Association Between Patellar and Femoral Bone Morphology, Overweight Status, and Sports Participation in Early Adolescents

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ABSTRACT

Introduction: Early adolescence is a crucial stage of skeletal growth where mechanical loading applied by body mass and sports activity can affect morphology of patellofemoral joints. The difference in patella shape and the femur is deemed as pertinent to the biomechanics of the joint as well as the possibility of future susceptibility of a patellofemoral pain or instability.

Aim: To examine the relationship between patellar bone morphology, femur bone morphology and overweight status and sports engagement in young adolescents by mouse-computerized statistical shape models.

Methodology:In 312 adolescents aged 11-14 years, a cross-sectional study was carried out. The BMI was categorized based on age and sex percentiles. The level of participation in sports was measured using structured questionnaires. Three-dimensional statistical shape modeling was used to get the shape modes of the patellar and the femur based on an analysis of knee MRI scans. Associations were investigated using multivariable regression models which factored age, sex, pubertal status and ethnicity. The effects of interaction between BMI category and sports participation were also identified.

Results: Multiple patella and femoral shape modes were significantly linked to higher BMI, which implies an increased morphology variability with body mass. There were selective relations between sports participation and particular modes of shapes. The analyses of interaction implied additive effects, and morphology variance increased more in higher BMI cohorts irrespective of the status of sports participation.

Conclusion: Overweight status shows stable relationships with patellofemoral bone morphology in the early adolescent period, whereas sports participation is associated with more specific structural changes. These results emphasize the significance of putting into consideration body mass and mechanical loading in the development of adolescent musculoskeletal development...

Keywords: patellofemoral joint, adolescence, bone morphology, body mass index, overweight, sports participation, MRI, statistical shape modeling, knee development...

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INTRODUCTION

Patellofemoral pain (PFP) is a highly prevalent knee complaint in both active and sedentary populations and is particularly widespread in adolescence as neuromuscular control, maturing volume loads, and changing training loads become concurrent. The workings of international consensus has stressed the issue that PFP is commonly characterized by diffuse anterior knee pain which occurs as a result of a patellofemoral loading activity such as squatting, walking up and down stairs, running, and long periods of sitting, and the symptoms do not disappear, they continue in many people (1). Epidemiologic synthesis indicates adolescents have a significant burden and pooled point-prevalence rates are 7 percent in mixed-sex adolescent cohorts and an even greater prevalence has been described in adolescent female athletes, highlighting the importance of adolescent-specific mechanisms and exposures (2). The observation of longitudinality and clinical, also favor adolescence as a susceptible period where school-going populations have indicated that they have difficulty with previous activities and dropping out of a sport due to knee-related pains reported (3). Due to the growing importance of the clinical management practice to load modification and targeted exercise, there is a need to be more clear about upstream, potentially modifiable determinants of patellofemoral joint structure and function that arise in early adolescence (1,3).

The morphology of the patella and the femoral trochlea is one of the central structural determinants of patellofemoral mechanics. The geometry, height, and orientation of the patella in reference to the trochlear groove influences contact position, distribution of stress, whereas trochlear depth and structure impact on the containment and tracking of the patella. The original radiographic studies of patellar height, such as the InsallSauvati technique, have developed commonly used procedures of measuring the patella position, and patella alta, which has been associated with both changes in patella engagement in the trochlea and as a cause of instability (4). Having a well-characterized trochlear dysplasia at the femur is an established anatomic risk factor of recurrent instability of the patella; a range of historic radiographic studies has elaborated upon the anatomic characteristics linked with recurrent instability, and have established the basis of commonly used classifications (5). Recent studies of imaging have gone beyond uni-dimensional descriptions and emphasized that patellofemoral morphology is multi-dimensional, with patterns of patellar shape, trochlear curve, and joint congruence having the potential to affect both kinematics and symptoms (6). One particular instance of this multidimensionality in adolescents is that normal structure remains under development and that even minor deviations could have increased impacts in high loading conditions.

There is also active morphologic development of the patellofemoral joint in early adolescence. Normal MRI scans of pediatric knees have revealed that trochlear morphology variability changes as age advances and that the cartilage and subchondral bone shape may not align in maturity and therefore developing joint may have temporarily incongruent cartilage shape and subchondral bone shape (7). The normative pediatric MRI data show that a number of trochlear parameters change throughout the growth with evidence that final trochlear morphologic formation approaches stabilize at early adolescence in healthy growth (7). Serial MRI work used as a complement to their skeletally immature patients has also demonstrated that trochlear morphology is both developmentally variable and that development may take different pathways across the individuals with and without instability-related conditions (8). All these findings suggest that patellofemoral joints are not anatomically stable during childhood and the early adolescence, and encourage the conclusion that morphology is a potentially load-sensitive phenomenon, rather than just an underlying predetermination to it.

