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ORIGINAL PAPER

Knee alignment in adolescents is correlated with participation in weight-bearing sports

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Abstract

Purpose Weight-bearing sports might influence the alignment of the lower extremities during growth. The relationship between participation in weight-bearing sports and the alignment of the lower extremities in adolescents has not been adequately studied yet. The aim of the study was to investigate whether sports participation during growth in early adolescence is correlated with the development of genu varum.

Methods The design was a correlation study in which 1008 (564 boys, 444 girls) healthy adolescents (from 12 to 19 years of age) were recruited in secondary schools. The alignment of the knee was determined by measuring the intercondylar (IC) and intermalleolar (IM) distance using a specially designed instrument and an inside calliper. The degree of sports participation of the participants was determined by a questionnaire in which they were asked how many hours a week they participated in sports and for how many years in total.

Results The results of this study revealed a significant correlation between participation in weight-bearing sports and genu varum in each of three different age groups, both for boys and girls.

Conclusion Our results show that there is an association between the alignment of the knee joint and participation in weight-bearing sports during early adolescence.

Keywords Alignment · Varus · Knee · Weight-bearing · Sports · Adolescents

Introduction

Children with genu varum and genu valgum are regularly seen in the paediatric orthopaedic practice. For a proper approach to this issue, accurate knowledge of the normal limits of the tibiofemoral angle is needed. Multiple studies have demonstrated the evolution of the alignment of the knee in young children [1, 2]. Yet little is known about this evolution at the end of growth and about the factors contributing to this evolution.

Recent studies suggest a link between the participation in soccer and certain other impact sports on the development of genu varum. Witvrouw et al. compared the degree of varus in a group of male soccer players with a group of male non-soccer players who were all active in other sports [3]. At the age of 16–18 years, a significantly higher degree of genu varum was observed in the soccer players compared to the non-soccer players ($p = 0.028$). Another study by Bellemans et al. revealed that a percentage of the normal population has constitutional varus knees. Constitutional varus was associated with increased sports activity during growth [4].

In weight-bearing sports, the knee joint endures an excessive amount of load. The medial compartment of the knee joint has been reported to bear approximately 75% of its compressive loads in the neutrally aligned knee [5]. Yet minor alterations in knee alignment have been shown to result in abnormal load distribution across the joint. An increase of 4–6% in varus alignment has been reported to increase loading in the medial compartment by up to 20% [6]. This change

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towards a medial overload is an important predisposing factor for osteoarthritis [7]. Not only do people with varus alignment suffer a twofold increased risk of developing osteoarthritis [8] but the disease also progresses more rapidly in these subjects [6, 9]. Besides the development of osteoarthritis of the knee, the presence of genu varum predisposes sportsmen to injuries at the patellofemoral joint, such as patellofemoral pain syndrome [10].

Since this concept of constitutional varus has only been introduced, there is a growing need to understand the factors that contribute to the development of genu varum [4, 11], even more so because genu varum also leads to and accelerates the progression of osteoarthritis [6, 8]. We therefore investigated the occurrence of genu varum in young adolescents and its relationship with sports participation. Our hypothesis was that participation in weight-bearing sports during growth alters the alignment of the knee towards varum.

Material and methods

Subjects

One thousand eight young healthy children between 12 and 19 years of age were recruited for this cross-sectional correlation study. Only healthy volunteers with no orthopaedic or trauma history could participate. We excluded subjects who had been treated or seen for a musculoskeletal condition or trauma and/or had been seen by a specialist. All participants were recruited as volunteers at three different schools. All volunteers consented to participate in the study, which was approved by the ethical commission of our institution before the first inclusion.

Included were 564 male and 444 female volunteers. The volunteers were first divided into two groups by gender. Then these groups were further split into three age groups: group 1 (12–13 years of age), group 2 (14–15 years of age) and group 3 (16–18 years of age). Participant's demographic data are presented in Table 1.

Measurement of leg alignment

All participants were weighted in kilogrammes (kg), and their height was measured in centimetres (cm). From these measurements, the body mass index (BMI) was calculated.

The alignment of the knee was determined by measuring the intercondylar (IC) and intermalleolar (IM) distance. The subject was asked to stand in an anatomic position with the hips and knees in maximal extension with the medial condyles or malleoli touching as it has been described before [1].

