much for your fruitful revision of our manuscript. Attached a detailed reply below. Moreover, the Discussion has been rewritten following the specific comments proposed by the reviewer.

The term football in the title should be replaced with soccer to reduce confusion with the term football as in American football.

R: We have change the term 'football' for 'soccer' along the manuscript. We have also changed 'FOOT-HP' and 'FOOT-LP' for 'SOC-HP' and 'SOC-LP'.

This study has one statistically significant finding – differences in MPs between the groups – but the authors state other differences that were not substantiated or found (there was no difference between the groups for bone geometry

measurements).

R: The reviewer is right. After including a control group in this study, we have rewritten the results section in the abstract and the second paragraph of the discussion section as follows:

Abstract, Results

'Nevertheless, no significant bone geometry and strength differences were found between soccer groups and between SOC-LP and CG (*p*>.05).'

Discussion, Paragraph 4

'In the present study, ~~higher but not significant differences at Tt.Ar, Ct.Ar, Ct.Th, fracture load in X-axis and SSIp between FOOT-HP and FOOT-LP~~ when SOC-LP were compared to SOC-HP and CG, no bone differences at any bone geometry and strength parameters were found.'

Although stress fractures are associated with repetitive stresses, the relationship between the MPs in this study and stress fracture is not substantiated by the results of the study (is speculative, at best).

R: We agree with the reviewer and, consequently, all explanations which related the results of the present study with stress fractures have been deleted.

The authors need a better explanation for the importance or practical application of their actual results.

R: Due to only those soccer players who developed high-plantar pressures showed higher Tt.BMC, Ct.BMC and Ct.Ar than controls, it could be observed that developing high plantar pressures could provoke an extra stimuli on bone. Thus, the main practical implication of the present study is that those soccer players who are capable of performing soccer-specific actions at high intensity might increase the impact received and consequently, improve their bone health. For instance, the inclusion of high-intensity exercises during trainings would help to increase the intensity of the actions performed during matches and, at the same, bone status. We have added this information in conclusion section as follows:

Conclusion, paragraph 1

'Overall, mechanical loading produced by ~~football~~ ~~an excessive repetition of these high-intensity loadings could also increase the risk of stress fracture in lower limbs. Thus, adequate training volume (both training frequency and duration of these trainings) and rest between sessions might prevent from stress fractures without hindering the potential benefit of football practice on bone.~~ soccer-specific actions increases bone development; nevertheless, performing soccer actions at high intensity might increase the stimulus on bone and, at the same time, provide an extra gain of bone geometry. Thus, an increment of the intensity of soccer trainings could also increase the intensity during matches and, at the same time, bone health of soccer players.'

The authors should explain why there were differences in MP between these two groups of soccer players. Were these differences due to playing position, skill level, other maturational differences, or what?

R: In our opinion, these differences in MP between soccer groups are mainly explained by the ability to perform soccer actions at high intensity instead of playing position and skill level. Furthermore, all participants were instructed to performed the whole circuit at maximum speed and only those players who were capable of doing at higher intensity demonstrated greater Tt.BMC, Ct.BMC and Ct.Ar than controls. On the other hand, we think that these differences were not due to maturity status because soccer groups did not show different maturity offset. This information has been added in the manuscript as follows:

Discussion, paragraph 2

'The results obtained in the present study also demonstrated significant MP differences between the two soccer groups with different plantar pressures. These differences might be explained by the fact that those players with high plantar pressures have the ability to perform soccer specific actions at high intensity. On the other hand, to reduce the possible influence of playing position and skill level of participants on plantar pressures, soccer players performed two sub-maximal familiarization trials of the circuit and, afterwards, they were instructed to execute other two trials at maximum speed.'

The manuscript would be strengthened if the results (e.g., BMC, bone geometry measurements) were presented and explained in relation to values for nonexercising, "normal" males 11-14 yrs of age.

R: As the reviewer has proposed, one way analyses of variance (ANOVA) has been applied to compare bone variables between two soccer groups and controls using weight and the length of the tibia as covariates and applying Bonferroni adjustment. In this analysis, Tt.BMC and Ct.BMC differences between soccer groups which were observed in previous analyses have disappeared. It could be explained by the fact that the inclusion of controls in the analysis changes how the statistical analysis adjusts the results by the covariates used and Bonferroni corrections. Nonetheless, the findings obtained in this analysis are in line with previous results since only soccer players with high plantar pressures showed greater Tt.BMC, Ct.BMC and Ct.Ar. than controls. Due to the inclusion of a control group in the present study, Table II, material and methods, results and discussion sections have been modified. The results obtained are shown in the following table:

Table II. Adjusted pQCT values of soccer players with low and high plantar pressures and controls.

	SOC-HP (n = 15)	SOC-LP (n = 25)	CON (n = 13)	Test statistic
Bone geometry				
Tt.BMC (g)	3.22 ± 0.28*	3.05 ± 0.28	2.95 ± 0.28	F(2,48) = 3.3, p = .044, η^2_p = 0.12
Ct.BMC (g)	2.95 ± 0.26*	2.77 ± 0.26	2.68 ± 0.26	F(2,48) = 3.8, p = .030, η^2_p = 0.14
Tt.Ar (mm^2)	398 ± 35	388 ± 35	369 ± 35	F(2,48) = 2.4, p = .097, η^2_p = 0.09
Ct.Ar (mm^2)	280 ± 27*	266 ± 27	253 ± 27	F(2,48) = 3.4, p = .043, η^2_p = 0.12
Bone strength				
Ct.Th (mm)	5.12 ± 0.43	4.88 ± 0.43	4.77 ± 0.43	F(2,48) = 2.4, p = .098, η^2_p = 0.09
Frc.LdX (N)	3233.3 ± 428.6	3041.8 ± 426.1	3015.1 ± 424.9	F(2,48) = 1.2, p = .315, η^2_p = 0.05
SSIp (mm^3)	1445.8 ± 181.8	1362.7 ± 180.8	1292.3 ± 180.2	F(2,48) = 2.5, p = .092, η^2_p = 0.10

Values are mean ± SD. pQCT variables adjusted by weight and tibia length.
SOC-HP: soccer players with high maximum values of the average pressure; SOC-LP: soccer players with low maximum values of the average pressure; CON: controls; pQCT: peripheral quantitative computed tomography; MD: mean difference; CI: confidence interval; Tt.BMC: total volumetric bone mineral content; Tt.Ar: total cross sectional area; Ct.BMC: cortical volumetric bone mineral content; Ct.Ar: cortical cross sectional area; Ct.Th: cortical thickness; Frc.LdX: fracture load in axe X; SSIp: strength strain index in polar; η^2_p: partial eta squared.
*: p < .05 differences between SOC-HP and CON.

In addition, it would be interesting to know if actual MPs during two separate steps (cut vs. push-off) in the circuit were different.

R: We agree with the reviewer; nevertheless, we only have the mean of the entire circuit, without separating by soccer-specific actions. Thus, we have added this information as a limitation of this study as follows:

Discussion, Paragraph 6

'Another limitation is that MP were measured for the whole circuit instead of being measured for each task separately.'

Major corrections (main criticisms):

Major edits:

Procedures

Page 5, line 34: Maturity offset needs to be defined. In addition, how this was used in the data analysis needs to be described. Also, a reference is needed for the peak height velocity calculation.

R: We have defined maturity offset as follows:

Material and methods, Maturity offset, paragraph 1

'Maturity offset, described as the time (years) before and after the age of peak height velocity, was calculated using the following equation proposed by Moore et al.'

Maturity offset and the age of peak height velocity were used to describe participants included in the present study and to demonstrate that all groups had similar characteristics. Nonetheless, if the reviewer suggests removing these variables, we will do it.

The reference for the age of peak height velocity calculation is also Moore et al. (reference number 19 in the manuscript). This reference has been added in the manuscript.

Pages 6, lines 19-30: The authors should insert sentences about the validity and reliability for determining plantar mean pressures (e.g., margin of error is ?% or coefficients of variation).

R: We agree with the reviewer, nevertheless, we cannot calculate coefficients of variation for plantar pressures because only the trial with the highest plantar pressures was saved. This information has been added as a limitation of this study as follows:

Discussion, Paragraph 6

'Furthermore, the validity and reliability for determining MP could not be calculated because only the trial with the highest plantar pressures was saved.'

Page 9, Line 16: There is NO Table III.

R: This table refers to the supplementary Table III that was submitted in the manuscript as additional material. The Supplementary Table III is the following one:

Supplementary Table III Adjusted maximum values of the average pressure of ~~football~~ soccer players with low and high plantar pressures.

	SOC-HP (n = 15)	SOC-LP (n = 25)	MD (95% CI)	Test statistic
MP (kPa)				
Lateral	333.6 ± 129.4	205.9 ± 129.2	127.7 (41.8, 213.5)*	$F(1,37) = 9.1$, $p = .005$, $\eta^2_p = 0.20$
Medial	420.9 ± 66.1	244.7 ± 65.9	176.3 (132.5, 220.1)*	$F(1,37) = 66.4$, $p < .001$, $\eta^2_p = 0.64$
Rearfoot	608.2 ± 166.2	429.9 ± 165.9	178.2 (68.0, 288.5)*	$F(1,37) = 10.7$, $p = .002$, $\eta^2_p = 0.23$
Midfoot	224.3 ± 165.8	187.1 ± 165.5	37.1 (-72.8, 147.1)	$F(1,37) = 0.5$, $p = .498$, $\eta^2_p = 0.01$
Forefoot	376.7 ± 76.2	237.1 ± 76.1	139.6 (89.1, 190.2)*	$F(1,37) = 31.3$, $p < .001$, $\eta^2_p = 0.46$

Values are mean ± SD. Plantar pressure data adjusted by weight.
~~FOOT~~ SOC-HP: ~~football~~ soccer players with high maximum values of the average pressure; ~~FOOT~~ SOC-LP: ~~football~~ soccer players with low maximum values of the average pressure; MP: maximum value of the average pressure.
* significant differences between groups. The effect size for η^2_p can be small (0.01 – 0.06), medium (0.06 – 0.14) or large (>0.14).

Discussion

Page 9, Lines 34-36: A hypothesis cannot be partially confirmed. Omit this and state bone mineral contents were not statistically significantly different between the groups. The authors can't report what they hoped to have in the results.

R: This statement has been deleted and this paragraph has been rewritten as follows:

Discussion, paragraph 1

'The present study shows that adolescent ~~footballers~~ soccer players with higher plantar pressures present enhanced Tt.BMC, ~~and~~ Ct.BMC and Tt.Ar when compared to ~~those with low pressures~~ CG. ~~However, bone strength indexes are not different between groups. Thus, the hypothesis that FOOT-HP will exhibit better bone geometry and greater bone strength indexes is partially confirmed~~'

Page 10, Lines 1-10: The rationale that the two groups did similar exercises is plausible, however, the rationale for similar impacts is not substantiated by the data. The authors reported higher MP in one group vs. the other. This is not

logical. Please rewrite.

R: The reviewer is right and consequently, the rationale for similar impacts during soccer practice has been deleted. The paragraph has been rewritten as follows: Discussion, paragraph 4.

'The lack of differences between ~~football~~ soccer groups could be explained by the fact that both groups did similar ~~football~~ soccer exercises, and probably, had comparable enhancements of the bone.'

Page 10, Lines 27-53: This is all speculation and really does not "discuss the results of the present study". Omit.

R: Following the comment of the reviewer, this paragraph referring to stress fractures has been removed.

Page 11, Lines 11-14: The authors indicated that the first limitation (shoe or foot differences) was not different between the groups. Omit the first sentence. The limitations of the study should be stated as the small sample size. Whether the sample size was larger or smaller than other studies is not relevant. Omit that this is the first study – seems unlikely.

R: As the reviewer has suggested, the limitation of shoe differences and the strength of being the first study in this area have been removed. Moreover, after answering one of the previous comment, the limitation of not measuring plantar pressures in each task separately has been included. Thus, we have rewritten this paragraph as follows: Discussion, paragraph 6.

'~~The main limitations of the present study are that football players wore shoes with different stud designs and they had different foot types. Despite this, neither MP nor proportion differences were found between these football players with different foot type and stud designs (Supplementary Table I and II). Although, the total sample size of male football players in the present study (n = 40) was lower compared to those in other pQCT studies (99[36] or 71 male football players[37]), this sample size was higher than those in studies measuring plantar pressures (15[13] or 21[15]). On the other hand, the main strength is that this is the first study comparing bone geometry and strength based on~~

~~biomechanical parameters such as plantar pressures.~~ The main limitation of the present study is that the sample size of young soccer players is small and, therefore, the power of this study is reduced. Another limitation is that MP were measured for the whole circuit instead of being measured for each task separately. Furthermore, the validity and reliability for determining MP could not be calculated because only the trial with the highest plantar pressures was saved.'

Conclusion

Page 11, Lines, 18-24: The authors did not find a difference in bone geometry between the groups. This should be omitted.

R: In this sentence bone geometry refers to total and cortical bone mineral content. In order to clarify this statement, we have modified this paragraph as follows:

Conclusions, Paragraph 1

'In summary, the present study shows that adolescent ~~football~~ soccer players with higher plantar pressures have better ~~bone geometry than those players with lower plantar pressures~~ Tt.BMC, Ct.BMC and Ct.Ar than controls; nevertheless, those players with lower plantar pressures do not show differences in bone geometry and strength compared to those with high plantar pressures and controls.'