Ecologically realistic motivations of structural change during growth include mechanical loading. According to the mechanostat theory, the bone structure is increased to the habitual mechanical strain, and there are thresholds that put the bone to modeling and remodeling in order to get to an extent of strength capable of delivering the loads applied (9). Even in adolescence and pediatrics, empirical studies have indicated that bone geometry and strength indices are correlated with mechanical load and activity measures despite other factors (age, maturation and body size) (10). Literature comparing physical activity and bone acculturation in adolescents is more often associated with greater impact of higher-impact multi-stress-bearing activity, which promotes a favorable skeletal reaction whenever compared to low-impact exposure (11,12). This is a general law applicable to the knee: the patellofemoral joint is repetitively loaded in daily activities and sports and the geometry of the articular and subchondral bone might react to the history of cumulative loading in growth. Such adaptation, however, has a direction and clinical meaning, which are not easy to discern. Adaptation may be advantageous when it enhances congruence and evenly balances loads, or it may be disadvantageous when it supports shapes that are linked to an increase in contact stress, maltracking, instability, especially when loads are excessively heavy or not redistributed.

Overweight condition and sports are two key exposures that determine the loading in the patellofemoral during early adolescence. The term overweight and obesity is determined through age sex-specific reference of BMI to show normal growth patterns (13). Extra body mass is high in the amount of joint reaction forces of the weights that a person lifts in daily activities. Biomechanical research shows that the children with obesity have significantly higher contact forces upon the patella during walking in accurate magnitude and ratio to the area of the joint surface (14). This implies that high BMI can be one of the primary predictors of habitual stress throughout the patellofemoral joint during normal ambulation.

By comparison, sporting activity brings in repetitive high-load cycling by way of running, jumping, cutting, and deep knee bend. Although the regularity and severity of patellofemoral loading are augmented despite the logical sporting advantages that include significant cardiovascular and musculoskeletal advantages. These exposures might be interactive because adolescents having more BMI and playing high impact sports would be exposed to combined mechanical stress.

To investigate those relationships, imaging methods which can represent complex three-dimensional variation are required. Statistical shape modeling is a type of statistical technique used to measure the coordinated changes on whole bone surfaces and not individual measurements (15). MRI-based teenage research indicates that BMI is related to various patellar and femoral shape modes, but sports participation is selectively related (15). Additional longitudinal studies should be conducted to resolve the causal processes.

Methodology

Study Design and Setting

This research used cross-sectional analysis design to investigate the relationship between patellar and femur bone morphology, overweight conditions and participation in sports among early adolescents. The study was conducted in Faisal Chaudhary Hospital Lahore in May 2024 to May 2025. It was investigated on a population-based adolescent cohort basis so that proper variation of body mass index (BMI), physical activity exposure, and skeletal maturation were realized. The institutional review board gave ethical approval, and written informed consent was collected with permission given by all participants, especially the parents or guardians.

Participants

Those adolescents between the ages of 11-14 years were eligible. The behavioral period chosen was this age bracket because the age bracket is in the early puberty which is a stage of intense musculoskeletal growth and remodeling. People could not participate in the study in case of major preceding knee surgery history, congenital deformity of lower limbs, inflammatory joint disease, or global skeletal disorders. Demographic attributes were recorded; age, sex, and ethnicity. A standardized self-reported Tanner staging questionnaire was used to measure pubertal status in order to correct confounding that would occur because of maturation changes.

Assessment of Overweight Status

A calibrated digital scale was used to measure the weight of the body, and a stadiometer was mounted on a wall to measure the height. BMI (weight/height) was taken as the weight in kilos/height in meters squared (kg/m 2). The BMI percentile age and sex were established based on the established international percentiles of growth. The percentile cutoffs were used to categorize the participants as normal weight, overweight or obese. Along with pseudo-nominal classification, BMI was also under analysis as a continuous variable to sustain statistical sensitivity.

Sports Participation Assessment

A structured questionnaire was the instrument to measure sports participation by participants filled with the help of their parents and checked by them. Data gathered consisted of the type of sport, frequency (number of sessions a week), the length (hours per session), and years of experience. Sports were classified based on loading properties (e.g. high impact weight bearing sports versus weight activities of low impact). Mechanical loading patterns were assessed both in the short-term and the long-term by the calculation of both current participation and cumulative exposure.

MRI Acquisition and Morphological Analysis

The magnetic resonance imaging (MRI) of the knee predominantly used was conducted on the knee as a standardized procedure on a 1.5T or 3T system. Fine and sagittal sequences on high-resolution were acquired to enable proper segmentation of patella and distal femur. Semiautomatic segmentation software produced three dimensional surface reconstruction. The statistical shape modeling was used to measure independent modes of variance in patellar and femoral morphology. The individual scores of shape mode were given to each participant denoting the variation of the morphology of the population. Intraclass correlation coefficients were used in assessing inter- and intra-rater reliability of segmentation.