To have the subjects stand in a normal relaxed position, we used a specially designed instrument, first described by Witvrouw et al. [3]. The subjects were asked to assume a relaxed standing position, with their feet at shoulder width, each foot on a different platform. They were asked to position their feet as such that the medial border of the feet was above the inner border of the platform. Then a motor was used to bring the two platforms together at a constant low speed until the medial condyles or malleoli touched [3] (Fig. 1). The position of the patella facing forward was critically checked, as was done by authors who have studied lower leg alignment [5, 12]. This was done to control the rotational position of the lower extremity, since this might influence the outcome of the measurement [12, 13]. Eventually, the intercondylar distance (mm) in subjects with genu varum was measured with an inside calliper with the medial malleoli touching using the method described by Heath et al. [14]. The intermalleolar distance (mm) in subjects with genu valgum was measured with an inside calliper with the medial condyles touching. Intercondylar distances were expressed as positive values and intermalleolar distances were expressed as negative values. Both measurements were combined into one parameter: the IC/IM distance [2]. When a subject was positioned in a correct way, but neither the two malleoli nor the condyles

Table 1 Demographic data of the studied population

	N	Age (years) mean (SD)	Height (cm) mean (SD)	Weight (kg) mean (SD)	BMI (kg/m^2) mean (SD)	IC/IM (mm) mean (SD)
Total	1008	15.45 (1.69)	169.21 (9.99)	56.94 (10.62)	19.75 (2.45)	14.40 (22.30)
Boys	564	15.34 (1.69)	172.28 (10.75)	58.98 (11.73)	19.69 (2.52)	15.92 (21.98)
Girls	444	15.54 (1.57)	165.25 (7.22)	54.30 (8.32)	19.82 (2.37)	12.34 (22.56)
Group 1 boys	167	13.27 (0.40)	162.01 (9.03)	47.50 (7.57)	18.02 (0.15)	0.02 (19.25)
Group 1 girls	91	13.26 (0.59)	161.16 (6.83)	48.29 (7.53)	18.55 (2.41)	5.62 (20.68)
Group 2 boys	164	14.93 (0.60)	172.21 (8.81)	59.32 (9.99)	19.93 (2.75)	15.15 (18.18)
Group 2 girls	153	15.08 (0.67)	165.22 (7.51)	53.59 (7.32)	19.58 (2.05)	15.54 (22.37)
Group 3 boys	233	17.03 (0.,69)	179.39 (6.53)	66.70 (8.38)	20.68 (2.05)	27.41 (19.06)
Group 3 girls	200	16.93 (0.64)	167.22 (6.27)	57.63 (7.68)	20.58 (2.31)	13.02 (22.96)

IC intercondylar, *IM* intermalleolar

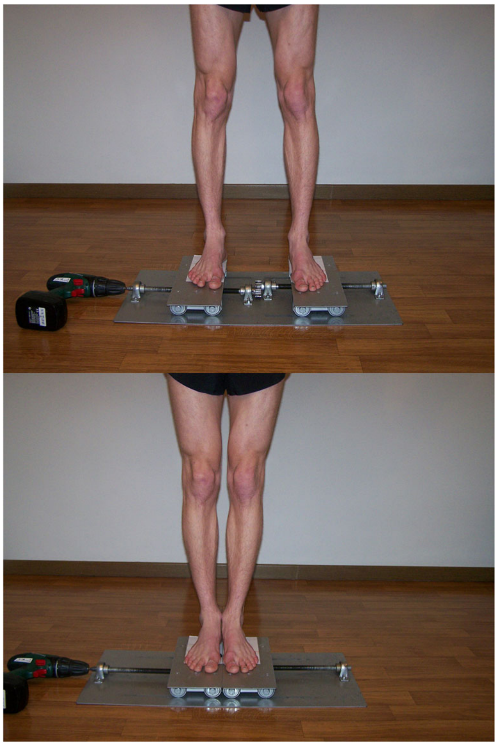

Fig. 1 Positioning of the subject on the measurement apparatus

touched, the bony intercondylar and intermalleolar distance was measured. When they had genu varum, half of the IM measurement was subtracted from the IC measurement. This value was then considered as the absolute IC/IM distance. When they had genu valgum, twice the IC measurement was subtracted from the IM measurement. This value was then considered as the absolute IC/IM distance. All IC/IM distances from all subjects were measured by the same examiner. The inter-tester reliability (ICC = 0.95) and the intra-tester reliability (ICC = 0.96) for the used technique of measuring IC/IM had a high interclass correlation coefficient [3].

Questionnaire

All participants were asked to fill in a questionnaire. They were asked about the date of birth, their sports participation, for how many years they had done so and for how many hours a week on average. They also answered the question whether they had already consulted a doctor in musculoskeletal injuries. They were not informed about the purpose of the study before the measurements were done and the questionnaire was filled in.