The authors need to state what they found in their results, not what they hoped to find. The implication for stress fractures is really not a focus of the study and should be of lesser importance in the Discussion. The authors need a better explanation for the importance or practical application of their results. Explain why there were differences in MP between these two groups of soccer players. Were these differences due to playing position, skill level, or what?

R: The reviewer is right and we have rewritten discussion section taking into account all the suggestions proposed by the reviewer.

Minor corrections (page, paragraph, line where the author must make the corrections):

Minor edits:

Page 2 of 24, Line 14: insert "foot" after nondominant

R: Done.

Lines 31-33: Values should be in the same order as presented in the text….greater values should be presented first. Please check carefully.

R: We have rewritten this sentence as follows:

Abstract, Results.

'Greater Tt.BMC, Ct.BMC and Tt.Ar. were found in SOC-HP compared to CG (Tt.BMC: 3.22vs2.95 g, Ct.BMC: 2.95vs2.68 g, Ct.Ar: 280vs253 mm^2; p<.05).'

Line 37: No need to specifically reference Frost's mechanostat theory in the abstract…it is commonly known that increased forces on the bone increase bone deposition. Omit the theory here.

R: Done

Introduction

Please indent paragraphs

R: All paragraphs of the manuscript has been intended.

Page 4, line 9-10: would should be substituted for will

R: We have changed 'will' for 'would'.

Page 7, Lines 1-5: just state the range of coefficients of variation. The reader should not have to look up another article to understand the variability in these measurements.

R: The reviewer is totally right and coefficients of variation for each pQCT variable included in the present study have been added.

Page 8, Lines 40-44: No need to state each range for Cohen's d or partial eta2. Omit.

R: These ranges has been deleted for both Cohen's and partial eta2.

Other comments:

Statistics – multiple t-tests increase Type II error; the Bonferroni adjustment should be used.

R: Bonferroni adjustment option proposed by SPSS was used in all ANOVA and ANCOVA tests performed in the present study. This statement has been added in the manuscript as follows:

Material and methods, Statistical analyses, paragraph 4

'Bonferroni corrections were applied to control the Type II error of multiple comparisons.'

References

Journal article titles should be italicized.

R: Done.

Comment 2

General comment (originality, scientific accuracy, strengths and/or weaknesses): The study is clear and well-written.

R: Thank you very much for your fruitful revision of our manuscript, we are grateful for your insightful comments.

Methodology, including statistical analyses, for the most part, could be replicated (except the determination of the high/low plantar pressure groups- there no cutoffs).

R: Cluster analysis was performed to divide soccer players in different groups with similar plantar pressures. This analysis is specific for participants included in the study and their descriptive characteristics, therefore, to replicate the analysis of the present study, the similar steps explained in material and methods should be followed. On the other hand, this analysis has been widely used in previous articles such as Prokasky et al. (reference 24 in the revised manuscript) and Sanson et al. (reference 25 in the revised manuscript).

The reader is left wondering how coaches could use this information to better inform their players' techniques or practices.

R: We think that the main practical implication of this study is that those soccer players who are capable of performing soccer-specific actions at high intensity might increase the impact received and consequently, improve their bone status. Consequently, those soccer players who perform high-intensity exercises during trainings could increase the intensity of their actions performed during matches and, at the same, their bone health.

Major corrections (main criticisms):

The practicality for the study in this population is unclear. Although adolescence is a critical stage to gain bone mass, only 6% of males get osteopenia or osteoporosis, while 50% of women over age 50 have low bone mass. Therefore, one wonders why, for example, female soccer players were not studied. And though much of the risk of low bone mass is inherited, active soccer players do not seem like a high-risk population for the development of low bone mass.

R: We totally agree with the reviewer in the fact that the incidence of osteoporosis in females is higher than males. Although this study is a part of a project which include both male and female adolescent soccer players, the small sample size of female players was the main reason for not including them in this study. It was very difficult to recruit a high sample of female players because in Spain, the number of female adolescents who play soccer is very low in comparison to the number of male adolescents. Moreover, some of the girls included at the beginning of the project stopped playing soccer and they did not perform plantar pressures measurements.

Authors did not make a compelling case for separating the subjects into the high and low-pressure groups.

R: We have followed an exigent analysis to group soccer players depending on their plantar pressures. In this study, the analysis identified two groups which had different plantar pressures. This statistical analysis does not provide cut-offs to be in a group since these cut-offs are dependent of the sample and the descriptive characteristics of the participants included in the analysis.

Several of the measurements were not different between groups, and in fact, in the discussion, there was mention of higher injury rates in those with higher plantar pressure. In the future, it would be best to use age-matched controls who are sedentary or lightly active.

R: As the other reviewer has suggested, we have deleted all statements related to injuries and stress fractures. Moreover, we have also performed ANOVA tests to compare bone parameters between soccer groups and 13 age-matched controls. The results of this analysis are in line with the results showed in the previous submission since only soccer players with high plantar pressures demonstrated greater Tt.BMC, Ct.BMC and Tt.Ar compared to controls.

More discussion is needed as to why authors think there were no differences between the three foot types as well.

R: In general, different foot types might be associated with different plantar pressures distribution between players, nevertheless, these differences were not found in the present study. This lack of differences between groups could be explained by the fact that plantar pressure variables are obtained from the average of the maximum value of all steps during the whole circuit. If plantar pressures values of different foot types were compared in each task separately, maybe some differences would be found between groups as Eils et al. demonstrated (reference number 15 in the manuscript). However, we have not measured plantar pressures in each task separately. Thus, we have added this information in discussion section as follows:

Discussion, Paragraph 1

'On the other hand, no plantar pressures differences were found between those soccer players who wore different stud designs and had different foot types. This lack of differences could be explained by the fact that plantar pressures values were measured for the whole circuit instead of for each task separately. Moreover, this circuit consisted of diverse soccer actions such as jumps, zigzag run or changes of direction and, as Eils et al.[15] demonstrated, each soccer-specific action mainly loads a different foot area. Therefore, after calculating the mean of all tasks, the possible differences between foot types could disappear.'

Discussion, paragraph 5:

'Another limitation is that MP were measured for the whole circuit instead of being measured for each task separately.'

What is the reliability/validity of the measurement tool used? Is it sensitive enough to dichotomize athletes into "high" or "low" after performing a few sets of calisthenics?

R: We cannot calculate the validity and reliability for determining plantar pressures because only the trial with the highest plantar pressures was saved. This information has been added as a limitation in the manuscript as follows:

Discussion, Paragraph 6

'Furthermore, the validity and reliability for determining MP could not be calculated because only the trial with the highest plantar pressures was saved.'

On the other hand, cluster analysis was performed to identify groups of soccer players with similar plantar pressures being in this manuscript. Thus, we think that this division performed by cluster analysis could be sensitive enough to group players with similar plantar pressures.

How was the high vs. low cutoff determined?

R: There are no cutoffs to determine which soccer players are in the high or low plantar pressures groups. The cluster analysis used identified in how many homogenous groups (similar plantar pressures) the sample of soccer players were divided into (in this sample were two groups: soccer players with high and low plantar pressures).

Could the data be skewed if the athlete simply didn't try their very best or altered their gait mechanics to safely perform the drill while running with unfamiliar cleat insoles?

R: We think that the data are not skewed for none of these reasons because soccer players performed two familiarization trials of the circuit and, afterwards, they were instructed to perform two trials at maximum speed. Moreover, the stud design was not unfamiliar for them since they had been playing with their stud design for at least five months.

Minor corrections (page, paragraph, line where the author must make the corrections):

Introduction

Page 3

Line 8 Is there evidence that children who exercise before/during puberty are at lower-risk for osteoporosis/osteopenia during adulthood? Please elaborate on this.

R: Childhood and adolescence are important periods to prevent osteoporosis during adulthood and old ages as 95% of maximum adult bone mass is achieved approximately at 18 years in females and at 19 in males (Baxter-Jones et al.; reference number 3). This information has been included in the manuscript as follows:

Introduction, paragraph 1

'Peak bone accretion occurs at 12.5 years in females and at 14.1 years in males[2] and, after 4 years from this peak, 95% of the maximum adult bone mass has been already attained.[3] Therefore, the prepubertal and peripubertal years are windows of opportunity for maximizing the response to exercise and osteoporosis prevention.[4]'

Line 14  A lot of discussion about peak bone mass, but primary outcomes in this paper revolve around bone-mineral content. Are these different measurements? Is one more pertinent to injury risk than the other?

R: Peak bone mass is the amount of bone mineral content gained by the time a stable bone status at the age of 25-30 years. Thus, both peak bone mass and bone mineral content are directly associated. In addition to this, both variables are critical to know the risk of having a bone injury since low bone mineral content values and peak bone mass increase bone weakness and, at the same time, its injury risk.

Line 24  not sure what "bone during growth" is referring to.

R: We have rewritten this sentence to better explain it as follows:

Introduction, paragraph 2

'Focusing on bone-exercise interactions during growth, it is important to mention that not every sport produces the same effect on bone mass.'

Line 27  be more specific with "gain in bone mass." Have previous studies quantified how much bone-mass increase one can expect during each of these sports?

R: The reviewer is right and this sentence has been modified to be more specific as follows:

Introduction, paragraph 2

'In fact, it has been observed that participation in high-impact sports such as ~~football~~ soccer,[7,8] basketball,[9] racquet games[10] is associated with a gain in bone mineral content (BMC) and bone mineral density in most weight-bearing sites such as lumbar spine, hip and lower limbs; nevertheless, participation in nonimpact sports such as swimming,[11] cycling[12] do not present this association.'

Yes, they have. Vicente-Rodriguez et al. and Agostinete et al. (references number 8 and 9 respectively) quantified the amount of bone mineral content or density gained by these athletes. For instance, after three years of soccer practice, Vicente-Rodríguez et al. reported that soccer players gained 6% more bone mineral density at lower limbs, a third more bone mineral density at whole body, 13% more bone mineral content at lumbar spine and twice more bone mineral content at hip compared to controls. On the other hand, after nine months, Agostinete et al. demonstrated that basketball players had higher bone mineral density accrual at upper limbs than controls (17.6% vs 7.2%).

Line 30  I would indent and start a new paragraph after "demand."

R: We have followed the suggestion of the reviewer. Thank you.

Line 40  This might be a good place to mention whether higher or lower plantar pressures is better for bone health. Is it ideal for young athletes to experience high plantar pressures to catalyze the bone reformation process? Are stress fractures caused when plantar pressures are too high or repeated too often?

R: There are no studies which evaluate whether higher or lower plantar pressures are positively associated with bone health. It is the aim of the present study. As the hypothesis of this manuscript states, we think that these soccer players who experience high plantar pressures will have better bone geometry and greater bone strength than those players who experience low plantar pressures and controls. This statement is reported in the manuscript as follows:
Introduction, paragraph 5
'We hypothesized that ~~football~~ soccer players with higher plantar pressures (~~FOOT~~ SOC-HP) ~~will~~ would exhibit better bone geometry and greater bone strength compared to those with lower plantar pressures (~~FOOT~~ SOC-LP) and controls (CG)'

Following the hypothesis of our study and Frost's mechanostat theory, we think that experiencing high plantar pressures during growth might increase bone remodeling activity and, at the same time, bone mass.

We think that the main variable in terms of stress fracture is the repetition of an impact in a specific bone site. Moreover, whether these repetitive impacts are as high as possible, the risk of having a stress fracture would increase.

Line 53  please define what "adequate" volume/intensity is. Also, I don't think that "avoid" works here. Try "might help mitigate" instead.

R: We fully agree with the reviewer and we have added an example to define what 'adequate' volume/intensity is as follows:

Introduction, paragraph 4.

‘Thus, in terms of bone, an adequate training volume and intensity (e.g. two or three trainings of moderate-vigorous intensity per week) in children and adolescent soccer players might ~~avoid~~ help to mitigate the above-mentioned fractures and improve bone parameters.’

Following the suggestion of the reviewer, we have changed ‘avoid’ for ‘might help to mitigate’.

Methods

Page 4

Line 21  Why did you need such a homogenous sample? Why were non-Caucasians excluded? Could other outside activities (basketball, weightlifting) or diet influence bone growth just as much as being a different race?

R: We have selected a homogenous sample excluding non-Caucasian participants since bone mass might vary depend on the ethnicity. In fact, the International Society of Clinical Densitometry reports that ethnicity should be taken into consideration to evaluate bone mass (This information is obtained from the official website of the International Society of Clinical Densitometry; https://www.iscd.org/official-positions/2013-iscd-official-positions-pediatric/).

Bone mass is mainly determined by genetics (including the ethnicity); nevertheless, there are environmental factors such as physical exercise and diet which are capable to cause bone adaptations. Furthermore, it has been demonstrated that those athletes who train and play high-impacts sports increase their bone mass (Tenforde et al. 2011; PM R).

Line 37  We are to assume that the mechanical loading is identical among all players among these five teams. But, does mechanical loading vary among different positions? If I had to speculate, the mechanical loads of an active mid-fielder are probably greater than that of a goaltender.