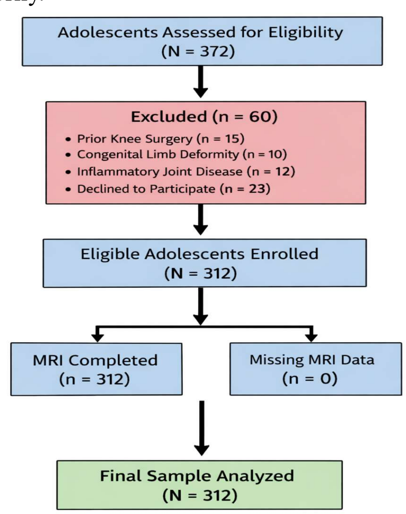
Statistical Analysis

Demographic, anthropometric, and activity variables were computed using the descriptive statistics. The multivariate linear regression model with shape mode scores as a dependent variable was used to determine the association between BMI, sports participation and bone morphology. When the bilateral knees were used, generalized estimating equations were used to consider any possible effects of clustering. Models were all age, sex and pubertal, ethnicity adjusted. The interaction terms of overweight condition and sport participation were examined in order to investigate the combined loading effect. The statistical significance value of 0.05 was used, and in cases where multiple comparisons were indicated, the correction was used.

Results

Participant Flow and Data Completeness

Figure 1 demonstrates the recruitment pathway and final analytic sample. Out of 372 teenagers screened to be eligible, 60 did not qualify because of the exclusionary criteria that comprised past surgery on the knee, congenital deformity, inflammatory joint disease, or non-consent. The rest of the 312 subjects were recruited and went through MRI evaluation, which made the total imaging data of all the recruited adolescents complete. The statistical modeling was robust and imputation procedures were not necessary because of the absence of missing MRI data. The sample size used was sufficient given that they varied sufficiently amongst the BMI types and different sports participation groups, and the multivariate regression was conducted satisfactorily.



Baseline Characteristics and Distribution of Overweight Status

Table 1 recounts the baseline demographic and anthropometric characteristics. The average age of the respondents was 12.6 years and this indicates early adolescents. There was an equal distribution of sex, which reduced the hazards of bias by variation of morphology according to sex. The mean BMI was 21.5 kg/m2, and the standard deviation was rather big and explained a high degree of inter-individual variation. Most subjects were in mid puberty stage and this fact is pertinent since puberty maturation affects skeletal growth and thus, this factor was factored as an adjustment variable in any given model.

Table 1. Baseline Demographic and Anthropometric Characteristics (N = 312)

Variable	Total Sample (N=312)	Males (n=156)	Females (n=156)
Age (years), mean ± SD	12.6 ± 0.9	12.5 ± 0.8	12.7 ± 0.9
Height (cm), mean ± SD	155.4 ± 9.8	157.8 ± 9.5	153.0 ± 9.6
Weight (kg), mean ± SD	52.3 ± 12.4	53.6 ± 13.1	51.0 ± 11.6
BMI (kg/m²), mean ± SD	21.5 ± 3.9	21.4 ± 4.1	21.6 ± 3.7
Pubertal Status (Tanner Stage ≥3), n (%)	201 (64.4%)	93 (59.6%)	108 (69.2%)
Ethnicity (Majority group), n (%)	248 (79.5%)	123 (78.8%)	125 (80.1%)

Table 2 shows the distribution of the BMI categories. About 63.5 percent of adolescents were normal weight with 23.1 percent being overweight and 13.5 percent obese. These fractions provided adequate representation of weight groups to be compared. Notably, the prevalence of both overweight and obesity did not differ significantly between men and women and thus it was not possible that sex imbalance would confound associations between BMI and bone morphology.

Table 2. Distribution of BMI Categories by Sex

BMI Category	Total (N=312)	Males (n=156)	Females (n=156)
Normal Weight	198 (63.5%)	101 (64.7%)	97 (62.2%)
Overweight	72 (23.1%)	34 (21.8%)	38 (24.4%)
Obese	42 (13.5%)	21 (13.5%)	21 (13.5%)