The degree of participation in sports

For every sport the subjects participated in, we calculated the product of the number of years and the average number of hours a week. We then added the products for all impact/weight-bearing sports (e.g. tennis, basketball, volleyball, athletics). We defined the result as 'the cumulative sports factor' and calculated it for every participant in the study in order to describe the cumulative load of impact sports. A similar approach has been described before by Asadi et al. [15].

Statistical analysis

Properties of the different groups are presented as mean and standard deviation. Graphs present the relation between height, IC/IM and age.

Within the group of boys and the group of girls, a one-way analysis of variance was performed to analyse the differences among the three age groups separately. Post hoc tests were performed using the least significant difference test. For each age group, the differences between the data of boys and girls were analysed using analyses of variance. Spearman's rank correlation coefficients between IC/IM, cumulative sports factor and BMI were calculated. Scatter plots were used to present the IC/IM in function of the cumulative sports factor on both the male and female subjects, separately for each group.

For this statistical analysis, *SPSS statistics 18* (SPSS Inc. Released 2009. PASW Statistics for Windows, Version 18.0. Chicago: SPSS Inc.) was used. Statistical significance was accepted at the level of $P < 0.05$.

Linear models are used for data analysis with IC/IM score as the response variable. A possible nonlinear shape of the association between two continuous measures (e.g., IC/IM score and cumulative sports factor) is explored using both quadratic effects and restricted cubic splines with 4 and 5 knots. Likelihood ratio tests are used for the comparison linear and nonlinear trends. The R^2 measure is used to compare the relative importance of different sports/cumulative sports factors in the explanation of the association between the cumulative sports factor and IC/IM. All these analyses have been performed using *SAS software version 9.2* (SAS Institute Inc. 2002. SAS System for Windows, Version 9.2. Cary: SAS Institute Inc.).

Results

The general demographic statistics of the participants are represented in Table 1. The Spearman's rank correlation coefficients between IC/IM and cumulative sport factor and between IC/IM and BMI are presented in Table 2. There is a significant correlation between IC/IM and the cumulative sport factor. This correlation is greater for girls and increases with age. In addition, a significant correlation between IC/IM and BMI in group 3 of the boys and group 2 and 3 of the girls is found.

The height and IC/IM distance are presented in relation to age in Figs. 2 and 3. We remark an increase in IC/IM in both

Table 2 Spearman's rank correlation (rho) between IC/IM and cumulative sports factor and BMI

	Cumulative sports factor Spearman (rho)	*p* value	BMI Spearman (rho)	*p* value
Group 1 boys	0.158	0.044	− 0.105	0.186
Group 2 boys	0.305	< 0.0001	− 0.098	0.213
Group 3 boys	0.344	< 0.0000001	− 0.133	0.043
Group 1 girls	0.252	0.018	− 0.069	0.525
Group 2 girls	0.353	< 0.0000001	− 0.210	0.009
Group 3 girls	0.464	< 0.000000001	− 0.267	0.0001

boys and girls. This increase of IC/IM in girls stagnates around the age of 15 years with a mean of 15.15 mm. The increase of IC/IM in boys stops around the age of 17 years with a mean of 30.3 mm. A similar evolution is observed regarding height in function of age, in both boys and girls. The one-way analysis of variance between the IC/IM of girls at the age of 15 showed no difference with the IC/IM of girls older than 15 ($F = 2.084$, $p = 0.15$).

Figure 4 shows a boxplot of the IC/IM distance in boys and girls, and Fig. 5 shows a boxplot of the cumulative sports factor in boys and girls. One-way analysis of variance was used to determine whether IC/IM differed between the age groups in boys and girls. The analysis showed significant differences between the age groups in boys ($F = 101.39$, $p < 0.0000001$) and girls ($F = 6.334$, $p = 0.002$). Post hoc Scheffé tests showed that the differences between all age groups in boys were significant. Post hoc Scheffé tests showed that in the girls, group 1 was statistically significantly different from group 2 ($p = 0.002$) and group 3 ($p = 0.021$). Yet the difference between group 2 and group 3 was not statistically significant ($p = 0.594$). Analysis of variance within the age groups between boys and girls showed a statistically significant difference between boys and girls in age group 1 ($F = 4.581$, $p = 0.033$) and age group 3 ($F = 50.761$, $p < 0.0000001$). In age group 2, no significant difference between boys and girls ($F = 0.030$, $p = 0.862$) was found.