R: We agree with the reviewer in the fact that each player position requires to perform different movements; nevertheless, we think that whether these soccer-specific actions are executed by each player at the highest intensity as they can, mechanical loading differences between these players who play in different positions will be low. On the other hand, when we measured plantar pressures in this study, all participants were instructed to performed the whole circuit at maximum speed and only those players who were capable to doing it at higher intensity demonstrated higher total and cortical bone mineral content.

Page 5

Line 16  I see an age range of 11-14 but were there any assessments to determine the maturity of the athletes or whether they were prepubertal or peripubertal (as outlined in your introduction)?

R: Maturity status of participants was measured by maturity offset and the age of peak height velocity. Pubertal status was also evaluated according the pubertal stages proposed by Tanner and Whitehouse (1976). We decided to report maturity offset and the age of peak height velocity because they are continuous variables in comparison to pubertal stages proposed by Tanner and Whitehouse which are categorical ones. Otherwise, if the reviewer suggests the inclusion of pubertal status measured by Tanner and Whitehouse, we will include them.

Line 33  What exactly does “maturity offset” measure? Is it a valid tool to measure maturity? What categories were the athletes separated into based on their “maturity offset” measurement?

R: As Moore et al. (reference number 19) reported, maturity offset is described as the time (years) before and after the age of peak height velocity and its calculation provides an accurate information about the maturity status of participants. Due to maturity status is a continuous variable, it is not divided in maturity categories. The definition of maturity offset has been added in the manuscript as follows:

Material and Methods, Maturity offset, Paragraph 1

‘Maturity offset, described as the time (years) before and after the age of peak height velocity, was calculated using the following equation proposed by Moore et al.:[19]’

Line 34 How were the foot types (flat foot, normal and high arch feet) determined?

R: Foot types were determined following the guidelines proposed by Shiang et al. (reference number 21). This information has been added in the manuscript as follows: Material and methods, Plantar pressure measurements, paragraph 3.

'Foot types were also determined following the guidelines proposed by Shiang et al.[21] To measure arch height and arch angle, participants stood with their arms relaxed and looking straight ahead. Arch height was assessed from the distal point of navicular bone to the floor. Then, flat foot was determined when navicular height was lower than 37 mm; normal foot with values between 37 and 40 mm; and high arch foot with values higher than 40 mm. Afterwards, arch angle was obtained from the line connecting the most medial point of the heel with the most medial point of the first metatarsal bone; and the line connecting the most lateral point of the medial foot with the most medial point of the first metatarsal bone. In terms of arch angle, flat foot was determined when arch angle was lower than 46º; normal foot with values between 46 and 55º; and high arch foot with values higher than 55º. Both navicular height and arch angle parameters should be the same in order to determine which foot were flat or high-arch.'

Line 49  Could the inclusion of multiple shoes confound your data?

R: Soccer players wore the same soccer shoes model with two different stud designs (turf and hard-ground stud designs). We also though that the use of different stud designs might confound the data of the present study thus, we compared plantar pressures between soccer players who wore different stud designs and no differences between soccer groups were found. This data is shown in Supplementary Table II:

Supplementary table II Maximum value of the average pressure of football players wearing turf and hard-ground stud designs.

	Turf stud design (n = 11)	Hard-ground stud design (n = 29)	Cohen's *d*
MP (kPa)			
Lateral	249.8 ± 206.0	255.3 ± 111.2	0.03
Medial	292.3 ± 73.8	317.8 ± 117.8	0.26
Rearfoot	517.1 ± 184.2	489.0 ± 191.1	0.15
Midfoot	181.8 ± 121.8	208.4 ± 175.9	0.18
Forefoot	241.4 ± 79.2	307.7 ± 102.8	0.72

Values are mean ± SD.
MP: maximum value of the average pressure.
No significant differences were found between between groups. Cohen's *d* can be small (0.2 – 0.5), medium (0.5 – 0.8) or large (>0.8).

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Line 4  Is this circuit representative of the demands placed on soccer athletes during a match? Has it been used by other labs for other studies?

R: We think that this circuit is representative of soccer demands because it includes several specific actions of soccer practice. Although the specific combination of this soccer actions has not been used by other labs for other studies, plantar pressures during most of these actions have been already measured separately in soccer players (e.g. Nunns et al. 2016, Wong. et al. 2007).

-Line 22- Change "shank" to leg.

R: Done

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Line 6-12 This belongs in the discussion, not in methodology/

R: This information was included in the methodology just for justifying the selection of non-dominant foot in this study. Due to these references do not discuss the results of the present study, we have decided to rewrite this paragraph and these references has been removing. This information has been modified as follows:

Material and methods, Bone assessment by peripheral quantitative computed tomography (pQCT), paragraph 2.

‘The lower limb dominance was determined by players preferred kicking leg.[23] Although the measurement of non-dominant or dominant lower limb has not been clarified yet in pQCT studies,[24] ~~adolescent football players showed higher bone strength indexes at non-dominant tibia than at dominant tibia.[25] Azevedo et al.[13] also reported greater plantar pressures at the non-dominant foot; accordingly,~~ the non-dominant lower limb was selected for the measurements.’

Results

Line 9  To me, it seems interesting that people with different types of feet (i.e. low-arch vs. high-arch) have similar plantar pressures. Is this to say that they transmit longitudinal force similarly? That seems unlikely. I would like to see this mentioned more in the discussion section.

R: As we have explained in a previous comment, this lack of differences between groups could be explained by the fact that we included the average of the maximum value of all steps during the whole circuit instead of plantar pressures of each task separately. Thus, this information has been included in discussion section as follows:

Discussion, paragraph 1.

‘On the other hand, no plantar pressures differences were found between those soccer players who wore different stud designs and had different foot types. This lack of differences could be explained by the fact that plantar pressures values were measured for the whole circuit instead of for each task separately. Moreover, this circuit consisted of diverse soccer actions such as jumps, zigzag run or changes of direction and, as Eils et al.[15] demonstrated, each soccer-specific action mainly loads a different foot area. Therefore, after calculating the mean of all tasks, the possible differences between foot types could disappear.’

Discussion, paragraph 6:

‘Another limitation is that MP was measured for the whole circuit instead of being measured for each task separately.’

Discussion

Page 9

Line 38  has been elucidated, write in past-tense. Also, I think because you took multiple measurements of bone geometry and only 2 of the 7 measurements were statistically different between your groups, it's too broad of a statement to say that plantar pressures are positively associated with bone parameters. Make it clear to the reader than only some bone parameters were related to plantar pressures.

R: The reviewer is totally right and the verb tense has been changed. Furthermore, we have modified this sentence being more specific as follows:

Discussion, paragraph 3.

'Although a positive association between high plantar pressures and ~~bone parameters~~ all bone geometry variables except Tt.Ar has been ~~is~~ elucidated, the findings related to bone strength indexes could be slightly mediated by bone growth.'

Line 43  The premise of this statement is unclear to me. If only three of the subjects were 14, what are the chances that they skewed the data and had enough cortical bone growth among them to make it seem like the entire group had more cortical bone? Maybe you could afford to remove their data as the "low" group had 25 subjects vs. only 15 in the "high" group.

R: These three players were 14.0, 14.2 and 14.4 years and all of them were in low plantar pressures groups. We have re-analysed the data without take into account these 3 players and similar results were obtained. A summary of these results is shown in the following table:

Adjusted pQCT values of ~~football~~ soccer players with high and low plantar pressures.

	SOC-HP (n = 15)	SOC-LP (n = 22)	MD (95% CI)	Test statistic	% Difference
Bone geometry					
Tt.BMC (g)	3.19 ± 0.26	3.02 ± 0.25	0.179* (0.00, 0.36)	$F(1,33) = 4.3$, $p = .047$, $\eta^2_p = 0.11$	-5.6
Ct.BMC (g)	2.92 ± 0.23	2.74 ± 0.23	0.184* (0.03, 0.34)	$F(1,33) = 5.6$, p = .024, $\eta^2_p = 0.15$	-6.3
Tt.Ar (mm^2)	395 ± 33	387 ± 33	8 (-15, 31)	$F(1,33) = 0.5$, $p = .481$, $\eta^2_p = 0.02$	-2.0
Ct.Ar (mm^2)	277 ± 25	265 ± 24	12 (-5, 29)	$F(1,33) = 2.2$, $p = .147$, $\eta^2_p = 0.06$	-4.5
Bone strength					
Ct.Th (mm)	5.09 ± 0.39	4.87 ± 0.38	0.22 (-0.05, 0.49)	$F(1,33) = 2.8$, $p = .105$, $\eta^2_p = 0{,}08$	-4.3
Frc.LdX (N)	3195.6 ± 394.1	3008.1 ± 391.6	187.5 (-84.4, 459.5)	$F(1,33) = 2.0$, $p = .170$, $\eta^2_p = 0{,}06$	-5.9
SSIp (mm^3)	1430.7 ± 158.9	1344.7 ± 157.9	86.0 (-23.7, 195.7)	$F(1,33) = 2.5$, $p = .120$, $\eta^2_p = 0.07$	-6.0

Values are mean ± SD. pQCT variables adjusted by weight and tibia length.
~~FOOT~~ SOC-HP: ~~football~~ soccer players with high maximum values of the average pressure; ~~FOOT~~ SOC-LP: ~~football~~ soccer players with low maximum values of the average pressure; pQCT: peripheral quantitative computed tomography; MD: mean difference; CI: confidence interval; Tt.BMC: total volumetric bone mineral content; Tt.Ar: total cross sectional area; Ct.BMC: cortical volumetric bone mineral content; Ct.Ar: cortical cross sectional area; Ct.Th: cortical thickness; Frc.LdX: fracture load in axe X; SSIp: strength strain index in polar; η^2_p: partial eta squared.*: $p < .05$ differences between soccer groups.

Due to the similar results were obtained without those players who were 14 years, we have not removing this players in order to not reduce the sample.

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Line 2  If this is the case, then what is the relationship between plantar pressure and bone strength? I thought the purpose of the study was to elucidate the interaction between plantar pressure and bone geometry. If the training volume and intensity produce similar bone adaptations regardless of high/low plantar pressure, what is the significance of divergent plantar pressure among athletes?

R: Although both soccer groups seem to be beneficiated by the effects of soccer practice and its specific high-intensity actions, these results demonstrated that those soccer players with high plantar pressures are capable of gaining an extra bone mass and, consequently, improving their bone geometry and strength. Concretely, when controls were included in the analysis, only soccer players with high plantar pressures demonstrated greater Tt.BMC, Ct.BMC and Ct.Ar. Higher but not significant values were found at all bone variables measured between soccer players with low plantar pressures and controls. Therefore, it can be also observed a tendency of higher bone values in soccer players than controls. To justify these findings, due to all participants included in the present study had not reached the age of peak height velocity yet, future studies including a sample of soccer players who have already reached the age of peak height velocity could help to clarify if these bone differences between soccer players with different plantar pressures are observed in later ages.

In summary, the findings of the present study demonstrated that developing high plantar pressures is associated with an increase of bone geometry parameters such as Tt.BMC, Ct.BMC and CT.Ar.

Line 22  Is it good for young soccer players to present with biomechanics that increase the amount of pressure exerted on their tibia? This seems like a good recipe for overuse injury.

R: Following the results obtained in this study, performing soccer actions as high-intensity as possible might causes an extra impact on tibia bone and, at the same time, an increase of bone mass. Thus, performing high-intensity exercises during trainings could increase the intensity of their actions performed during matches and, at the same, their bone health.

Line 38  When did you assess stress fractures? I didn't see this in the methods.

R: We have not evaluated stress fractures. This information was just for taking into account possible implications of receiving very high plantar pressures. Nevertheless, following the suggestion of the other reviewer, all statements related to stress fractures have been removing from this manuscript.

Line 46  If the HIGH and LOW groups both had similar bone geometry for 5 out of 7 measurements, and having high plantar pressures predisposes athletes to stress fractures, it seems that athletes with LOW plantar pressures can provide enough loading to their skeletal system while staying healthy…

R: Thank you for this interesting reasoning. Following the results of the present study, a tendency of greater bone values in those soccer players with high plantar pressures compared to those with low plantar pressures was found. A systematic review and meta-analysis performed by Lozano-Berges et al. (reference number 7) demonstrated the positive effects of soccer practice on bone independently of plantar pressures of soccer players. Thus, we think that soccer practice has a positive effect on bone mass independently of plantar pressures. On the other hand, the sentence which the reviewer refers to has been removing because of the suggestion of the previous reviewer.

Line 49  Is your study equipped to make this statement?

R: No, it is not. Thus, this statement and all information related to stress fractures have been removing from this manuscript.

Conclusion

Page 11

Line 18  Again, high plantar pressure was only positively associated with 2 of the 7 bone geometry measurements. I think this is a bit of an overstatement.

R: The reviewer is right and this sentence has been rewritten as follows:

Conclusions, paragraph 1

'In summary, the present study shows that adolescent ~~football~~ soccer players with higher plantar pressures have better ~~bone geometry than those players with lower plantar pressures~~ Tt.BMC, Ct.BMC and Ct.Ar than controls; nevertheless, those players with lower plantar pressures do not show differences in bone geometry and strength compared to those with high plantar pressures and controls.'