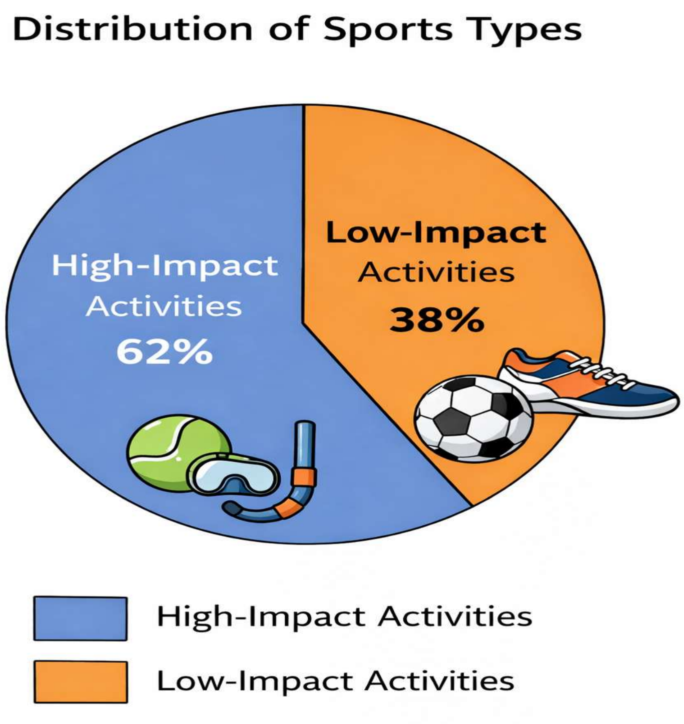
Sports Participation Profile

Table 3 describes the sports participation characteristics. Almost three quarters of the cohort said they were currently engaged in sports with high impact sports comprising the majority. The average frequency of attendance was 3.4 sessions per week with average session time of 1.6 hours which led to moderately cumulative weekly exposure. The occurrence of high and low impact sports is attractively represented in Figure 2. The high-impact nature of that indicates that a sizable percentage of participants have been subjected to repetitive load-bearing and dynamic loading patterns, which are also biomechanical to the stress of the patellofemoral joint.

Table 3. Sports Participation Characteristics

Variable	Value
Current Sports Participation, n (%)	229 (73.4%)
High-Impact Sports, n (%)	142 (45.5%)

Low-Impact Sports, n (%)	87 (27.9%)
Sessions per Week, mean ± SD	3.4 ± 1.2
Hours per Session, mean ± SD	1.6 ± 0.5
Years of Participation, mean ± SD	3.8 ± 1.9
Cumulative Exposure (hours/week), mean ± SD	5.4 ± 2.1



Descriptive Statistics of Patellar and Femoral Shape Modes

In a study that examined patellar morphology in a statistical shape modeling, there was a normally distributed score in shape mode and the scores were found to be centered around zero that was confirmed in Table 4. The variation ranges have gone up to about the ±2.8 standard deviations in some modes, which was significant heterogeneity in the patellar geometry. Femoral morphology was also distributed similarly as shown in Table 5 with standardized mode scores of various trochlear and distal femur structure and different subjects.

Table 4. Descriptive Statistics of Patellar Shape Mode Scores

Shape Mode	Mean ± SD	Range
Patella Mode 1	0.02 ± 1.01	-2.85 to 2.73
Patella Mode 2	-0.04 ± 0.98	-2.44 to 2.61
Patella Mode 3	0.01 ± 1.03	-2.67 to 2.91

Patella Mode 4	0.00 ± 0.95	-2.31 to 2.38
Patella Mode 5	-0.03 ± 0.99	-2.58 to 2.44

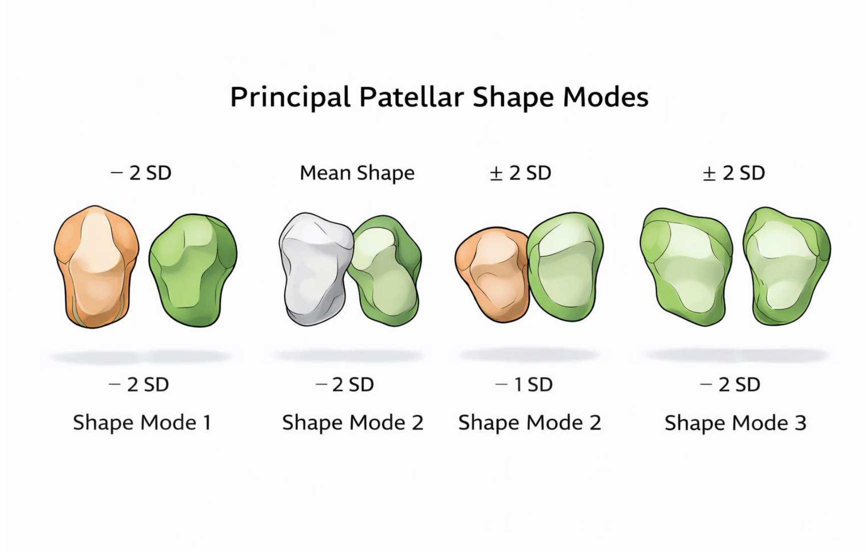


Figure 3. Visualization of Principal Patellar Shape Modes (Mean Shape and ±2 SD Variations)

