

Sagittal plane tilting deformity of the patellofemoral joint: a new concept in patients with chondromalacia patella

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Abstract

Purpose The aims of this study were to evaluate sagittal plane alignment in patients with chondromalacia patella via magnetic resonance imaging (MRI), analyse the relationships between the location of the patellar cartilaginous lesions and sagittal alignment and finally investigate the relationships between the sagittal plane malalignment and patellofemoral loadings using by finite element analysis.

Methods Fifty-one patients who were diagnosed with isolated modified Outerbridge grade 3–4 patellar chondromalacia based on MRI evaluation and 51 control subjects were evaluated. Chondromalacia patella patients were divided into three subgroups according to the chondral lesion location as superior, middle and inferior. The patella–patellar tendon angle (P–PT) was used for evaluation of sagittal alignment of patellofemoral joint. Each subgroup was compared

with control group by using P–PT angle. To investigate the biomechanical effects of sagittal plane malpositioning on patellofemoral joint, bone models were created at 30°, 60° and 90° knee flexion by using mean P–PT angles, which obtained from patients with chondromalacia patellae and control subjects. The total loading and contact area values of the patellofemoral joints were investigated by finite element analysis.

Results The mean age of all participants was 52.9 ± 8.2 years. The mean P–PT angle was significantly lower in chondromalacia group ($142.1^\circ \pm 3.6^\circ$) compared to control group ($144.5^\circ \pm 5.3^\circ$) ($p = 0.008$). Chondral lesions were located in superior, middle and inferior zones in 16, 20 and 15 patients, respectively. The mean P–PT angles in patients with superior (141.8 ± 2.7) and inferior subgroups (139.2 ± 2.3) were significantly lower than the values in the control group ($p < 0.05$). The contact area values were detected higher in models with chondromalacia than in the control models at the same flexion degrees. There were increased loadings at 30° and 90° flexions in the sagittal patellar tilt models.

Conclusion This study revealed that sagittal plain malpositioning of the patellofemoral joint might be related to chondromalacia, especially in the presence of lesions in the upper and lower part of the patella. This condition leads to supraphysiological loadings on the patellofemoral joint. Sagittal patellar tilt should be considered in the evaluation and management of patellar cartilage defects. Taking sagittal plane malalignment into consideration in patellofemoral joint evaluation will enable us to design new physical and surgical modalities.

Level of evidence IV.

Keywords Patellofemoral · Chondromalacia patella · Sagittal tilt · Finite element analysis

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Introduction

Chondromalacia patella, which is one of the major causes of chronic anterior knee pain, is characterized by the softening or breakdown of patellar cartilage and is frequently associated with decreased quality of life [25]. Patellar malalignment and direct or repetitive microtrauma are well-defined aetiological factors [36]. Patellofemoral malalignment leads to pathological loadings on the patellofemoral joint [13]. In the literature, patellofemoral malalignment is discussed as vertical plane malpositioning and patellar tilt or subluxation [15, 16, 22, 35, 38]. However, rotational malalignment of the patella in the sagittal plane is a new concept [1, 39]. In our previous study, rotational malalignment of patella on the sagittal plane was defined as ‘sagittal patellar tilt’ [2].

Sagittal patellar tilt leads to pathological loading by changing patellofemoral joint geometry as well as contact areas in cases of patellofemoral knee pain following tibial nailing [1]. To the best of our knowledge, the literature contains no study analysing the relationship between the chondromalacia patella and sagittal patellar tilt which might be a causative factor in patellar cartilage lesions by changing contact values and loading distributions.

The purposes of this study are: (1) to evaluate sagittal plane alignment in patients with chondromalacia patella via magnetic resonance imaging (MRI); (2) to analyse the relationship between the location of the patellar cartilaginous lesion and sagittal alignment; and (3) to investigate the relationship between the sagittal plane malalignment and patellofemoral loadings using finite element analysis. In the current study, it was hypothesized that the malalignment of the patella in the sagittal plane was related to chondromalacia patellae and this causes supraphysiological loadings on the patellofemoral joint. This is first study in the literature evaluating the relationship between the rotational alignment of the patella in the sagittal plane and patellar cartilage defects. Determination of this relation would further provide the development of different physical and surgical treatment modalities.