Line 22  Is this practical? What if I don't have access to the right equipment? Is it worth spending the money to make this measurement?

R: In our opinion, we think that it is practical because in this study has been demonstrated that developing high plantar pressures during soccer practice might be beneficial for bone geometry parameters such as Tt.BMC, Ct.BMC and Tt.Ar. Thus, increasing the intensity of soccer training might help to increase the intensity of soccer actions during matches as well as the bone health of soccer players.

Line 29  What do you consider to be adequate volume and rest? How do these data inform the definition of adequate volume and rest, especially considering that in general, the players all partook in similar, if not the same volume.

R: The reviewer is right and due to we have not studied which is the adequate volume and rest, we have deleted this information from the manuscript.

Plantar pressures in male adolescent ~~footballers~~ soccer players and its associations with bone geometry and strength

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ABSTRACT

BACKGROUND: Mechanical loads exerted by ~~football~~ soccer-specific actions increase bone remodeling activity. Nevertheless, little is known about the relationship between plantar pressure and bone structure. Therefore, the aim of this study was to compare bone geometry and strength between ~~football~~ soccer players who exhibited different maximum values of the average pressures (MP) when performing a combination of ~~football~~ soccer-specific tasks.

METHODS: Forty male adolescent ~~football~~ soccer players (mean age 13.2±0.5 y) and 13 controls (mean age 13.1±0.9 y) participated in this study. Biofoot® system was used to measure MP at the non-dominant foot during a circuit of ~~football~~ soccer-specific tasks. Cluster analysis was performed to classify players into groups of similar MP profiles resulting two different groups as follows: 15 players with high MP (~~FOOT~~ SOC-HP; mean MP: 392.7±68.2 kPa) and 25 with low MP (~~FOOT~~ SOC-LP; mean MP: 261.0±49.6 kPa). Total and cortical volumetric bone mineral content (Tt.BMC/Ct.BMC), cross-sectional area (Tt.Ar/Ct.Ar), cortical thickness (Ct.Th), fracture load in *X*-axis, and polar strength index (SSIp) were measured at 38% of the non-dominant tibia by peripheral quantitative computed tomography. Bone geometry and strength comparisons between ~~FOOT~~ SOC-HP and ~~FOOT~~ SOC-LP were performed using analyses of covariance controlling by weight and tibia length.

RESULTS: Greater Tt.BMC, Ct.BMC and Tt.Ar. were found in ~~FOOT~~ SOC-HP compared to CG (Tt.BMC: 3.22vs2.95 g, Ct.BMC: 2.95vs2.68 g, Ct.Ar: 280vs253 mm^2; p<.05). Nevertheless, no significant bone geometry and strength differences were found between soccer groups and between SOC-LP and CG (p>.05).

CONCLUSIONS: ~~According to Frost's mechanostat theory,~~ Developing high MP when training and playing ~~football~~ soccer might be favourable to bone development.

Key words: Adolescent, soccer, foot, bone and bones.

TEXT

Introduction

Osteoporosis has its clinical manifestations mainly through adulthood and old age. Nevertheless, childhood and adolescence are considered critical stages to gain bone mass and fight against this disease.[1] Peak bone accretion occurs at 12.5 years in females and at 14.1 years in males[2] and, after 4 years from this peak, 95% of the maximum adult bone mass has been already attained.[3] Therefore, the prepubertal and peripubertal years are windows of opportunity for maximizing the response to exercise and osteoporosis prevention.[4]

Although peak bone mass is mainly determined by genetics (60-80% of peak bone mass), there are other parameters such as physical activity, nutrition, and hormones that may influence it.[5] For instance, physical exercise and its inherent impacts and muscle forces cause high mechanical strains to the bone and, at the same time, an increase of bone remodeling activity to reinforce the bone and to protect its structure.[6] Focusing on bone-exercise interactions during growth, it is important to mention that not every sport produces the same effect on bone mass. In fact, it has been observed that participation in high-impact sports such as ~~football~~ soccer,[7, 8] basketball,[9] racquet games[10] is associated with a gain in bone mineral content (BMC) and bone mineral density in most weight-bearing sites such as lumbar spine, hip and lower limbs; nevertheless, participation in non-impact sports such as swimming,[11] cycling[12] do not present this association. Therefore, the effect on bone seems to be sport-dependent and is driven by the specific mechanical loads that sports demand.

An option to quantify mechanical loading is measuring plantar pressures when executing different sports actions. This technique has been widely used in ~~football~~ soccer research[13, 14] and provides an insight of the mechanical load intensity that the lower limbs receive during ~~football~~ soccer practice. Although some biomechanical studies have analysed plantar pressures and their association with bone in young ~~football~~ soccer players,[13, 15] these studies were only focused on stress fractures. Since plantar pressure is commonly measured, its association with bone structure could give further information about the effects of playing ~~football~~ soccer on bone health status.

Because ~~football~~ soccer practice is characterized by the repetition of several high-impact movements, the stress in different foot areas such as the 5th metatarsal (one of the most common non-contact injuries in ~~football~~ soccer[16]) increases, which may result in stress fractures. As Shuen et al.[16] reported, the type of surface or shoes and, more importantly, the intensity and the volume of ~~football~~ soccer trainings might be the main factors determining those stress fractures. Thus, in terms of bone, an adequate training volume and intensity (e.g. two or three trainings of moderate-vigorous intensity per week) in children and adolescent soccer players might ~~avoid~~ help to mitigate the above-mentioned fractures and improve bone parameters. To the best of our knowledge, there are no previous studies evaluating bone health of young ~~football~~ soccer players based on their plantar pressures.

Therefore, the aim of the present study was to compare bone geometry and strength between male adolescent ~~football~~ soccer players, taking into account their maximum values of the average pressures (MP) registered during a combination of ~~football~~ soccer-specific tasks. We hypothesized that ~~football~~ soccer players with higher plantar pressures (~~FOOT~~ SOC-HP) ~~will~~ would exhibit better bone geometry and greater bone strength compared to those with lower plantar pressures (~~FOOT~~ SOC-LP) and controls (CG).

Materials and methods

Participants

Forty-four male ~~football~~ soccer players from five different ~~football~~ soccer clubs of Aragon (Spain) and 23 CG agreed to participate in the present study. Four ~~football~~ soccer players were excluded from the analysis as they were not Caucasian, three controls as they had blurred pQCT images; and seven controls as they were older than 14 at the beginning of the study. Finally, a total of 40 ~~football~~ soccer players (mean age: 13.2 ± 0.5 y) and 13 age matched controls (mean age: 13.1 ± 0.9 y) were included in the study analysis. After performing hierarchical and K-means cluster analyses (see statistical analyses), these players were split into two groups according to their MP, registered in five areas of their non-dominant foot during a combination of game-specific tasks: 15 ~~FOOT~~ SOC-HP (mean age: 13.1 ± 0.4 y, mean MP of the all foot areas: 392.7 ± 68.2 kPa; Table I) and 25 ~~FOOT~~ SOC-LP (mean age: 13.3 ± 0.5 y, mean MP of the all foot areas: 261.0 ± 49.6 kPa; Table I). Moreover, these ~~football~~ soccer players had different foot types (16 players with normal foot, 14 with high arch, and 16 with flat foot). Measurements took place between May and July 2014.

Although the five ~~football~~ soccer teams did not perform exactly the same ~~football~~ soccer exercises, their trainings lasted approximately 90 min, including 5-min warm-up consisting of low-intensity running; 5-10 min of low-intensity games; 60 min of technical ~~football~~ soccer exercises (i.e. passing, kicking, running, dribbling); and finally, 5-10 min of cool down performing stretching exercises. On the other hand, these ~~football~~ soccer clubs competed at provincial level for their age category.

The protocol, and the possible benefits and risks of this study were explained to participants, parents and club managers. Before taking any data, all participants gave verbal assent and parents fulfilled and signed a written informed consent. This study was performed following the guidelines declaration of Helsinki 1961 (revision of Fortaleza 2013) and the protocol was approved by the Ethics Committee of Clinical Research from the Government of Aragon (CEICA, Spain) [C.I. PI13/0091]. The present study is a part of the FUTBOMAS project, which was registered in the public database Clinicaltrials.gov [NCT02399553]. The STrengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement was used as a guideline for reporting observational data.[17]

Inclusion criteria

Participants had to be Caucasian, playing ~~football~~ soccer for a period of at least one year prior to data collection (~~football~~ soccer players) or not being engaged in any regular sport (CG), between 11 and 14 years at the beginning of the FUTBOMAS project, and free of any medication affecting bone.

Anthropometric measurements

Following the procedures defined by the International Society for Advancement in Kinanthropometry (ISAK),[18] height (stadiometer SECA 225. SECA. Hamburg, Germany; to the nearest 0.1 cm) and weight (scale SECA 861. SECA. Hamburg, Germany; to the nearest 0.1 kg) were measured without shoes and with minimal clothes.

Maturity offset

Maturity offset, described as the time (years) before and after the age of peak height velocity, was calculated using the following equation proposed by Moore et al.:[19]

Maturity offset = -7.999994 + (0.0036124 x (age x height))

Additionally, the age of peak height velocity was calculated as the subtraction of the age from maturity offset.

Calcium intake

A validated calcium food frequency questionnaire was used to estimate milligrams per day of calcium intake.[20]

Protocol

Participants wore ~~football~~ soccer shoes (Adidas Nitrocharge 3.0 ~~football~~ soccer shoes, Adidas AG, Herzogenaurach, Germany) with two different stud designs suitable for use on artificial surfaces: 11 ~~football~~ soccer players wore a turf stud design (71 studs) and 29 soccer players wore a hard-ground stud design (22 studs).

All participants performed a warm-up that consisted of approximately three minutes of lower limb articular mobilization (hip, knee and ankle) and two sub-maximal familiarization trials of the combination of some ~~football~~ soccer-specific tasks. This circuit was composed of three two-footed jumps of 30-cm hurdles, a zigzag run around four poles, a lateral shuffle and two sprints separated by a 90º cut (see Figure 1). Before starting the test, participants were sitting on a chair putting their feet up to avoid plantar pressure interferences. They were instructed to perform two trials at maximum speed resting approximately two min between them. The trial with the highest MP was included in the present study.

Plantar pressure measurements

Biofoot® (IBV, Valencia, Spain) system was used to measure MP of both feet. This system is composed of two insoles that are connected to two amplifiers located on the lateral aspect of participants' ~~shanks~~ legs. At the same time, these amplifiers are linked with a transmission module that is located on the participant waist (at lower back) and sends the data to the computer by digital telemetry. These thin (0.7 mm thickness), flexible and polyester insoles are size-specific and have 64 piezoelectric sensors distributed along the foot. This system uses kilopascal units (kPa) and the sample frequency was set up at 100 Hz for 15 s.

Plantar pressures of the non-dominant foot were analysed as bone measurements were performed at this side. Following manufacturer's software instructions (version 6.1), plantar pressures were analysed in the following five areas of the foot: lateral foot, medial foot, forefoot, midfoot and rearfoot (Figure 2). The plantar pressure variable selected for each one of the 5 foot areas was MP. Firstly, the software computed for each step the mean of the maximum pressure measured by each sensor of a determined area; afterwards, the final data obtained represents the average maximum value of all steps during the whole circuit.

Foot types were also determined following the guidelines proposed by Shiang et al.[21] To measure arch height and arch angle, participants stood with their arms relaxed and looking straight ahead. Arch height was assessed from the distal point of navicular bone to the floor. Then, flat foot was determined when navicular height was lower than 37 mm; normal foot with values between 37 and 40 mm; and high arch foot with values higher than 40 mm. Afterwards, arch angle was obtained from the line connecting the most medial point of the heel with the most medial point of the first metatarsal bone; and the line connecting the most lateral point of the medial foot with the most medial point of the first metatarsal bone. In terms of arch angle, flat foot was determined when arch angle was lower than 46º; normal foot with values between 46 and 55º; and high arch foot with values higher than 55º. Both navicular height and arch angle parameters should be the same in order to determine which foot were flat or high-arch.

Bone assessment by peripheral quantitative computed tomography (pQCT)

Volumetric BMC, bone area and bone strength indexes were assessed at the non-dominant tibia with a Stratec XCT-2000 L pQCT scanner (Stratec Medizintechnik, Pforzheim, Germany). This device is a translate-rotate, small bore computed tomography scanner that acquires a trans-axial image. pQCT equipment was calibrated daily using a quality control phantom and following the manufacturer guidelines (Stratec Medizintechnik, Pforzheim, Germany). Coefficients of variation for each pQCT variable at non-dominant tibia in our laboratory ~~have been already~~ published. [22] were: 0.25% for total BMC (Tt.BMC), 0.50% for cortical BMC (Ct.BMC), 0.72% for total area (Tt.Ar), 0.73% for cortical area (Ct.Ar), 1.12% for cortical thickness (Ct.Th), 2.51% for fracture load in *X*-axis; and 2.08% for polar strength strain index (SSIp).

The lower limb dominance was determined by players preferred kicking leg.[23] Although the measurement of non-dominant or dominant lower limb has not been clarified yet in pQCT studies,[24] ~~adolescent football players showed higher bone strength indexes at non-dominant tibia than at dominant tibia.[25] Azevedo et al.[13] also reported greater plantar pressures at the non-dominant foot; accordingly,~~ the non-dominant lower limb was selected for the measurements.