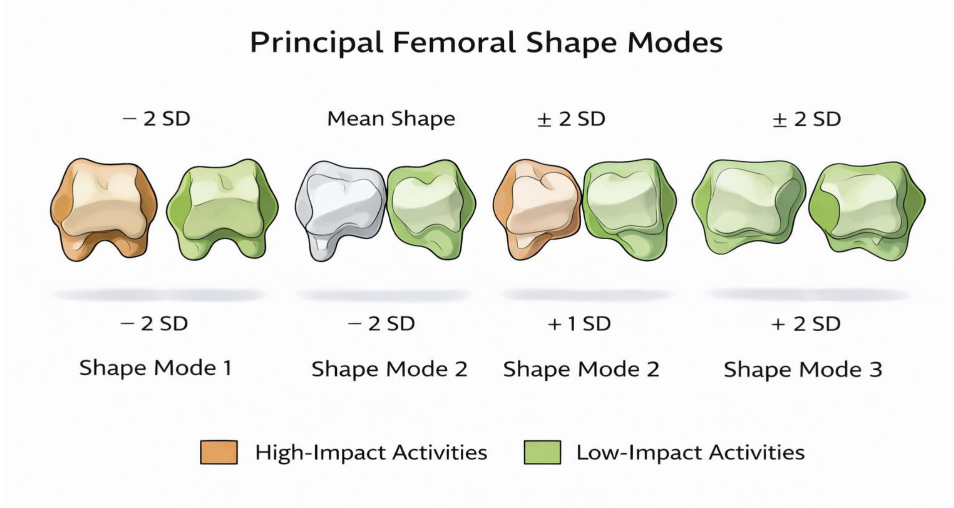


Figure 5. Forest Plot of Adjusted Associations Between BMI and Significant Shape Modes

The dominant patellar and femoral form modes are visually represented in figures 3 and 4, respectively. These values demonstrate mean forms, and variations of ±2 standard deviations, which show that the changes in morphology were systems of coordinated changes of bone surfaces, not solitary bone structural modifications. The three-dimensional reconstructions highlight the sophistication of morphological variation represented by the modeling method.

Association Between BMI and Patellar Morphology

Multivariate regression models involving continuous variables of BMI showed statistically significant positive correlation with patella Shape Modes 1, 3, and 5 (Table 6). Every 1kg/M 2 rise in BMI was associated with standardized shape mode scores increment. The second and fourth modes were not significant. These results suggest that the variation of the geometrical aspects of the patella is related to increased BMI in the youth at early adolescent stages. Although the effect sizes are small as individual units (based on BMI) are concerned, they become clinically significant in view of the entire range of the BMI values observed among the cohort.

Table 5. Descriptive Statistics of Femoral Shape Mode Scores

Shape Mode	Mean ± SD	Range
Femur Mode 1	-0.01 ± 1.02	-2.76 to 2.88
Femur Mode 2	0.03 ± 0.97	-2.42 to 2.55
Femur Mode 3	-0.02 ± 1.04	-2.93 to 2.70
Femur Mode 4	0.00 ± 0.99	-2.48 to 2.63
Femur Mode 5	0.01 ± 0.96	-2.37 to 2.29

Table 6. Multivariable Regression: BMI (Continuous) and Patellar Shape Modes
(Adjusted for age, sex, pubertal status, ethnicity)

Shape Mode	β (per 1 kg/m² BMI)	95% CI	p-value
Patella Mode 1	0.082	0.045 to 0.119	<0.001
Patella Mode 2	0.031	-0.006 to 0.067	0.099
Patella Mode 3	0.074	0.038 to 0.110	<0.001
Patella Mode 4	0.018	-0.015 to 0.051	0.287
Patella Mode 5	0.063	0.026 to 0.100	0.001

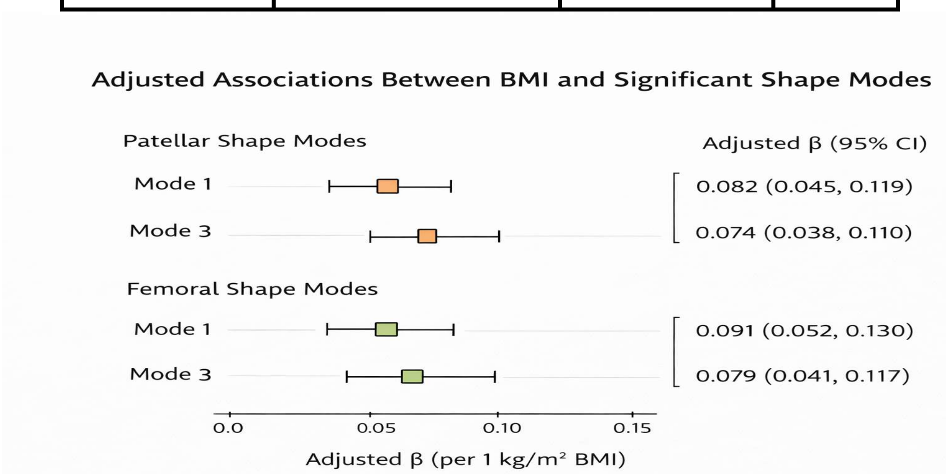


Figure 5. Forest Plot of Adjusted Associations Between BMI and Significant Shape Modes