Univariate relationships were explored between patient characteristics and the cumulative sports factor with the IC/IM. Quadratic effects of age, BMI and weight were observed. Length of a person is positively associated with IC/IM score. Further, we found higher IC/IM scores for males compared to females. Regarding impact sports, a quadratic association between cumulative sports factor and IC/IM score was found. We analysed the association between cumulative sports factor and IC/IM using a statistical model. This model includes an interaction term between sex and cumulative sports factor and corrects for age, sex and BMI. The quadratic trend observed in the univariable analysis between the cumulative sports factor and IC/IM is maintained after correction for age, sex and BMI. A significant interaction is observed between sex and cumulative sports factor: the association between cumulative sports factor and IC/IM is different for males and females. The model predicted trend by sex for age groups 1, 2 and 3 are presented in Fig. 6.

We explored which sports in the total population accounted for the correlation between sports participation and trend towards varus alignment: Table 3 shows that (1) the selection of six sports (biggest weight-bearing sport groups) together explains almost as much of the variability as the cumulative sports factor of all sports and (2) there is not one single sport responsible for that. In Table 3b, we combined step by step the sports going from highest to lowest R^2. This is to find out

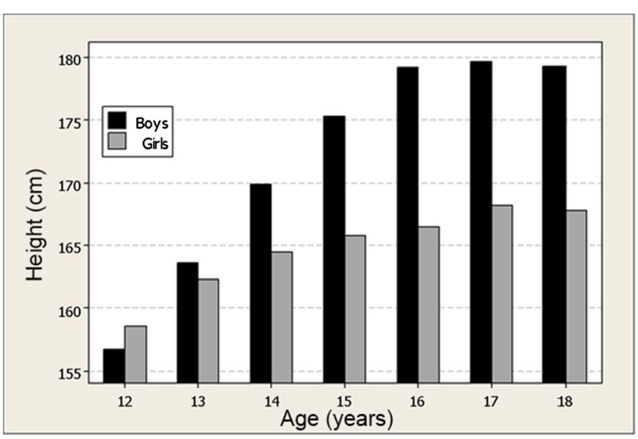

Fig. 2 Means of height in function of age for boys and girls

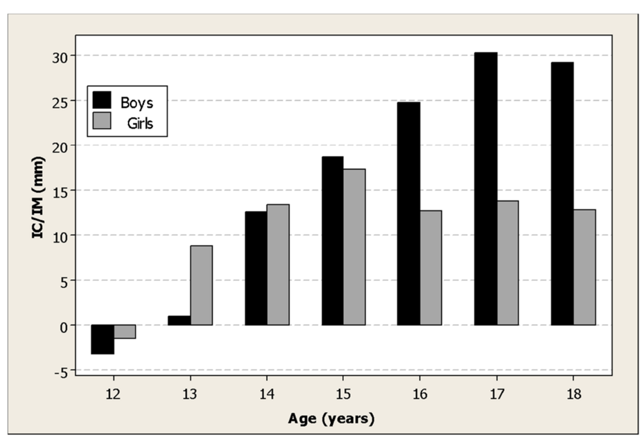

Fig. 3 Means of IC/IM in function of age for boys and girls

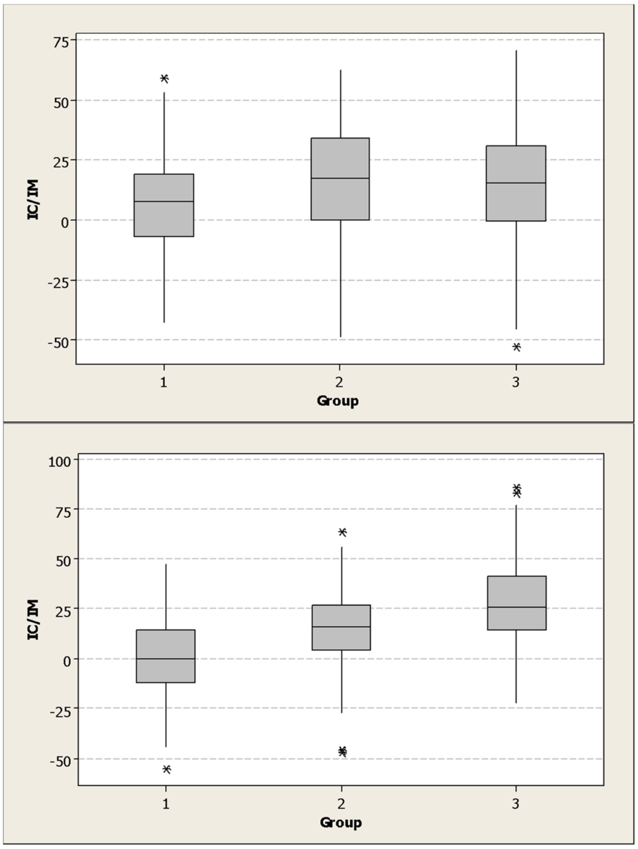

Fig. 4 Boxplots of the IC/IM distance in boys and girls by age groups

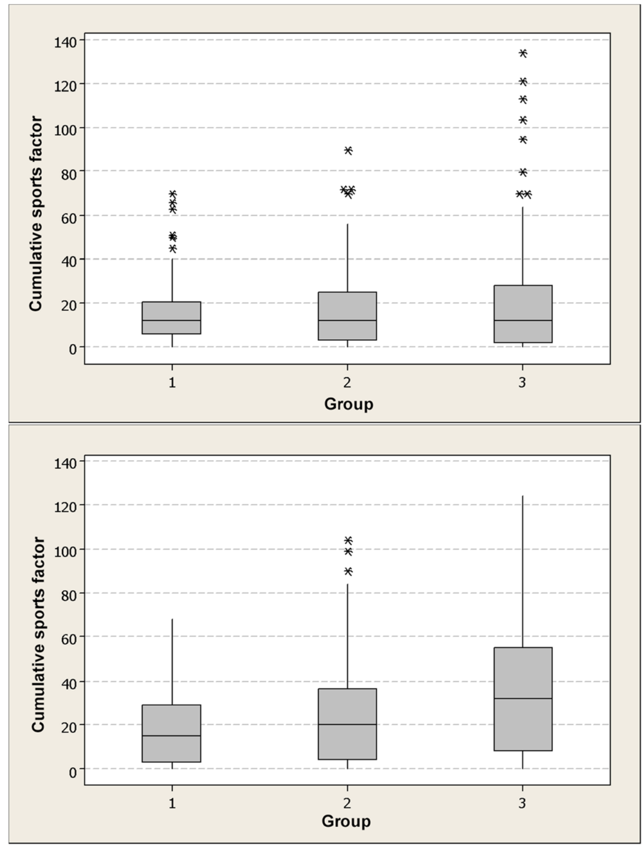

Fig. 5 Boxplots of the cumulative sports factor in boys and girls by age groups

whether there is a combination of a few sports that explain most variability. Overall, there is no combination of a few sports that explain the largest part of the variability, each sport makes a small contribution.