Participants were seated on a chair adjustable to the body proportions of each participant. The tibia length was assessed from the medial knee joint cleft to the medial malleolus of the tibia using a wooden ruler and was always measured by the same researcher (AML). Then, the non-dominant lower limb was centred in the imaging field, and the foot and knee were secured to reduce movement. Once the scanner was positioned on the distal tibia, a scout view was done to manually set the reference line on the midpoint of the distal tibia end plate. Scans were performed at 38% site of the length of the tibia to assess cortical bone and bone strength indexes. Following the International Society of Clinical Densitometry (ISCD) official positions,[24] the measured parameters at the 38% site of the length of the tibia were Tt.BMC (g), Ct.BMC (g), Tt.Ar (mm^2), Ct.Ar (mm^2), Ct.Th (mm), fracture load in *X*-axis (N) and SSIp (mm^3). Muscle and fat cross sectional areas (mm^2) were measured at the 66% site of the length of the tibia.

Version 6.20 of the manufacturer's software was used to analyse pQCT images. At 38% site of the tibia, the periosteal surface of the bone was determined using the contour mode 1 with a threshold of 280 mg/cm^3. Cortical bone was obtained using cortical mode 1 with a threshold of 710 mg/cm^3. To obtain bone strength variables (fracture load in *X*-axis and SSIp), cortical mode 1 with a threshold of 280 mg/cm^3 was used. After that, bone mineralization of 1200 mg/cm^3 was assumed.

Statistical analyses

The Statistical Package for the Social Sciences (SPSS) version 22.0 for Mac OS X (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Data were presented as mean ± standard deviation (SD). All variables showed normal distribution tested with the Shapiro-Wilk test.

Cluster analysis was performed to identify groups of ~~football~~ soccer players with similar MP. Following the methodology of clustering applied in Prokasky et al.[26] and Sanson et al.[27] studies, hierarchical clustering and K-means clustering were used. Firstly, to reduce the sensitivity of the Ward's method to outliers, univariate (those that were > 3 SD above or below the mean) and multivariate outliers (those that had high Mahalanobis distance) for MP at each foot area were examined, and no outliers were found. In the first step, hierarchical cluster analysis was performed to determine the number of clusters. After examining the dendrogram obtained from this analysis, the suggested number of clusters were two. In the second step, K-means clustering analysis was applied using as non-random starting points the cluster centres obtained by the previous Ward's hierarchical procedure.

In order to test the stability of these clusters, cluster analysis was repeated in two subsamples randomly obtained from the whole sample of this study. Afterwards, Cohen's Kappa coefficient (κ) was used to measure the agreement between the original cluster obtained from the whole sample with the merger of the new two clusters created by subsamples. This comparison showed an excellent agreement (Cohen's Kappa coefficient was 1).

~~Independent t test~~ One way analyses of variance (ANOVA) were performed to examine differences between ~~football~~ soccer groups and CG for descriptive characteristics; and between soccer groups for MP measured at different foot areas (lateral, medial, rearfoot, midfoot and forefoot). Furthermore, analyses of covariance (ANCOVAs) were applied to compare bone geometry and strength variables between the two ~~football~~ soccer groups and CG using weight and the length of the tibia as covariates. Bonferroni corrections were applied to control the Type II error of multiple comparisons.

Effect size statistics were reported as ~~Cohen's d for independent t test and~~ partial eta squared (η^2_p) for ANCOVAs. Taking into account cut-off points established by Hopkins et al.,[28] ~~the effect size for Cohen´s d can be trivial (0.0 – 0.2), small (0.2 – 0.6), moderate (0.6 – 1.2), large (1.2 – 2.0) or very large (> 2.0). Additionally,~~ the effect size for η^2_p can be small ~~(0.01 – 0.06)~~, medium ~~(0.06 – 0.14)~~ or large ~~(>0.14)~~. Statistical significance was set at $p < .05$.

Results

Despite the different type of foot and stud design used, no proportion differences between ~~football~~ soccer players with different type of foot ($\chi^2(2) = 0.770$, $p = .681$) and who wore different stud designs ($\chi^2(1) = 0.677$, $p = .411$) were found. Furthermore, no significant MP differences were found in any foot area when ~~football~~ soccer players who had different foot type and those who wore different stud designs were compared (Supplementary Table I and II).

No descriptive differences were found between ~~FOOT~~ SOC-HP, ~~FOOT~~ SOC-LP and CG ($p > .05$; Table I). In contrast, ~~FOOT~~ SOC-HP showed higher MP at the lateral foot, medial foot, rearfoot and forefoot compared to ~~FOOT~~ SOC-LP ($p < .05$; Table I). Additionally, when MP comparisons between ~~FOOT~~ SOC-HP and ~~FOOT~~ SOC-LP were adjusted by weight, similar results were found (Supplementary Table III).

Table II shows the adjusted pQCT values of ~~FOOT~~ SOC-HP, ~~FOOT~~ SOC-LP and CG and the statistics of the comparisons between these groups. Tt.BMC, Ct.BMC and Ct.Ar were significantly greater in ~~FOOT~~ SOC-HP compared to CG (mean differences were ~~5.4 and 5.9%~~9.1, 9.8 and 10.4 %; $p < .05$; Table II). ~~No significant differences were found in the other pQCT variables (p > .05; η^2_p ranged from 0.03 and 0.14; Table II).~~ SOC-LP did not show significant differences in any of the pQCT variables compared to SOC-HP and controls ($p > .05$; Table II).

Discussion

The present study shows that adolescent ~~footballers~~ soccer players with higher plantar pressures present enhanced Tt.BMC, ~~and~~ Ct.BMC and Tt.Ar when compared to ~~those with low pressures~~ CG. ~~However, bone strength indexes are not different between groups. Thus, the hypothesis that FOOT-HP will exhibit better bone geometry and greater bone strength indexes is partially confirmed.~~ On the other hand, no plantar pressures differences were found between those soccer players who wore different stud designs and had different foot types. This lack of differences could be explained by the fact that plantar pressures values were measured for the whole circuit instead of for each task separately. Moreover, this circuit consisted of diverse soccer actions such as jumps, zigzag run or changes of direction and, as Eils et al.[15] demonstrated, each soccer-specific action mainly loads a different foot area. Therefore, after calculating the mean of all tasks, the possible differences between foot types could disappear.

The results obtained in the present study also demonstrated significant MP differences between the two soccer groups with different plantar pressures. These differences might be explained by the fact that those players with high plantar pressures had the ability to perform soccer specific actions at high intensity. On the other hand, a study which evaluated the distribution of different plantar pressures during soccer-specific tasks, suggested to consider player positions when plantar pressures during different soccer-specific actions are evaluated.[15] Concretely, in the present study, to reduce the possible influence of playing position and also skill level of participants on plantar pressures, soccer players were instructed to perform two sub-maximal familiarization trials of the circuit and, afterwards, to execute other two trials at maximum speed.

Although a positive association between high plantar pressures and ~~bone parameters~~ all bone geometry variables except Tt.Ar has been ~~is~~ elucidated, the findings related to bone strength indexes could be slightly mediated by bone growth. Cortical bone and bone strength parameters regularly increase until the age of 14 years in males and, afterward, these parameters abruptly increase.[29] As only three ~~FOOT~~ SOC-LP had just achieved this age, future studies including a sample of ~~football~~ soccer players older than 14 years could help to clarify if these bone differences between ~~football~~ soccer players with different plantar pressures and CG can be observed in later ages.

The main response of bone to physical exercise in both male prepubertal or pubertal athletes is periosteal apposition increasing, at the same time, bone area, ~~Tt.Ar, Ct.Ar,~~ Ct.Th and bending and torsional forces.[30] In the present study, ~~higher but not significant differences at Tt.Ar, Ct.Ar, Ct.Th, fracture load in X-axis and SSIp between FOOT-HP and FOOT-LP~~ when SOC-LP were compared to SOC-HP and CG, no bone differences at any bone geometry and strength parameters were found. The lack of differences between ~~football~~ soccer groups could be explained by the fact that both groups did similar ~~football~~ soccer exercises, and probably, had comparable enhancements of the bone. Therefore, both groups might have benefited from the effects of ~~football~~ soccer practice on bone. On the other hand, the absence of significant differences in most of bone variables between soccer players and controls could be due to the early maturity status of all participants included in the present study. The effects of soccer practice on bone could be observed more clearly in the following years when the peak of bone accretion is reached.[2]

As Frost explained,[31] high intensity strains (i.e. ~~football~~ soccer actions) increase bone remodeling activity resulting in bone adaptations to loads. Additionally, the intensity of these strains may provoke different bone adaptations.[31] For instance, a study performed with young ~~football~~ soccer players[25] showed higher bone parameters at their non-dominant lower limb compared to their dominant one. In terms of ~~football~~ soccer practice, the non-dominant lower limb supports each action performed by dominant one (skilled lower limb), meaning that mechanical strains received by each lower limb are different (higher in non-dominant lower limb). The present study shows that ~~football~~ only soccer players receiving higher mechanical strains have higher ~~bone geometry~~ Tt.BMC, Ct.BMC and Ct.Ar. compared to controls which is in agreement with the mechanostat theory and previous studies developed in ~~football~~ soccer players.[25, 31]

~~A stress fracture is defined by Warden et al.[32] as "*the inability of the skeleton to withstand repetitive bouts of mechanical loading, which results in structural fatigue and resultant signs and symptoms of localized pain and tenderness*". This type of fracture is~~

~~a common overuse injury in athletes[33] and, specifically, in football, the fracture of the fifth metatarsal is one of the most frequent stress fractures[34] being the non-dominant foot the most affected one [35]. These fractures are due to extrinsic (i.e. sport, type of surface, training duration) and intrinsic factors (i.e. body composition, biomechanics).[32] With regards to football players included in the present study, the absence of stress fractures prior to measurements could be explained by their low exposure time to football practice (FOOT-HP: 5 ± 2 training years and 3.1 ± 1.2 hours per week; FOOT-LP: 6 ± 2 training years and 4.0 ± 1.6 hours per week). As they grow up, it is expected that they will play in upper categories and, probably, they will train more hours and at higher intensity. It has been demonstrated that an increase of football training volume enhances bone density and cortical bone area;[36] nevertheless, the possibility of having a stress fracture might also increase. Thus, the measurement of plantar pressures could provide information about which players have an increased risk of stress fracture and even, in which foot sites these fractures are more probably to occur.~~

~~The main limitations of the present study are that football players wore shoes with different stud designs and they had different foot types. Despite this, neither MP nor proportion differences were found between these football players with different foot type and stud designs (Supplementary Table I and II). Although, the total sample size of male football players in the present study (n = 40) was lower compared to those in other pQCT studies (99[36] or 71 male football players[37]), this sample size was higher than those in studies measuring plantar pressures (15[13] or 21[15]). On the other hand, the main strength is that this is the first study comparing bone geometry and strength based on biomechanical parameters such as plantar pressures.~~ The main limitation of the present study is that the sample size of young soccer players is small and, therefore, the power of this study is reduced. Another limitation is that MP were measured for the whole circuit instead of being measured for each task separately. Furthermore, the validity and reliability for determining MP could not be calculated because only the trial with the highest plantar pressures was saved.

Conclusions

In summary, the present study shows that adolescent ~~football~~ soccer players with higher plantar pressures have better ~~bone geometry than those players with lower plantar pressures~~ Tt.BMC, Ct.BMC and Ct.Ar than controls; nevertheless, those players with lower plantar pressures do not show differences in bone geometry and strength compared to those with high plantar pressures and controls. ~~Thus, measurement of plantar pressures might provide a general insight of which is the bone health status of football players.~~ Overall, mechanical loading produced by ~~football~~ soccer-specific actions increases bone development; nevertheless, ~~an excessive repetition of these high-intensity loadings could also increase the risk of stress fracture in lower limbs. Thus, adequate training volume (both training frequency and duration of these trainings) and rest between sessions might prevent from stress fractures without hindering the potential benefit of football practice on bone.~~ performing soccer actions at high intensity might increase the stimulus on bone and, at the same time, provide an extra gain of bone geometry. Thus, an increment of the intensity of soccer trainings could also increase the intensity of soccer actions during matches and, at the same time, bone health of soccer players.

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NOTES

Conflicts of interest. The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors’ contributions. JAC designed the study. GLB, AML, AGB, VAS and AGA performed experiments. GLB, AML, AGA and JAC analysed the data. GLB, AML, AGB, VAS, AGA, GVR and JAC wrote the paper. All authors approved the manuscript.

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Table I. Descriptive characteristics and maximum values of the average pressure of ~~football~~ soccer players with low and high plantar pressures and controls.