Materials and methods

Sixty-five patients who were diagnosed with modified Outerbridge grade 3–4 patellar chondromalacia based on MRI evaluation between January 2013 and December 2013 were evaluated retrospectively. The exclusion criteria were any history of knee surgery, meniscal pathologies, inflammatory arthritis, anterior or posterior cruciate ligament injuries, medial and lateral collateral injuries, any diagnosis of space occupying knee lesion, patellofemoral malalignment in the horizontal plane (patellar tilt, subluxation), sagittal

plane malpositioning pathology (patella baja, patella alta) and trochlear dysplasia.

In the axial fat-suppressed MRI images, the patellar tilt angle that was described by Grelsamer [16], sulcus angle and patellar congruence [26, 31] were measured. Patellar height was evaluated using the Caton–Deschamps index [8]. Cases with sulcus angle in a range of 115°–172°, congruence angle 27°–43°, Caton–Deschamps index 0.6–1.2 and patella–patellar tendon (P–PT) angle less than 10° considered as physiological and included in the study. Cases without providing these criteria were excluded from the study. Thus, the study was conducted with the exclusion of 2 patients for patellar tilt, 3 patients for subluxation and 4 patients for trochlear dysplasia. Furthermore, 4 patients with anterior cruciate ligament tears and one patient with a medial collateral ligament tear were excluded. A total of 51 patients were included in the chondromalacia group (Group I). The control group (Group II) was composed of 51 patients who were matched for age, sex and side and had been evaluated with the MRI but had no diagnosed pathology.

MRI evaluation

MRI evaluations were performed using a GE Sigma 1.5 Tesla (Optima, GE Medical System, Milwaukee, Wisconsin, USA) machine in a supine position without the administration of any contrast injection. An extremity coil was used to obtain images of the patients. The axial fat-suppressed proton density-weighted (PDW) (FSE, TR: 2742 ms, TE: 39.8 ms, thickness: 3 mm, matrix: 288 × 224, FOV: 18 cm) section images were analysed to evaluate the defects in the patellar cartilage. Patients with an irregularity on the cartilage surface and the loss of cartilage thickness on at least two consecutive slices were considered to have a patellar cartilage defect. These defects were graded with the modified Outerbridge classification system [29, 30]. Loss of greater than 50 % of the cartilage thickness without exposed bone and full-thickness cartilage loss with exposed bone were defined as grade 3 and 4 chondromalacia, respectively. The patellar articular surface in the sagittal MRI plane was divided into three equal parts as superior, middle and inferior (Fig. 1) to determine the lesion location. The part of the patellar surface with the deepest cartilage lesion was recorded, and the chondromalacia patients were divided in three subgroups according to lesion location.

T1-weighted FSE (TR: 508 ms, TE: 10.3 ms, thickness: 4 mm, matrix: 288 × 224, FOV: 18 cm) cross-sectional images were obtained to evaluate P–PT angle. Measurements of the sections were taken using the Onis software (2.0 Free Edition). P–PT angle [32] was used to analyse the sagittal alignment of the patella on

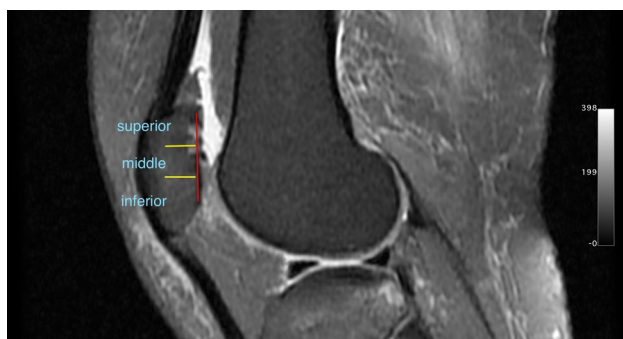


Fig. 1 Zones of patellar articular surface on the sagittal plane MRI



Fig. 2 Measurement of the P–PT angle

the patellofemoral joint. The P–PT angle was defined as the angle between the upper patellar pole and the lower patellar pole, and the tuberositas tibia (Fig. 2). P–PT angle measurements were taken by one of the authors (SD), who was blinded to the study groups. To avoid any interobserver errors in the measurements of the angles, the parameters mentioned above on mid-sagittal scans were measured by the second author (OK). To evaluate intraobserver reliability, measurements were taken by the same author (SD) 2 weeks after the first evaluation. In the current study, Bland–Altman method was used for the agreement of the P–PT angle measurements [6]. The mean P–PT angles and intraobserver and interobserver differences were calculated. Bland–Altman plots were created by data obtained from mean and standard deviation values of P–PT angle measurements. It was calculated that 96 (94.1 %) and 97 (95.1 %) of the intraobserver and interobserver measurements were in the 95 % confidence interval.