Figure 5 condenses adjusted correlations between BMI and important patellar and femoral shape modes in a forest figure. Significant patellar mode confidence intervals never crossed zero, so it is clear that associations were robust even after the variables of age, sex, pubertal status, and ethnicity were controlled. The shape consistency between major modes indicates that the relationship between elevated body mass and the systematic patellar shape change is valid but not due to random morphological change.

Association Between BMI and Femoral Morphology

The analysis of the shape of the femur showed the widest relationships with BMI than the outcomes of the patella. Table 7 indicates that Femur Modes 1, 2, 3, and 5 had significant correlation with BMI. Mode 4 was the only one that failed to reveal a statistically significant correlation. The values of beta coefficients were comparable to or a little higher than the values of patellar modes which indicated the possibility of distal femoral morphology being particularly sensitive to habitual mechanical loading due to increased body mass. These results were graphically constructed with figure 5, which depicts that BMI-related associations of the femur were consistent and statistically steady in several shape dimensions.

Table 7. Multivariable Regression: BMI (Continuous) and Femoral Shape Modes

Shape Mode	β (per 1 kg/m² BMI)	95% CI	p-value
Femur Mode 1	0.091	0.052 to 0.130	<0.001
Femur Mode 2	0.044	0.008 to 0.080	0.017
Femur Mode 3	0.079	0.041 to 0.117	<0.001
Femur Mode 4	0.022	-0.013 to 0.057	0.216
Femur Mode 5	0.058	0.019 to 0.097	0.004

Association Between Sports Participation and Patellofemoral Morphology

When the participation in sports was modelled as categorical exposure, only significant associations were found with selected shape modes. Table 8 demonstrates that the participation in sports was greatly related to Patella mode 1 and mode 3, but no other modes significantly varied when compared with the participants and non-participants. Equally, Table 9 shows that there are considerable associations between Femur Modes 1 and 3, compared to others (Mode 2, 4, and 5), and no significant results between sports participation and Femur Mode 2. The selective associations indicate that exposure to organized sports does not result in a large-scale structural variation but affects specific morphologic features of the patella-femur in particular ways.

Table 8. Multivariable Regression: Sports Participation and Patellar Shape Modes

(Reference = No Sports Participation)

Shape Mode	β	95% CI	p-value
Patella Mode 1	0.144	0.041 to 0.247	0.006
Patella Mode 2	0.038	-0.065 to 0.141	0.468
Patella Mode 3	0.112	0.014 to 0.210	0.025
Patella Mode 4	0.027	-0.071 to 0.125	0.587
Patella Mode 5	0.089	-0.012 to 0.190	0.084

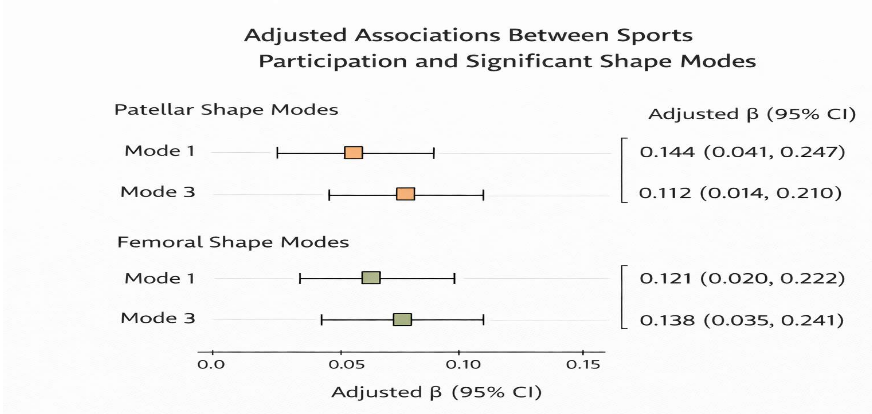


Figure 6. Forest Plot of Adjusted Associations Between Sports Participation and Significant Shape Modes

A forest plot of adjusted associations between sports participation and non-significant modes of shape compression shows the results of Figure 6. The strengths of associations with sports participation were a little less and confidence intervals broader than the strengths with the effects of BMI in Figure 5 and indicate the differences in exposure intensity and type. However, the statistically significant results of the associations regardless of multivariate adjustment reveal that sports participation is an independent determinant of morphological variation.