	SOC-HP (n = 15)	SOC-LP (n = 25)	CG (n = 13)
Descriptive characteristics			
Age (y)	13.1 ± 0.4	13.3 ± 0.5	13.1 ± 0.9
Weight (kg)	49.0 ± 9.9	46.4 ± 11.6	49.5 ± 9.8
Height (cm)	157.9 ± 9.0	155.5 ± 8.6	156.2 ± 6.2
BMI ($kg \cdot m^{-2}$)	19.6 ± 3.3	19.0 ± 3.1	20.2 ± 2.9
Tibia length (mm)	361 ± 22	351 ± 21	355 ± 23
Muscle CSA (mm^2)	5692 ± 835	5370 ± 1100	5348 ± 1256
Fat CSA (mm^2)	2123 ± 1057	1870 ± 721	2518 ± 726
Daily calcium intake (mg)	731.4 ± 211.5	787.9 ± 374.2	991.0 ± 543.1
Maturity offset (y)	-0.5 ± 0.6	-0.5 ± 0.5	-0.6 ± 0.7
Age PHV (y)	13.6 ± 0.4	13.8 ± 0.4	13.7 ± 0.3
Training years (y)	6 ± 2	5 ± 2	-
Training hours (h/week)	4.0 ± 1.6	3.1 ± 1.2	-
MP (kPa)			
Lateral	330.6 ± 185.1	207.6 ± 78.8*	-
Medial	420.1 ± 79.3	245.2 ± 55.2*	-
Rearfoot	612.5 ± 191.5	427.3 ± 148.9*	-
Midfoot	224.2 ± 203.9	187.2 ± 133.2	-
Forefoot	375.9 ± 83.2	237.6 ± 70.0*	-

Values are mean ± SD.

~~FOOT~~ SOC-HP: ~~football~~ soccer players with high maximum values of the average pressure; ~~FOOT~~ SOC-LP: ~~football~~ soccer players with low maximum values of the average pressure; CG: controls; BMI: body mass index; CSA: cross sectional area; PHV: peak height velocity; MP: maximum value of the average pressure.

* significant differences between soccer groups.

~~Table II. Adjusted pQCT values of football players with low and high plantar pressures.~~

	~~FOOT-LP (n = 25)~~	~~FOOT-HP (n = 15)~~	~~MD (95% CI)~~	~~Test statistic~~	~~% Difference~~
~~**Bone geometry**~~					
~~Tt.BMC (g)~~	~~3.04 ± 0.25~~	~~3.21 ± 0.24~~	~~0.17 (0.01, 0.34)*~~	~~F(1,36) = 4.6, p = .038, η^2_p = 0.11~~	~~-5.4~~
~~Ct.BMC (g)~~	~~2.76 ± 0.22~~	~~2.94 ± 0.22~~	~~0.17 (0.03, 0.32)*~~	~~F(1,36) = 5.7, p = .022, η^2_p = 0.14~~	~~-5.9~~
~~Tt.Ar (mm^2)~~	~~386 ± 32~~	~~397 ± 33~~	~~11 (-10, 33)~~	~~F(1,36) = 1.1, p = .301, η^2_p = 0.03~~	~~-2.8~~
~~Ct.Ar (mm^2)~~	~~265 ± 23~~	~~279 ± 24~~	~~14 (-2, 29)~~	~~F(1,36) = 3.0, p = .090, η^2_p = 0.08~~	~~-4.9~~
~~**Bone strength**~~					
~~Ct.Th (mm)~~	~~4.88 ± 0.38~~	~~5.10 ± 0.38~~	~~0.21 (-0.04, 0.47)~~	~~F(1,36) = 2.9, p = .098, η^2_p = 0.07~~	~~-4.2~~
~~Frc.LdX (N)~~	~~3017.1 ± 384.8~~	~~3223.5 ± 387.4~~	~~206.4 (-52.8, 465.6)~~	~~F(1,36) = 2.6, p = .115, η^2_p = 0.07~~	~~-6.4~~
~~SSIp (mm^3)~~	~~1350.6 ± 153.4~~	~~1442.9 ± 154.5~~	~~92.3 (-11.1, 195.6)~~	~~F(1,36) = 3.3, p = .078, η^2_p = 0.08~~	~~-6.4~~

~~Values are mean ± SD. pQCT variables adjusted by weight and tibia length.~~

~~FOOT-LP: football players with low maximum values of the average pressure; FOOT-HP: football players with high maximum values of the average pressure; pQCT: peripheral quantitative computed tomography; MD: mean difference; CI: confidence interval; Tt.BMC: total volumetric bone mineral content; Tt.Ar: total cross sectional area; Ct.BMC: cortical volumetric bone mineral content; Ct.Ar: cortical cross sectional area; Ct.Th: cortical thickness; Frc.LdX: fracture load in axe X; SSIp: strength strain index in polar; η^2_p: partial eta squared.~~

~~*: p < .05 differences between football groups.~~

Table II. Adjusted pQCT values of soccer players with low and high plantar pressures and controls.

	SOC-HP (n = 15)	SOC-LP (n = 25)	CG (n = 13)	Test statistic
Bone geometry				
Tt.BMC (g)	3.22 ± 0.28*	3.05 ± 0.28	2.95 ± 0.28	F(2,48) = 3.3, p = .044, η^2_p = 0.12
Ct.BMC (g)	2.95 ± 0.26*	2.77 ± 0.26	2.68 ± 0.26	F(2,48) = 3.8, p = .030, η^2_p = 0.14
Tt.Ar (mm^2)	398 ± 35	388 ± 35	369 ± 35	F(2,48) = 2.4, p = .097, η^2_p = 0.09
Ct.Ar (mm^2)	280 ± 27*	266 ± 27	253 ± 27	F(2,48) = 3.4, p = .043, η^2_p = 0.12
Bone strength				
Ct.Th (mm)	5.12 ± 0.43	4.88 ± 0.43	4.77 ± 0.43	F(2,48) = 2.4, p = .098, η^2_p = 0.09
Frc.LdX (N)	3233.3 ± 428.6	3041.8 ± 426.1	3015.1 ± 424.9	F(2,48) = 1.2, p = .315, η^2_p = 0.05
SSIp (mm^3)	1445.8 ± 181.8	1362.7 ± 180.8	1292.3 ± 180.2	F(2,48) = 2.5, p = .092, η^2_p = 0.10

Values are mean ± SD. pQCT variables adjusted by weight and tibia length.

SOC-HP: soccer players with high maximum values of the average pressure; SOC-LP: soccer players with low maximum values of the average pressure; CG: controls; pQCT: peripheral quantitative computed tomography; Tt.BMC: total volumetric bone mineral content; Tt.Ar: total cross sectional area; Ct.BMC: cortical volumetric bone mineral content; Ct.Ar: cortical cross sectional area; Ct.Th: cortical thickness; Frc.LdX: fracture load in axe X; SSIp: strength strain index in polar; η^2_p: partial eta squared.

*: p < .05 differences between SOC-HP and CON.

TITLES OF FIGURES

Figure 1. Experimental setup. Black circles represent slalom poles and black triangles represent ~~football~~ soccer cones. 1) three two-footed jumps of 30-cm hurdles, 2) a zigzag run around four slalom poles, 3) a three-m sprint, 4) a lateral shuffle, 5-6) two three-m sprints separated by a 90º cut.

Figure 2. Foot areas for plantar pressure analysis. Area 1 represents medial foot, area 2 represents lateral foot, area 3 represents forefoot, area 4 represents midfoot and area 5 represents rearfoot.

Plantar pressures in male adolescent soccer players and its associations with bone geometry and strength

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ABSTRACT

BACKGROUND: Mechanical loads exerted by soccer-specific actions increase bone remodeling activity. Nevertheless, little is known about the relationship between plantar pressure and bone structure. Therefore, the aim of this study was to compare bone geometry and strength between soccer players who exhibited different maximum values of the average pressures (MP) when performing a combination of soccer-specific tasks.

METHODS: Forty male adolescent soccer players (mean age 13.2±0.5 y) and 13 controls (mean age 13.1±0.9 y) participated in this study. Biofoot® system was used to measure MP at the non-dominant foot during a circuit of soccer-specific tasks. Cluster analysis was performed to classify players into groups of similar MP profiles resulting two different groups as follows: 15 players with high MP (SOC-HP; mean MP: 392.7±68.2 kPa) and 25 with low MP (SOC-LP; mean MP: 261.0±49.6 kPa). Total and cortical volumetric bone mineral content (Tt.BMC/Ct.BMC), cross-sectional area (Tt.Ar/Ct.Ar), cortical thickness (Ct.Th), fracture load in *X*-axis, and polar strength index (SSIp) were measured at 38% of the non-dominant tibia by peripheral quantitative computed tomography. Bone geometry and strength comparisons between SOC-HP and SOC-LP were performed using analyses of covariance controlling by weight and tibia length.

RESULTS: Greater Tt.BMC, Ct.BMC and Tt.Ar. were found in SOC-HP compared to CG (Tt.BMC: 3.22vs2.95 g, Ct.BMC: 2.95vs2.68 g, Ct.Ar: 280vs253 mm^2; p<.05). Nevertheless, no significant bone geometry and strength differences were found between soccer groups and between SOC-LP and CG (p>.05).

CONCLUSIONS: Developing high MP when training and playing soccer might be favourable to bone development.

Key words: Adolescent, soccer, foot, bone and bones.

TEXT

Introduction

Osteoporosis has its clinical manifestations mainly through adulthood and old age. Nevertheless, childhood and adolescence are considered critical stages to gain bone mass and fight against this disease.[1] Peak bone accretion occurs at 12.5 years in females and at 14.1 years in males[2] and, after 4 years from this peak, 95% of the maximum adult bone mass has been already attained.[3] Therefore, the prepubertal and peripubertal years are windows of opportunity for maximizing the response to exercise and osteoporosis prevention.[4]

Although peak bone mass is mainly determined by genetics (60-80% of peak bone mass), there are other parameters such as physical activity, nutrition, and hormones that may influence it.[5] For instance, physical exercise and its inherent impacts and muscle forces cause high mechanical strains to the bone and, at the same time, an increase of bone remodeling activity to reinforce the bone and to protect its structure.[6] Focusing on bone-exercise interactions during growth, it is important to mention that not every sport produces the same effect on bone mass. In fact, it has been observed that participation in high-impact sports such as soccer,[7, 8] basketball,[9] racquet games[10] is associated with a gain in bone mineral content (BMC) and bone mineral density in most weight-bearing sites such as lumbar spine, hip and lower limbs; nevertheless, participation in non-impact sports such as swimming,[11] cycling[12] do not present this association. Therefore, the effect on bone seems to be sport-dependent and is driven by the specific mechanical loads that sports demand.

An option to quantify mechanical loading is measuring plantar pressures when executing different sports actions. This technique has been widely used in soccer research[13, 14] and provides an insight of the mechanical load intensity that the lower limbs receive during soccer practice. Although some biomechanical studies have analysed plantar pressures and their association with bone in young soccer players,[13, 15] these studies were only focused on stress fractures. Since plantar pressure is commonly measured, its association with bone structure could give further information about the effects of playing soccer on bone health status.

Because soccer practice is characterized by the repetition of several high-impact movements, the stress in different foot areas such as the 5th metatarsal (one of the most common non-contact injuries in soccer[16]) increases, which may result in stress fractures. As Shuen et al.[16] reported, the type of surface or shoes and, more importantly, the intensity and the volume of soccer trainings might be the main factors determining those stress fractures. Thus, in terms of bone, an adequate training volume and intensity (e.g. two or three trainings of moderate-vigorous intensity per week) in children and adolescent soccer players might help to mitigate the above-mentioned fractures and improve bone parameters. To the best of our knowledge, there are no previous studies evaluating bone health of young soccer players based on their plantar pressures.

Therefore, the aim of the present study was to compare bone geometry and strength between male adolescent soccer players, taking into account their maximum values of the average pressures (MP) registered during a combination of soccer-specific tasks. We hypothesized that soccer players with higher plantar pressures (SOC-HP) would exhibit better bone geometry and greater bone strength compared to those with lower plantar pressures (SOC-LP) and controls (CG).

Materials and methods

Participants

Forty-four male soccer players from five different soccer clubs of Aragon (Spain) and 23 CG agreed to participate in the present study. Four soccer players were excluded from the analysis as they were not Caucasian, three controls as they had blurred pQCT images; and seven controls as they were older than 14 at the beginning of the study. Finally, a total of 40 soccer players (mean age: 13.2 ± 0.5 y) and 13 age matched controls (mean age: 13.1 ± 0.9 y) were included in the study analysis. After performing hierarchical and K-means cluster analyses (see statistical analyses), these players were split into two groups according to their MP, registered in five areas of their non-dominant foot during a combination of game-specific tasks: 15 SOC-HP (mean age: 13.1 ± 0.4 y, mean MP of the all foot areas: 392.7 ± 68.2 kPa; Table I) and 25 SOC-LP (mean age: 13.3 ± 0.5 y, mean MP of the all foot areas: 261.0 ± 49.6 kPa; Table I). Moreover, these soccer players had different foot types (16 players with normal foot, 14 with high arch, and 16 with flat foot). Measurements took place between May and July 2014.

Although the five soccer teams did not perform exactly the same soccer exercises, their trainings lasted approximately 90 min, including 5-min warm-up consisting of low-intensity running; 5-10 min of low-intensity games; 60 min of technical soccer exercises (i.e. passing, kicking, running, dribbling); and finally, 5-10 min of cool down performing stretching exercises. On the other hand, these soccer clubs competed at provincial level for their age category.