Furthermore, the strength of association between the six sports of interest separately and IC/IM is explored: a significant positive association between the cumulative sports factor and IC/IM is found for football, jogging and volleyball individually. For females, significant positive association is found for all six sports. A pairwise comparison between sports indicates significant difference in slope (strength of association) between football and volleyball, and basket and volleyball for males, with the strongest association between IC/IM and impact score for volleyball. For females, no significant differences are observed between the slopes for different sports (Table 4).

Discussion

This study demonstrates the correlation between participation in weight-bearing sports and evolution of knee alignment towards varum. This correlation is determined by a combination of all weight-bearing sports in the total population, with each sport making a small contribution. The degree of association between different weight-bearing sports differs and is further explored. Furthermore, our results show that the evolution towards varum alignment takes place during the growth spurt.

Millions of children around the world are encouraged to practice sports, since it is considered to improve general health. Yet little is known about the musculoskeletal consequences caused by this sports participation. Recent studies suggest that a relation exists between sports participation in adolescents and the development of varus knee alignment at the end of growth [3, 4]. There is a great need to further explore this relation, since varus alignment predisposes to the development of osteoarthritis and accelerates the progression of the disease [6, 8]. This statement was supported by the documentation of both a higher incidence of osteoarthritis of the knee and a higher prevalence of knee varus in veteran soccer players in comparison with a random population of the same age [12].

The degree in which the adolescents participated in weight-bearing sports was described by the cumulative sports factor. Since this factor was arrived at by calculating, for each weight-bearing sport, the product of the average number of hours a week and the number of years they participated in it, and then adding all these products, it gave us a good impression of sports participation.