Interaction Effects Between BMI and Sports Participation

Interaction analyses were done to examine possible combined effects of the selected patellar and femoral shape modes. Figure 7 shows the dependence between the sports participation and BMI category of a typical patellar mode. The scores of shape mode were on a progressive rise between normal weight and obese. Sports participation effect in predicting values changed moderately within each category of BMI though overall gradients of BMI were clear despite the lack of participation. The trend implies that the overweight condition has a leading impact on morphology, and sports activity can alter the nature of change.

Table 9. Multivariable Regression: Sports Participation and Femoral Shape Modes

Shape Mode	β	95% CI	p-value
Femur Mode 1	0.121	0.020 to 0.222	0.019
Femur Mode 2	0.057	-0.042 to 0.156	0.256
Femur Mode 3	0.138	0.035 to 0.241	0.009
Femur Mode 4	0.019	-0.083 to 0.121	0.712
Femur Mode 5	0.072	-0.029 to 0.173	0.162

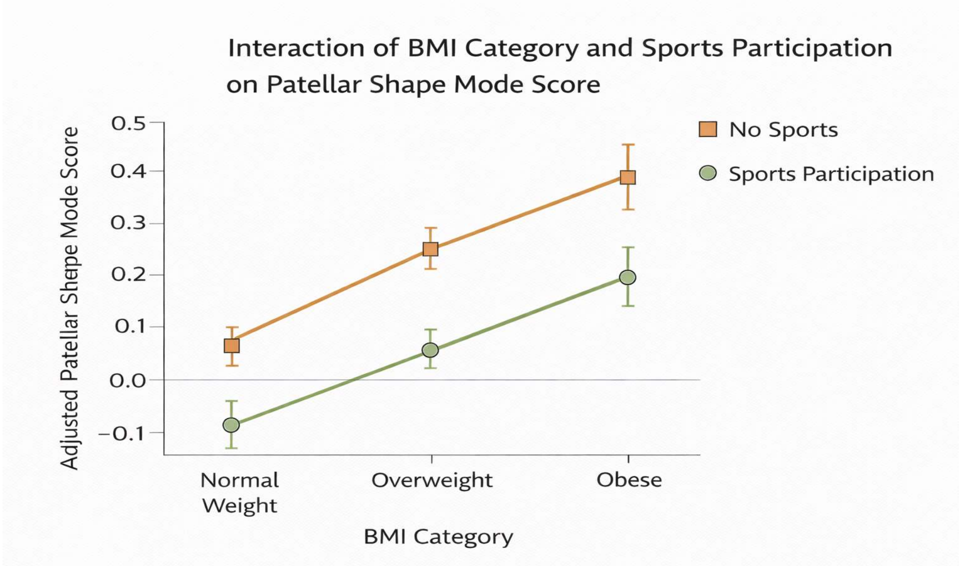


Figure 7. Interaction Plot Demonstrating Combined Effects of BMI Category and Sports Participation on Selected Patellar Shape Mode

Figure 8 illustrates the same interaction of a chosen mode of shape of the femur. Growth of BMI category was associated with an elevated adjusted score of femoral shape. The level of the outcome in the stratification of the BMI was once again impacted by the sports activity without obviating the BMI-related gradient. All these interaction plots imply the additive over the multiplicative nature effect whereby BMI is a dominant structural correlate and sports participation is a secondary modulator.

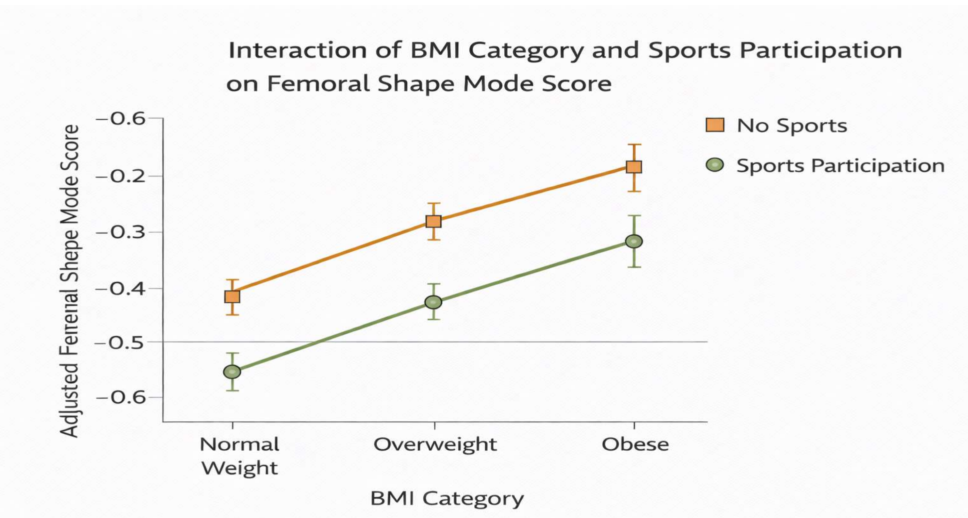


Figure 8. Interaction Plot Demonstrating Combined Effects of BMI Category and Sports Participation on Selected Femoral Shape Mode