Finite element analysis

The study was performed with three-dimensional static linear finite element analyses. Three-dimensional bone models were made with the data of ‘Visible Human Project’ (19). 3D Doctor software (Able Software Corp., Lexington, MA) was used for three-dimensional bone modelling. Furthermore, Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103, USA) and VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA) mesh editing and fixing software programs were utilized. Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932 USA) software was used for the finite element analysis.

The physiological and sagittal patellar tilt models in full extension were created using mean P–PT angles in the MRI evaluations for the chondromalacia patellae and the control groups. After the acquisition of bone models in full extension, 3 physiological (control) and 3 sagittal patellar tilt bone modellings at 30°, 60° and 90° were created. The sliding and rotational movements of bony structures were taken into consideration during the modelling [14].

Following the bone modelling, the menisci, cartilaginous structures, ligaments and tendons of the knee joint were modelled according to the literature [27]. The vectors of the quadriceps muscle were created as vastus lateralis (VL), rectus femoris–vastus intermedius (RF/VIM) and vastus medialis obliques (VM). The vectors of the quadriceps muscle were positioned as follows: rectus femoris–vastus intermedius parallel to frontal femoral axis, vastus medialis obliques 41° medial and vastus lateralis 22° lateral. The RF/VIM was oriented 4° anterior to the femoral axis in the sagittal plane, whereas VMO and V were oriented parallel to it. The values of the elastic modulus and Poisson’s indexes were 11000, 6, 10 Gpa and 0.3, 0.47, 0.45 for bone, cartilage and meniscus, respectively [5, 27]. The tendons were modelled as spring elements with a stiffness of 2000.

A total of 137 N force was applied along the VL, RF/VIM and VMO vectors. The loading values of VL, RF/VIM and VMO were 50, 60 and 40 N according to muscle dimensions [27]. The total loading and contact area values of the patellofemoral joints were recorded.

The present study was approved by the Institutional Review Board (Ankara Numune Education and Research Hospital, ID: 704/2013).

Statistical analyses

Statistical analyses were performed using SPSS (version 20.0; SPSS Inc, Chicago, IL). The distribution between the groups was found to be normal with the Kolmogorov–Smirnov test. The test data were nonhomogeneous distributed ($p < 0.05$) in the Levene test, and nonparametric tests were used for the group comparisons. The results of the

patella–patellar tendon angle (P–PT angle) between control and chondromalacia groups were analysed with a Mann–Whitney *U* test. The Kruskal–Wallis test was used for the comparison of more than two groups, and Dunn’s test was used for post hoc analysis. A *p* value of <0.05 was considered statistically significant.

Power analysis was performed using G Power 3.1 software. To estimate the power analysis, the means of each group, the sample size of each group and the alpha and effect size *f* values were used. The alpha error probability, effect size *f* value and statistical power of the study (1–beta) were 0.05, 0.44 and 0.81, respectively.

Results

The demographic characteristics of the patients are presented in Table 1.

Radiological evaluation

The mean P–PT angles were $142.1^\circ \pm 3.6^\circ$ and $144.5^\circ \pm 5.3^\circ$ in the patients with chondromalacia and the control subjects, respectively. The mean P–PT angle was significantly lower in Group I compared to Group II (*p* = 0.008).

Cartilage lesions were detected to be localized in the inferior part of the patella in 15, the middle part in 20 and the superior part in 16 patients. The mean P–PT angles in patients with superior (141.8 ± 2.7) and inferior (139.2 ± 2.3) part of patella involvements were significantly lower than the values in the control group (*p* < 0.05). The measurement results of both groups are summarized in Table 2.