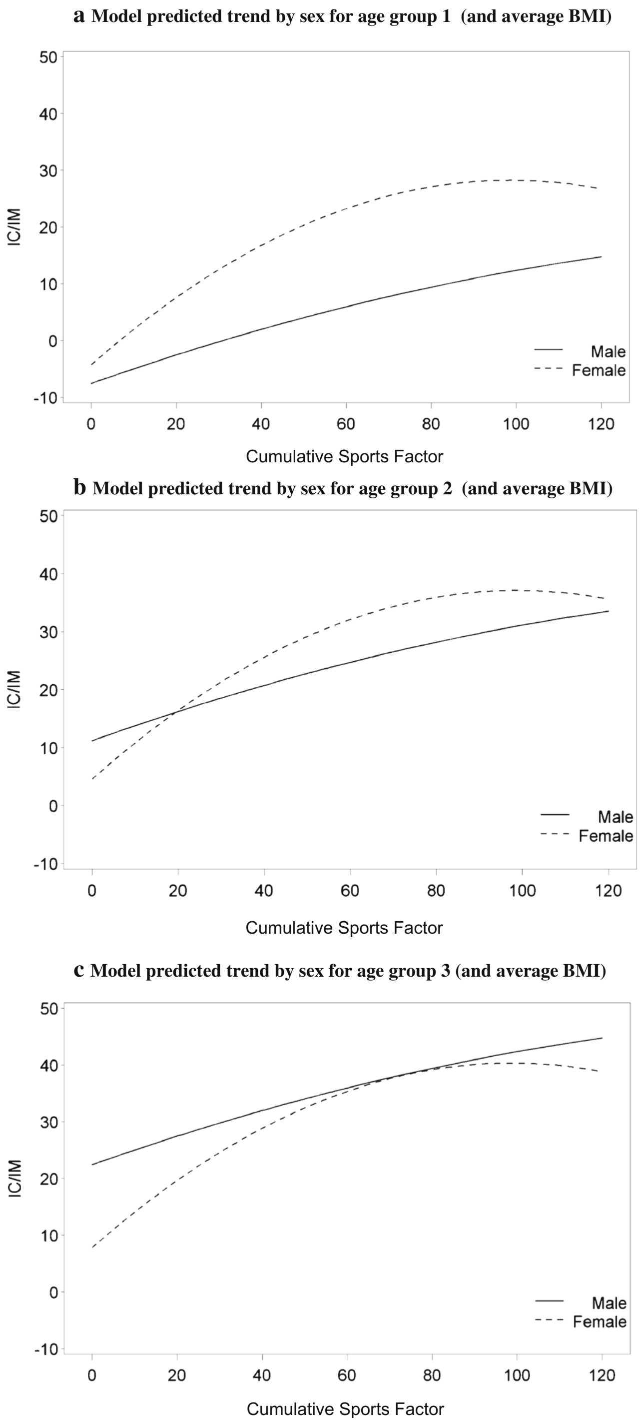

Fig. 6 **a** Model predicted trend by sex for age group 1 (and average BMI). **b** Model predicted trend by sex for age group 2 (and average BMI). **c** Model predicted trend by sex for age group 3 (and average BMI)

A significant correlation between the cumulative sports factor and varus alignment is seen in all the different groups (Table 2). This observation is in line with previous studies [3, 4]. We believe that the explanation for this correlation can be found in the Heuter-Volkmann law. It states that compression forces will halt physeal growth whilst distraction will lead to overgrowth [16]. Thus, growth changes at the tibial plateau could be the result of cumulative stress caused by weight-bearing sports. Since approximately 70% of the loads go through the medial compartment of the knee [5], a halt in growth is expected medially in subjects who participate excessively in weight-bearing sports. Evidence of the role that this mechanical overload plays in the development of genu varum and the connection with restricted physeal growth was presented in a previous study [17]. Previously, the external knee adduction moment, which correlates with increased load on the medial compartment relative to that of the lateral compartment [18], has been correlated with the mechanical axis of young normal subjects [19].

Table 3 Relative importance of different sports with respect to the cumulative sports score

Model	R^2
A	
Covariates only (age, sex, BMI)	0.227850
Cumulative sports factor	0.319394
All six sports	0.299037
Football	0.234610
Tennis	0.235118
Jogging	0.237140
Volley	0.246179
Basket	0.239154
Dance	0.233798
B	
Volley	0.246179
Volley + Basket	0.257928
Volley + Basket + Jogging	0.269460
Volley + Basket + Jogging + Tennis	0.276529
Volley + Basket + Jogging + Tennis + Voetbal	0.289167
Volley + Basket + Jogging + Tennis + Voetbal + Dance	0.300382

The R^2 indicates the percentage of the total variability that is explained by the model. This takes a value between 0 and 1, with higher values indicating stronger associations. The first model (covariates only) indicates the variance explained by age, sex and BMI. In the rest of the table, the cumulative sports factors of the different sports separately (in different forms; also the cumulative sports factor) are additionally included in the model

We saw an association between most of the six biggest sports separately and IC/IM distance: A significant positive association between the cumulative sports factor for each sport separately and IC/IM is found for football, jogging and volleyball. For females, significant positive association is found for all six sports. When evaluating differences in between those sports, only significant differences could be found between football, and volleyball and basket and volleyball for males, with the strongest association between IC/IM and impact score for volleyball. For females, no significant

Table 4 Table with slopes for different sports and by sex

Sport	Males Slope	Females Slope
Football	0.1522	0.4014
Tennis	0.1947	0.5328
Jogging	0.3138	0.4540
Volleyball	0.3718	0.5509
Dance	0.1190	0.3235
Basket	0.0982	0.3282

The slope indicates the change in IC/IM score with a one-unit increase of the cumulative sports factor

differences are observed between the slopes for different sports. This is most likely a result of low power. Although our total sample size is rather large, the number of subjects with cumulative sports factor scores larger than zero is not that big. Most likely there is a difference between the strength of association between the different sports and varus alignment. Our study is the first to suggest that volleyball participation correlates stronger with varus alignment than football does.