The protocol, and the possible benefits and risks of this study were explained to participants, parents and club managers. Before taking any data, all participants gave verbal assent and parents fulfilled and signed a written informed consent. This study was performed following the guidelines declaration of Helsinki 1961 (revision of Fortaleza 2013) and the protocol was approved by the Ethics Committee of Clinical Research from the Government of Aragon (CEICA, Spain) [C.I. PI13/0091]. The present study is a part of the FUTBOMAS project, which was registered in the public database Clinicaltrials.gov [NCT02399553]. The STrengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement was used as a guideline for reporting observational data.[17]

Inclusion criteria

Participants had to be Caucasian, playing soccer for a period of at least one year prior to data collection (soccer players) or not being engaged in any regular sport (CG), between 11 and 14 years at the beginning of the FUTBOMAS project, and free of any medication affecting bone.

Anthropometric measurements

Following the procedures defined by the International Society for Advancement in Kinanthropometry (ISAK),[18] height (stadiometer SECA 225. SECA. Hamburg, Germany; to the nearest 0.1 cm) and weight (scale SECA 861. SECA. Hamburg, Germany; to the nearest 0.1 kg) were measured without shoes and with minimal clothes.

Maturity offset

Maturity offset, described as the time (years) before and after the age of peak height velocity, was calculated using the following equation proposed by Moore et al.:[19]

Maturity offset = -7.999994 + (0.0036124 x (age x height))

Additionally, the age of peak height velocity was calculated as the subtraction of the age from maturity offset.

Calcium intake

A validated calcium food frequency questionnaire was used to estimate milligrams per day of calcium intake.[20]

Protocol

Participants wore soccer shoes (Adidas Nitrocharge 3.0 soccer shoes, Adidas AG, Herzogenaurach, Germany) with two different stud designs suitable for use on artificial surfaces: 11 soccer players wore a turf stud design (71 studs) and 29 soccer players wore a hard-ground stud design (22 studs).

All participants performed a warm-up that consisted of approximately three minutes of lower limb articular mobilization (hip, knee and ankle) and two sub-maximal familiarization trials of the combination of some soccer-specific tasks. This circuit was composed of three two-footed jumps of 30-cm hurdles, a zigzag run around four poles, a lateral shuffle and two sprints separated by a 90º cut (see Figure 1). Before starting the test, participants were sitting on a chair putting their feet up to avoid plantar pressure interferences. They were instructed to perform two trials at maximum speed resting approximately two min between them. The trial with the highest MP was included in the present study.

Plantar pressure measurements

Biofoot® (IBV, Valencia, Spain) system was used to measure MP of both feet. This system is composed of two insoles that are connected to two amplifiers located on the lateral aspect of participants' legs. At the same time, these amplifiers are linked with a transmission module that is located on the participant waist (at lower back) and sends the data to the computer by digital telemetry. These thin (0.7 mm thickness), flexible and polyester insoles are size-specific and have 64 piezoelectric sensors distributed along the foot. This system uses kilopascal units (kPa) and the sample frequency was set up at 100 Hz for 15 s.

Plantar pressures of the non-dominant foot were analysed as bone measurements were performed at this side. Following manufacturer's software instructions (version 6.1), plantar pressures were analysed in the following five areas of the foot: lateral foot, medial foot, forefoot, midfoot and rearfoot (Figure 2). The plantar pressure variable selected for each one of the 5 foot areas was MP. Firstly, the software computed for each step the mean of the maximum pressure measured by each sensor of a determined area; afterwards, the final data obtained represents the average maximum value of all steps during the whole circuit.

Foot types were also determined following the guidelines proposed by Shiang et al.[21] To measure arch height and arch angle, participants stood with their arms relaxed and looking straight ahead. Arch height was assessed from the distal point of navicular bone to the floor. Then, flat foot was determined when navicular height was lower than 37 mm; normal foot with values between 37 and 40 mm; and high arch foot with values higher than 40 mm. Afterwards, arch angle was obtained from the line connecting the most medial point of the heel with the most medial point of the first metatarsal bone; and the line connecting the most lateral point of the medial foot with the most medial point of the first metatarsal bone. In terms of arch angle, flat foot was determined when arch angle was lower than 46º; normal foot with values between 46 and 55º; and high arch foot with values higher than 55º. Both navicular height and arch angle parameters should be the same in order to determine which foot were flat or high-arch.

Bone assessment by peripheral quantitative computed tomography (pQCT)

Volumetric BMC, bone area and bone strength indexes were assessed at the non-dominant tibia with a Stratec XCT-2000 L pQCT scanner (Stratec Medizintechnik, Pforzheim, Germany). This device is a translate-rotate, small bore computed tomography scanner that acquires a trans-axial image. pQCT equipment was calibrated daily using a quality control phantom and following the manufacturer guidelines (Stratec Medizintechnik, Pforzheim, Germany). Coefficients of variation for each pQCT variable at non-dominant tibia in our laboratory were: 0.25% for total BMC (Tt.BMC), 0.50% for cortical BMC (Ct.BMC), 0.72% for total area (Tt.Ar), 0.73% for cortical area (Ct.Ar), 1.12% for cortical thickness (Ct.Th), 2.51% for fracture load in *X*-axis; and 2.08% for polar strength strain index (SSIp).

The lower limb dominance was determined by players preferred kicking leg.[22] Although the measurement of non-dominant or dominant lower limb has not been clarified yet in pQCT studies,[23] the non-dominant lower limb was selected for the measurements.

Participants were seated on a chair adjustable to the body proportions of each participant. The tibia length was assessed from the medial knee joint cleft to the medial malleolus of the tibia using a wooden ruler and was always measured by the same researcher (AML). Then, the non-dominant lower limb was centred in the imaging field, and the foot and knee were secured to reduce movement. Once the scanner was positioned on the distal tibia, a scout view was done to manually set the reference line on the midpoint of the distal tibia end plate. Scans were performed at 38% site of the length of the tibia to assess cortical bone and bone strength indexes. Following the International Society of Clinical Densitometry (ISCD) official positions,[23] the measured parameters at the 38% site of the length of the tibia were Tt.BMC (g), Ct.BMC (g), Tt.Ar (mm^2), Ct.Ar (mm^2), Ct.Th (mm), fracture load in *X*-axis (N) and SSIp (mm^3). Muscle and fat cross sectional areas (mm^2) were measured at the 66% site of the length of the tibia.

Version 6.20 of the manufacturer's software was used to analyse pQCT images. At 38% site of the tibia, the periosteal surface of the bone was determined using the contour mode 1 with a threshold of 280 mg/cm^3. Cortical bone was obtained using cortical mode 1 with a threshold of 710 mg/cm^3. To obtain bone strength variables (fracture load in *X*-axis and SSIp), cortical mode 1 with a threshold of 280 mg/cm^3 was used. After that, bone mineralization of 1200 mg/cm^3 was assumed.

Statistical analyses

The Statistical Package for the Social Sciences (SPSS) version 22.0 for Mac OS X (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Data were presented as mean ± standard deviation (SD). All variables showed normal distribution tested with the Shapiro-Wilk test.

Cluster analysis was performed to identify groups of soccer players with similar MP. Following the methodology of clustering applied in Prokasky et al.[24] and Sanson et al.[25] studies, hierarchical clustering and K-means clustering were used. Firstly, to reduce the sensitivity of the Ward's method to outliers, univariate (those that were > 3 SD above or below the mean) and multivariate outliers (those that had high Mahalanobis distance) for MP at each foot area were examined, and no outliers were found. In the first step, hierarchical cluster analysis was performed to determine the number of clusters. After examining the dendrogram obtained from this analysis, the suggested number of clusters were two. In the second step, K-means clustering analysis was applied using as non-random starting points the cluster centres obtained by the previous Ward's hierarchical procedure.

In order to test the stability of these clusters, cluster analysis was repeated in two subsamples randomly obtained from the whole sample of this study. Afterwards, Cohen's Kappa coefficient (κ) was used to measure the agreement between the original cluster obtained from the whole sample with the merger of the new two clusters created by subsamples. This comparison showed an excellent agreement (Cohen's Kappa coefficient was 1).

One way analyses of variance (ANOVA) were performed to examine differences between soccer groups and CG for descriptive characteristics; and between soccer groups for MP measured at different foot areas (lateral, medial, rearfoot, midfoot and forefoot). Furthermore, analyses of covariance (ANCOVAs) were applied to compare bone geometry and strength variables between the two soccer groups and CG using weight and the length of the tibia as covariates. Bonferroni corrections were applied to control the Type II error of multiple comparisons.

Effect size statistics were reported as partial eta squared (η^2_p) for ANCOVAs. Taking into account cut-off points established by Hopkins et al.,[26] the effect size for η^2_p can be small, medium or large. Statistical significance was set at $p < .05$.

Results

Despite the different type of foot and stud design used, no proportion differences between soccer players with different type of foot ($\chi^2(2) = 0.770$, $p = .681$) and who wore different stud designs ($\chi^2(1) = 0.677$, $p = .411$) were found. Furthermore, no significant MP differences were found in any foot area when soccer players who had different foot type and those who wore different stud designs were compared (Supplementary Table I and II).

No descriptive differences were found between SOC-HP, SOC-LP and CG ($p > .05$; Table I). In contrast, SOC-HP showed higher MP at the lateral foot, medial foot, rearfoot and forefoot compared to SOC-LP ($p < .05$; Table I). Additionally, when MP comparisons between SOC-HP and SOC-LP were adjusted by weight, similar results were found (Supplementary Table III).

Table II shows the adjusted pQCT values of SOC-HP, SOC-LP and CG and the statistics of the comparisons between these groups. Tt.BMC, Ct.BMC and Ct.Ar were significantly greater in SOC-HP compared to CG (mean differences were 9.1, 9.8 and 10.4 %; $p < .05$; Table II). SOC-LP did not show significant differences in any of the pQCT variables compared to SOC-HP and controls ($p > .05$; Table II).

Discussion

The present study shows that adolescent soccer players with higher plantar pressures present enhanced Tt.BMC, Ct.BMC and Tt.Ar when compared to CG. On the other hand, no plantar pressures differences were found between those soccer players who wore different stud designs and had different foot types. This lack of differences could be explained by the fact that plantar pressures values were measured for the whole circuit instead of for each task separately. Moreover, this circuit consisted of diverse soccer actions such as jumps, zigzag run or changes of direction and, as Eils et al.[15] demonstrated, each soccer-specific action mainly loads a different foot area. Therefore, after calculating the mean of all tasks, the possible differences between foot types could disappear.

The results obtained in the present study also demonstrated significant MP differences between the two soccer groups with different plantar pressures. These differences might be explained by the fact that those players with high plantar pressures had the ability to perform soccer specific actions at high intensity. On the other hand, a study which evaluated the distribution of different plantar pressures during soccer-specific tasks, suggested to consider player positions when plantar pressures during different soccer-specific actions are evaluated.[15] Concretely, in the present study, to reduce the possible influence of playing position and also skill level of participants on plantar pressures, soccer players were instructed to perform two sub-maximal familiarization trials of the circuit and, afterwards, to execute other two trials at maximum speed.

Although a positive association between high plantar pressures and all bone geometry variables except Tt.Ar has been elucidated, the findings related to bone strength indexes could be slightly mediated by bone growth. Cortical bone and bone strength parameters regularly increase until the age of 14 years in males and, afterward, these parameters abruptly increase.[27] As only three SOC-LP had just achieved this age, future studies including a sample of soccer players older than 14 years could help to clarify if these bone differences between soccer players with different plantar pressures and CG can be observed in later ages.

The main response of bone to physical exercise in both male prepubertal or pubertal athletes is periosteal apposition increasing, at the same time, bone area, Ct.Th and bending and torsional forces.[28] In the present study, when SOC-LP were compared to SOC-HP and CG, no bone differences at any bone geometry and strength parameters were found. The lack of differences between soccer groups could be explained by the fact that both groups did similar soccer exercises, and probably, had comparable enhancements of the bone. Therefore, both groups might have benefited from the effects of soccer practice on bone. On the other hand, the absence of significant differences in most of bone variables between soccer players and controls could be due to the early maturity status of all participants included in the present study. The effects of soccer practice on bone could be observed more clearly in the following years when the peak of bone accretion is reached.[2]

As Frost explained,[29] high intensity strains (i.e. soccer actions) increase bone remodeling activity resulting in bone adaptations to loads. Additionally, the intensity of these strains may provoke different bone adaptations.[29] For instance, a study performed with young soccer players[30] showed higher bone parameters at their non-dominant lower limb compared to their dominant one. In terms of soccer practice, the non-dominant lower limb supports each action performed by dominant one (skilled lower limb), meaning that mechanical strains received by each lower limb are different (higher in non-dominant lower limb). The present study shows that only soccer players receiving higher mechanical strains have higher Tt.BMC, Ct.BMC and Ct.Ar. compared to controls which is in agreement with the mechanostat theory and previous studies developed in soccer players.[29, 30]

The main limitation of the present study is that the sample size of young soccer players is small and, therefore, the power of this study is reduced. Another limitation is that MP were measured for the whole circuit instead of being measured for each task separately. Furthermore, the validity and reliability for determining MP could not be calculated because only the trial with the highest plantar pressures was saved.