Finite element analysis

The maximum contact area values (sagittal patellar tilt: 862 mm^2 , control: 738.5 mm^2) were calculated for the 60° knee flexion models, whereas the minimum values

Table 2 The measurements of P–PT angle in both groups

Lesion location	Sample size	P–PT angle
Chondromalacia	51	$142.1 \pm 3.6^*$ (134.2–152.8)
Inferior part	16	$139.2 \pm 2.3^*$ (134.2–144.6)
Middle part	20	144.5 ± 3.2 (139.7–152.8)
Superior part	15	$141.8 \pm 2.7^*$ (135.6–146.7)
Control	51	144.5 ± 5.3 (132.1–155.2)

Values are expressed as mean \pm SD, with range in parentheses

P–PT angle patella–patellar tendon angle

* Represents the statistically significant difference (*p* < 0.05) with respect to control group

were achieved in the 30° knee flexion (sagittal patellar tilt: 480 mm^2 , control: 296.5 mm^2) models. The contact area values were determined to be higher in models with chondromalacia than in the physiological ones at the same degree of flexion (Fig. 3).

When the total loadings in the patellofemoral joints were interpreted, there were increased loadings at 30° and 90° flexions in the sagittal patellar tilt models (Figs. 4, 5).

Discussion

One of the main findings of this study is the existence of a sagittal patellar tilt in the patellofemoral joint in patients with grade 3–4 patellar chondromalacia. Moreover, it was revealed that, with respect to the control group, there was a significant decrease in P–PT angle in patients with chondromalacia patella, which was localized in the superior and inferior zones of the patellar cartilage. Finite element analysis also supported the radiological findings. In the pathological models, loadings were found to be higher than in the normal models at 30° and 90° flexion on the inferior and superior sides of the patella, respectively.

Patellar malalignment, loss of patellofemoral tracking and trauma are common aetiological causes of patellofemoral chondromalacia [28, 36]. Patellofemoral malalignment is discussed as a vertical plane malpositioning and patellar tilt or subluxation in the literature [16, 38]. However, there are limited studies in the literature, dealing with the alignment of the patella in the sagittal plane [1, 2, 10].

The P–PT angle was previously reported to be used to evaluate patellar tendon pathologies [21]. In our previous report, the P–PT angle was used to analyse sagittal plane patellofemoral alignment. In these reports [2], it was revealed that the changes in the P–PT angle were correlated

Table 1 Demographic characteristics of patients

	Group I	Group II	Total	<i>p</i> value
Age (year)	55.1 ± 8.1 (38–81)	53.3 ± 6.9 (40–81)	52.9 ± 8.28 (38–81)	n.s
Female:male	36:15	28:23	64:38	n.s
Right:left	36:15	28:23	64:38	n.s

Values are expressed as mean \pm SD, with range in parentheses

Group I: chondromalacia; Group II: control

n.s statistically nonsignificant

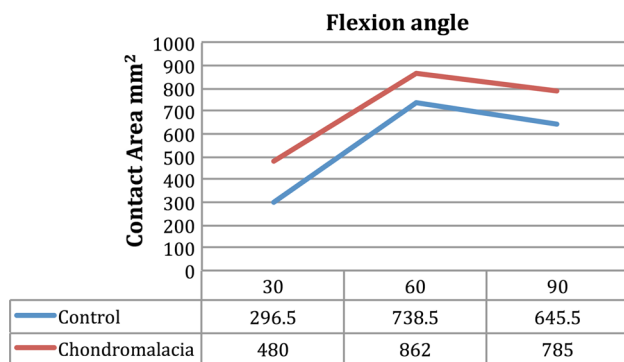


Fig. 3 Representation of relationships between flexion angle and contact area in all models. The contact area values were observed to be higher in models with chondromalacia than in physiological ones at the same degree of flexion

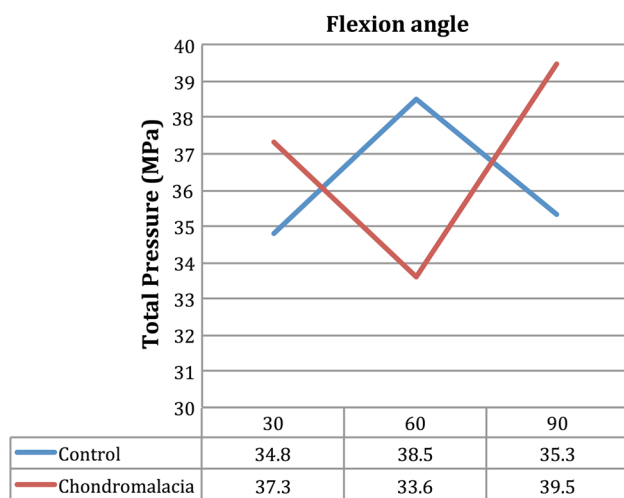


Fig. 4 Representation of relationships between flexion angle and total loading values. There were higher loading values in chondromalacia models at 30° and 90° flexion