When looking at the total population of our study, which is a good sample of normal population of adolescents, no combination of a few sports accounts fully for the correlation between sports participation and trend towards varus alignment (Table 3). Each sport makes a small contribution to the correlation with varus alignment. This can be explained as our population participated in a large amount of different (weight-bearing) sports, which effect all comes together when calculating the cumulative sports factor for all those sports.

The results of this study show that there is a trend towards varus alignment from the age period of 12 to 14 years (Fig. 3) as seen in a previous study [13]. It is interesting to observe that the evolution in varus corresponds with the period of the growth spurt, this in both boys and girls (Figs. 2 and 3). We can see that when growth slows down, the trend to genu varum takes halt too.

We found no statistically significant difference in IC/IM between age group 2 and age group 3 in girls, whilst there was between groups 2 and 3 of the boys. The largest difference in IC/IM between both sexes is seen from the age period of 16–18 years. This difference between sexes is in accordance with previous studies [2, 13], whereas other studies state exactly the opposite [1, 20]. We believe a part of this difference can be explained by an earlier stagnation of the growth in girls compared to boys.

An alternative explanation for the correlation could be presented by considering it as a form of natural selection. It has previously been stated that soccer players with genu varum may be at an advantage when participating in soccer [21]. The player's bowlegs may increase the balance and stability during the game. This might also apply to athletes participating in other weight-bearing sports. In this way, more children with varus knees end up being athletes. Also, it has previously been stated that people with valgus knees can experience a disadvantage in sports [22]. They have an awkward gait with the knees rubbing together and the feet kept apart. They tire more easily and lag behind in physical activity. Additionally, the varus angulations in athletes can be genetically determined and might be a product of normal development rather than a result of training [12].

The negative correlation between IC/IM and BMI, mostly significant in girls, was not expected. This has not been described in other studies where clinical measurement of the alignment was performed. This can be explained by the relatively thick thighs of the heavier children, who give an overestimation of the IM distance. The higher negative correlation in the girls group can be explained by the higher amount of IM measurements in comparison with boys group.

With the negative consequences of genu varum in mind, we must ask ourselves what efforts can be made to reduce this evolution towards varus legs. We believe a reduction can be achieved by lowering the adduction moment of the knee, since it corresponds to increased load on the medial compartment [18]. In a recent study, gait retraining was evaluated for reducing the knee adduction moment and showed a reduction of knee adduction moment of 29 to 48% [23]. Another option would be a footwear intervention, since recent studies show that a shoe sole with a more rigid lateral side or a thicker lateral side reduces the peak adduction moment during walking by up to 16% [24, 25].

Some limitations of this study must be considered. Due to the cross-sectional design of our study, we cannot determine cause and effect relationships. As we described earlier, the relation between genu varum and high intensity of sports participation could be a form of natural selection, where athletes with varus legs have an advantage over athletes with valgus legs. This should be addressed in future prospective studies, where a large cohort of adolescents is followed through time. Another limitation is that our measurements of IC/IM using the specially designed measurement device had a negative correlation with BMI and may not be as exact as radiography. This can be explained by the effect of the thickness of the thighs, but further studies should investigate whether this is an effect of the measurement.

Conclusion

Our results show that there is a significant correlation between the alignment of the knee and participation in weight-bearing sports during adolescence. Overall, there is no combination of a few sports that explain the largest part of the correlation with varus alignment, with each sport making a small contribution. Future prospective research should address the cause/effect relationship, the biomechanical aetiology of this phenomenon and question whether prevention is useful.