DISCUSSION

The paper has analyzed the connections between overweight conditions, involvement in sports and the morphology of patella and femur in the early adolescent population through statistical shape modeling on MRI images. The mode-specific association came out to be consistent and mode-specific at higher BMI in multivariate analysis volumes of patellar and femoral shape modes. Sports participation in contrast was found to be associated with fewer and more selective modes. The effects of shape variation in three dimensions were visualized to prove that these effects were representative of coordinating geometry variations as opposed to independent linear changes. The analysis of interaction revealed that the differences in the BMI were existent between the sport strata and participation in sports moved the selected mode levels in the BMI category.

Comparison against the previous studies.

Morphological relationships were observed by BMI more than by sports participation, which reflects the idea of body mass implying the result of continuous load day by day, and sports exposure is discontinuous and patchy. Ability- A systematic review indicated that BMI was not always predictive of the incident of patellofemoral pain in adolescents (16). This evidence is not inconsistent with the current results since the results of pain were not modeled. Alternatively, the evidence indicates that developmental variation in the bone shape correlates with BMI, which can affect the mechanics and susceptibility to symptoms among particular subgroups.

Literature on adolescent knee pain reveals that the symptoms could extend to the adult stage and long-term functionality (17). The reviews focus on connections between body size, exposure to activities, and heterogeneous pain pathways (18). Long-term life-course studies also reveal that increased weight at an earlier age is linked to subsequent knee pain and functional diminishing (19,20). The results would indicate that BMI-related morphological change in growth may have more long-term consequences.

The sports-related associations were restricted to the chosen modes, which corresponds to the evidence that adolescents are able to be active, but to experience sports-specific impairment in case of knee pain (21). According to the biomechanical studies, the pain of patella-femur is multifactorial patella, entailing structural, mechanical, and neuromuscular aspects (22). Therefore, morphology is but a piece in a greater system, which affects symptoms.

Visual and Shape Modeling Situation.

The technique is developed as an extension of preceding studies of MRI-based morphometry in adolescents, which gives a multivariate, three-dimensional description of bone morphology. Previous research had recorded structural disparities in young active users (23). There is also statistical shape modeling of geometric complexity in patellofemoral pathology that is not measured in discrete terms (24). Other more recent studies indicate that bone cartilage morphology combinations can be used to identify instability phenotypics (as well as predictive modeling) (25). This literature is consistent with the current findings as it indicates that shape modeling is sensitive to clinically significant variation.

Potential Mechanisms

According to the mechanobiological models bone responds to its biomechanical environment by modeling and remodeling (29). Constant loading during adolescence could cause several shape modes because of unremitting exposure. By comparison, sports participation offers high-magnitude but intermittent loading, which could be the reason why it is selectively related. Youth intervention research evidence shows that high-impact loading can also induce skeletal adaptation observable through measurements (30), which confirm the general concept of this study that skeletal growth is affected by mechanical loading.

Patella-fibular anatomy is also an indication of female-male congruency of the structure. Variations in patellar morphology have been reported with regards to the trochlear dysplasia (26). Any given difference in measurement based indices of alignment can depend on the technique and reliability (27,28) and in this respect, statistical shape modeling encodes any diffuse geometry variation that would have otherwise not been detected.

Clinical and Public Health Implications.

At the age of early adolescence, multidimensional changes in patellar and femoral shape were linked to higher BMI, and more specific morphology patterns were linked to sports participation. Clinically, this helps to take a risk-stratified approach in which a sustained loading of greater body mass could affect structural context but without necessarily suggesting that adolescents are not supposed to be in sport. Rather, load-centred advice where progressive training and strength building are prioritized could be useful. Since it has been shown adolescent pain in the knee is persistent into adulthood (17), an early detection of the morphology patterns linked to long-term loading can shape prevention measures. In the context of public health, healthy body weight through adolescence can help to promote positive musculoskeletal trajectories in line with the life-course (19,20).

Limitations

The causal inference cannot take place due to cross-sectional design. Measurements of sports may not give the cumulative load in questionnaires. Adjustment may still leave behind residual confounding associated with maturation. Shape modes are statistical modes and do not necessarily reflect individual clinical modes. Lastly, the cartilage morphology and pain outcomes were not modelled.

Conclusion

Higher BMI in early adolescents showed multi-dimensional relationships between patellofemoral bone shape change and selective relationships with sports participation. The findings give credence to the idea that there is a long-term mechanical loading of the body in relation to body mass that is likely to affect morphology at a critical stage of development. To establish the nature of the relationship between these morphology patterns and future symptoms and functional status, longitudinal studies are necessary..

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