with parapatellar muscle status, especially with the quadriceps femoris in patients suffering from anterior knee pain following tibial nailing. In addition, the significant effect of these alterations on patellofemoral loadings was reported with finite element analyses [1]. In this study, by excluding the patients with any coronal or axial plane malalignment, the deformity was determined to be an isolated deformity of the patellar tilt in the sagittal plane, which was called *sagittal patellar tilt*. To the best of our knowledge, it was the first study analysing the patellofemoral joint alignment from the sagittal plane point of view in patients with anterior knee pain. The main difference between the findings of this study [2] and the previous study is that, although the P–PT angle was increased in the knees of patients suffering from anterior knee pain following tibial nailing with respect to their normal side, it was found to be lower in

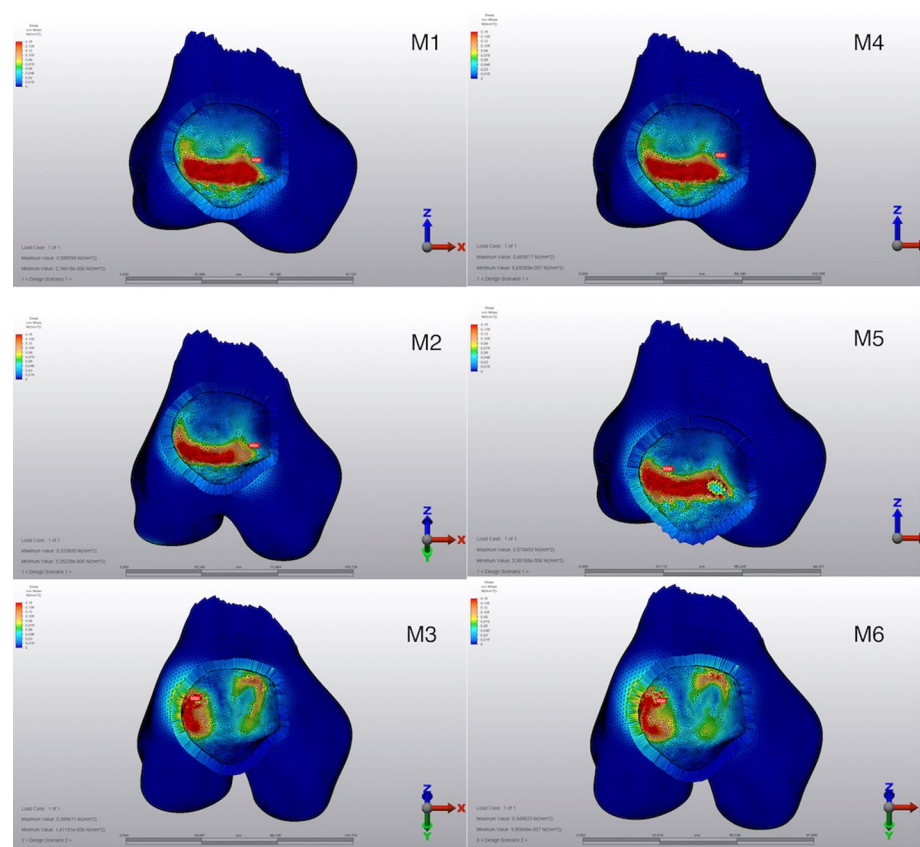
patients with chondromalacia patella with respect to the control group.

Patellar flexion in the sagittal plane is a natural component of patellofemoral tracking in the sagittal plane [33, 39]. On the other hand, sagittal patellar tilt is a completely different entity from physiological patellar flexion. Furthermore, by excluding the patients with any axial and coronal plane malalignment and vertical plane patellar malpositioning as well as patients with sulcus dysplasia, the findings in patients with chondromalacia patellae could be defined as *isolated sagittal patellar tilt entity*. To avoid any ambiguity, an increase in the P–PT angle is called a *positive sagittal tilt*, while a decrease in the P–PT angle is called a *negative patellar tilt*. In the previous study [2], the positive patellar tilt was attributed to quadriceps muscle atrophy. Since *negative sagittal patellar tilt* was detected in patients with chondromalacia patella, it seems that the pathophysiology of the chondromalacia patella is different from what occurs in patients having anterior knee pain following tibial nailing. Studies analysing parapatellar muscle status correlating with sagittal patellar alignment may help to delineate the real pathophysiology of chondromalacia patella.