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Compliance with ethical standards

Conflict of interest No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References

1. Cheng JC, Chan PS, Chiang SC, Hui PW (1991) Angular and rotational profile of the lower limb in 2,630 Chinese children. J Pediatr Orthop 11:154–161
2. Arazi M, Ogun TC, Memik R (2001) Normal development of the tibiofemoral angle in children: a clinical study of 590 normal subjects from 3 to 17 years of age. J Pediatr Orthop 21:264–267
3. Witvrouw E, Danneels L, Thijs Y et al (2009) Does soccer participation lead to genu varum? Knee Surg Sports Traumatol Arthrosc 17:422–427. https://doi.org/10.1007/s00167-008-0710-z
4. Bellemans J, Colyn W, Vandenneucker H, Victor J (2012) The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res 470:45–53. https://doi.org/10.1007/s11999-011-1936-5
5. Hsu RW, Himeno S, Coventry MB, Chao EY (1990) Normal axial alignment of the lower extremity and load-bearing distribution at the knee. Clin Orthop Relat Res 255:215–227
6. Tanamas S, Hanna FS, Cicuttini FM et al (2009) Does knee malalignment increase the risk of development and progression of knee osteoarthritis? A systematic review. Arthritis Rheum 61:459–467. https://doi.org/10.1002/art.24336
7. Bruns J, Volkmer M, Luessenhop S (1994) Pressure distribution in the knee joint. Influence of flexion with and without ligament dissection. Arch Orthop Trauma Surg 113:204–209
8. Brouwer GM, van Tol AW, Bergink AP et al (2007) Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis Rheum 56:1204–1211. https://doi.org/10.1002/art.22515
9. Sharma L, Song J, Dunlop D et al (2010) Varus and valgus alignment and incident and progressive knee osteoarthritis. Ann Rheum Dis 69:1940–1945. https://doi.org/10.1136/ard.2010.129742
10. Lun V, Meeuwisse WH, Stergiou P, Stefanyshyn D (2004) Relation between running injury and static lower limb alignment in recreational runners. Br J Sports Med 38:576–580. https://doi.org/10.1136/bjsm.2003.005488
11. Bellemans J (2011) Neutral mechanical alignment: a requirement for successful TKA: opposes. Orthopedics 34:e507–e509. https://doi.org/10.3928/01477447-20110714-41
12. Chantraine A (1985) Knee joint in soccer players: osteoarthritis and axis deviation. Med Sci Sports Exerc 17:434–439
13. Cahuzac JP, Vardon D, Sales de Gauzy J (1995) Development of the clinical tibiofemoral angle in normal adolescents. A study of 427 normal subjects from 10 to 16 years of age. J Bone Joint Surg Br 77:729–732
14. Heath CH, Staheli LT (1993) Normal limits of knee angle in white children—genu varum and genu valgum. J Pediatr Orthop 13:259–262
15. Asadi K, Mirbolook A, Heidarzadeh A et al (2015) Association of soccer and genu varum in adolescents. Trauma Mon 20:e17184. https://doi.org/10.5812/traumamon.17184
16. Eastwood DM, Sanghrajka AP (2011) Guided growth: recent advances in a deep-rooted concept. J Bone Joint Surg Br 93:12–18. https://doi.org/10.1302/0301-620X.93B1.25181
17. Cook SD, Lavernia CJ, Burke SW et al (1983) A biomechanical analysis of the etiology of tibia vara. J Pediatr Orthop 3:449–454
18. Zhao D, Banks SA, Mitchell KH et al (2007) Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. J Orthop Res 25:789–797. https://doi.org/10.1002/jor.20379
19. Andrews M, Noyes FR, Hewett TE, Andriacchi TP (1996) Lower limb alignment and foot angle are related to stance phase knee adduction in normal subjects: a critical analysis of the reliability of gait analysis data. J Orthop Res 14:289–295. https://doi.org/10.1002/jor.1100140218
20. Salenius P, Vankka E (1975) The development of the tibiofemoral angle in children. J Bone Joint Surg Am 57:259–261
21. Yaniv M, Becker T, Goldwirt M et al (2006) Prevalence of bowlegs among child and adolescent soccer players. Clin J Sport Med 16:392–396. https://doi.org/10.1097/01.jsm.0000244602.74460.e4
22. Howorth B (1971) Knock knees. With special reference to the stapling operation. Clin Orthop Relat Res 77:233–246
23. Shull PB, Lurie KL, Cutkosky MR, Besier TF (2011) Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback. J Biomech 44:1605–1609. https://doi.org/10.1016/j.jbiomech.2011.03.016
24. Fisher DS, Dyrby CO, Mundermann A et al (2007) In healthy subjects without knee osteoarthritis, the peak knee adduction moment influences the acute effect of shoe interventions designed to reduce medial compartment knee load. J Orthop Res 25:540–546. https://doi.org/10.1002/jor.20157
25. Hinman RS, Bennell KL (2009) Advances in insoles and shoes for knee osteoarthritis. Curr Opin Rheumatol 21:164–170. https://doi.org/10.1097/BOR.0b013e32832496c2