Conclusions

In summary, the present study shows that adolescent soccer players with higher plantar pressures have better Tt.BMC, Ct.BMC and Ct.Ar than controls; nevertheless, those players with lower plantar pressures do not show differences in bone geometry and strength compared to those with high plantar pressures and controls. Overall, mechanical loading produced by soccer-specific actions increases bone development; nevertheless, performing soccer actions at high intensity might increase the stimulus on bone and, at the same time, provide an extra gain of bone geometry. Thus, an increment of the intensity of soccer trainings could also increase the intensity of soccer actions during matches and, at the same time, bone health of soccer players.

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NOTES

Conflicts of interest. The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors' contributions. JAC designed the study. GLB, AML, AGB, VAS and AGA performed experiments. GLB, AML, AGA and JAC analysed the data. GLB, AML, AGB, VAS, AGA, GVR and JAC wrote the paper. All authors approved the manuscript.

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Table I. Descriptive characteristics and maximum values of the average pressure of soccer players with low and high plantar pressures and controls.

	SOC-HP (n = 15)	SOC-LP (n = 25)	CG (n = 13)
Descriptive characteristics			
Age (y)	13.1 ± 0.4	13.3 ± 0.5	13.1 ± 0.9
Weight (kg)	49.0 ± 9.9	46.4 ± 11.6	49.5 ± 9.8
Height (cm)	157.9 ± 9.0	155.5 ± 8.6	156.2 ± 6.2
BMI (kg·m^{-2})	19.6 ± 3.3	19.0 ± 3.1	20.2 ± 2.9
Tibia length (mm)	361 ± 22	351 ± 21	355 ± 23
Muscle CSA (mm^2)	5692 ± 835	5370 ± 1100	5348 ± 1256
Fat CSA (mm^2)	2123 ± 1057	1870 ± 721	2518 ± 726
Daily calcium intake (mg)	731.4 ± 211.5	787.9 ± 374.2	991.0 ± 543.1
Maturity offset (y)	-0.5 ± 0.6	-0.5 ± 0.5	-0.6 ± 0.7
Age PHV (y)	13.6 ± 0.4	13.8 ± 0.4	13.7 ± 0.3
Training years (y)	6 ± 2	5 ± 2	-
Training hours (h/week)	4.0 ± 1.6	3.1 ± 1.2	-
MP (kPa)			
Lateral	330.6 ± 185.1	207.6 ± 78.8*	-
Medial	420.1 ± 79.3	245.2 ± 55.2*	-
Rearfoot	612.5 ± 191.5	427.3 ± 148.9*	-
Midfoot	224.2 ± 203.9	187.2 ± 133.2	-
Forefoot	375.9 ± 83.2	237.6 ± 70.0*	-

Values are mean ± SD.

SOC-HP: soccer players with high maximum values of the average pressure; SOC-LP: soccer players with low maximum values of the average pressure; CG: controls; BMI: body mass index; CSA: cross sectional area; PHV: peak height velocity; MP: maximum value of the average pressure.

* significant differences between soccer groups.

Table II. Adjusted pQCT values of soccer players with low and high plantar pressures and controls.

	SOC-HP (n = 15)	SOC-LP (n = 25)	CG (n = 13)	Test statistic
Bone geometry				
Tt.BMC (g)	3.22 ± 0.28*	3.05 ± 0.28	2.95 ± 0.28	$F(2,48) = 3.3$, $p = .044$, $\eta^2_p = 0.12$
Ct.BMC (g)	2.95 ± 0.26*	2.77 ± 0.26	2.68 ± 0.26	$F(2,48) = 3.8$, $p = .030$, $\eta^2_p = 0.14$
Tt.Ar (mm^2)	398 ± 35	388 ± 35	369 ± 35	$F(2,48) = 2.4$, $p = .097$, $\eta^2_p = 0.09$
Ct.Ar (mm^2)	280 ± 27*	266 ± 27	253 ± 27	$F(2,48) = 3.4$, $p = .043$, $\eta^2_p = 0.12$
Bone strength				
Ct.Th (mm)	5.12 ± 0.43	4.88 ± 0.43	4.77 ± 0.43	$F(2,48) = 2.4$, $p = .098$, $\eta^2_p = 0.09$
Frc.LdX (N)	3233.3 ± 428.6	3041.8 ± 426.1	3015.1 ± 424.9	$F(2,48) = 1.2$, $p = .315$, $\eta^2_p = 0.05$
SSIp (mm^3)	1445.8 ± 181.8	1362.7 ± 180.8	1292.3 ± 180.2	$F(2,48) = 2.5$, $p = .092$, $\eta^2_p = 0.10$

Values are mean ± SD. pQCT variables adjusted by weight and tibia length.

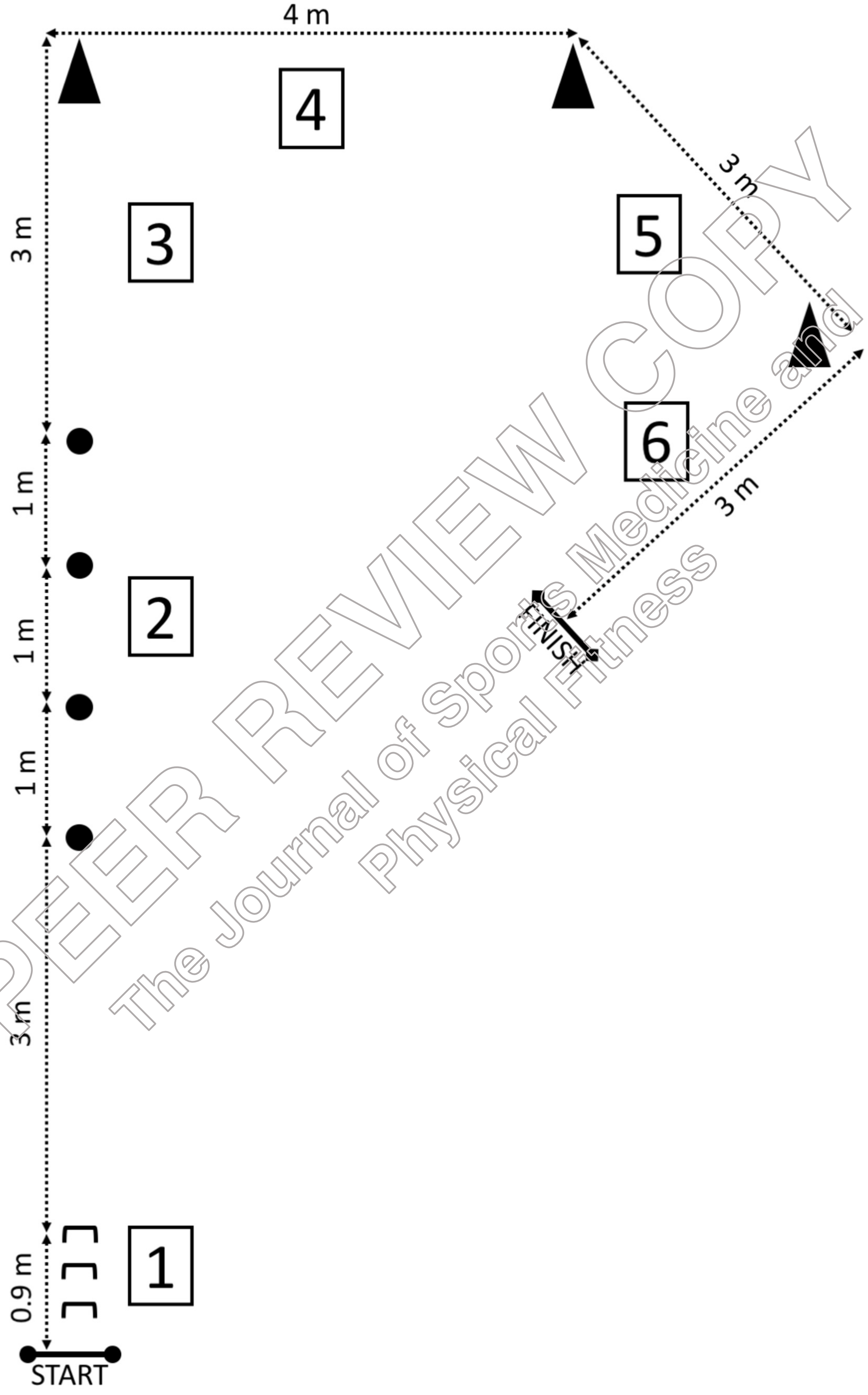
SOC-HP: soccer players with high maximum values of the average pressure; SOC-LP: soccer players with low maximum values of the average pressure; CG: controls; pQCT: peripheral quantitative computed tomography; Tt.BMC: total volumetric bone mineral content; Tt.Ar: total cross sectional area; Ct.BMC: cortical volumetric bone mineral content; Ct.Ar: cortical cross sectional area; Ct.Th: cortical thickness; Frc.LdX: fracture load in axe X; SSIp: strength strain index in polar; η^2_p: partial eta squared.

*: $p < .05$ differences between SOC-HP and CON.

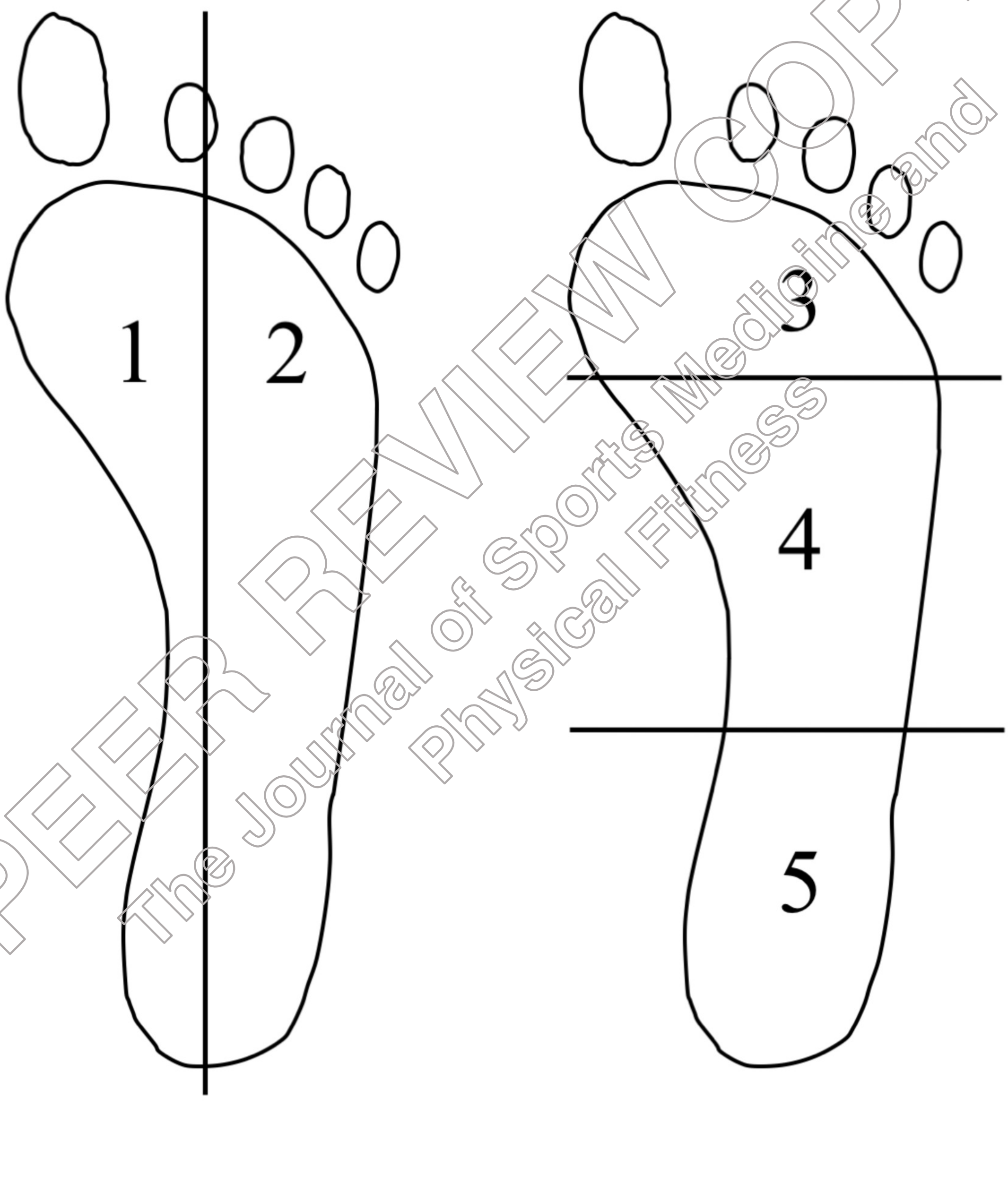
TITLES OF FIGURES

Figure 1. Experimental setup. Black circles represent slalom poles and black triangles represent soccer cones. 1) three two-footed jumps of 30-cm hurdles, 2) a zigzag run around four slalom poles, 3) a three-m sprint, 4) a lateral shuffle, 5-6) two three-m sprints separated by a 90º cut.

Figure 2. Foot areas for plantar pressure analysis. Area 1 represents medial foot, area 2 represents lateral foot, area 3 represents forefoot, area 4 represents midfoot and area 5 represents rearfoot.



4 m
4
3 m
3
5
3 m
6
3 m
FINISH
1 m
2
1 m
1 m
3 m
1
0.9 m
START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