The association between patellar malalignment and the localization of patellar cartilage lesion had been evaluated in limited studies in the literature [9, 12, 20, 34]. Kalichman et al. [20] revealed that malpositioning of the patella in the sagittal plane (patella baja, alta) and an increase in the sulcus angle were significantly correlated with an increase in cartilage loss in the medial and lateral sides of the patellar surface. Moreover, they found that lateral patellar tilt was associated with lateral cartilage loss. To the best of our knowledge, neither these studies nor the other studies analysing patellofemoral chondromalacia took ‘sagittal patellar tilt’ into consideration as a etiopathogenetic factor of chondromalacia patella or as a causative factor for cartilage lesion in different localizations. In the present study, we detected a decrease in the P–PT angle in patients with superiorly and inferiorly located patellar cartilage lesions. The PTA angle was not found to be significantly changed in patients with cartilage lesion located in middle zone. There was an approximately 5° increase in the sagittal patellar tilt angle in patients with inferiorly located (139.5 vs. 144.3) cartilage lesions and a 3° increase in patients with superiorly located (141.6 vs. 144.3) cartilage defects with respect to the control group. The PTA angle was not significantly different between the control group and patients with middle zone cartilage defects.

A variety of methods were used to analyse the impact of malalignment on patellofemoral joint kinematics [4, 7, 23, 24, 37]. Finite element analysis is a method being used with increasing popularity for patellofemoral kinematics evaluation [3, 18, 19]. In the present study, finite element analysis was used to evaluate the biomechanical

Fig. 5 Finite element analysis and loading distributions in all models. **M1** 30° flexion; **M2** 60° flexion; **M3** 90° flexion; **M4** 30° flexion with chondromalacia; **M5** 60° flexion with chondromalacia; **M6** 90° flexion with chondromalacia



reflections of MRI findings on patellofemoral joint load distribution. The results of the finite element analysis supported the radiological findings. Total loadings were found to be increased at 30° and 90° knee flexions in the sagittal patellar tilt models. It is known that in 30° and 90° knee flexion patellofemoral loadings are mainly localized on the inferior and superior sides of the patella, respectively [11, 17]. All these findings supported the hypothesis that malalignment of the patella in the sagittal plane, so-called negative sagittal patellar tilt, is one of the aetiological factors for chondromalacia patellae, especially on the superior and inferior sides of the patella due to the changes in patellofemoral loadings and their distributions.

The current study has some limitations. The sagittal tilt models at different flexion degrees were designed based on findings, which were obtained from MRI sections in extension. Malalignment in the sagittal plane may change at different degrees of flexion, and the impact of this on patellofemoral loadings may also change. If the models could be designed based on dynamic MRI data, it would increase the impact of the results. On the other hand, this is first study presenting the relationships between the chondromalacia patella and sagittal plane malalignment of the patellofemoral joint following the exclusion of patients with axial and coronal plane patellofemoral malalignment and/or sulcus

dysplasia. Features that strengthen the study were the investigation of patients with isolated sagittal plane malpositioning, which increased the impact of our results and the application of finite element analysis to simulate the effect of the radiological findings on patellofemoral loadings. The clinical relevance of the study was that, in patients with chondromalacia patella, sagittal plane analysis of the patellofemoral joint should also be done. Further clinical studies analysing patellofemoral joint geometry with dynamic as well as static methods will improve our understanding of the pathophysiology of chondromalacia patella. Taking the sagittal plane alignment into consideration in patellofemoral joint evaluation will enable us to design new physical and surgical modalities.

Conclusions

The results of the present study indicate that sagittal patellar tilt might be one of the factors that leads to chondromalacia patella, especially localized in the inferior and superior zones of the patella. This new concept will be a cornerstone in patellofemoral pain management. In conclusion, not only patellar height but also sagittal patellar alignment should be included in the list of routine evaluations of PF joints.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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