Limb Alignment, Subluxation, and Bone Density Relationship in the Osteoarthritic Varus Knee

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Abstract

Lower limb alignment, tibiofemoral (TF) subluxation, and bone density changes around the knee are significant factors related to the development of knee osteoarthritis (OA) and have great impact on its severity. The relation of each factor to knee OA was evaluated separately in previous studies; however, few studies have attempted to integrate their respective effects. The purpose of this study was to determine if an identifiable interaction exists between coronal limb alignment, TF subluxation, and bone density in the development of knee OA. A total of 120 patients with symptomatic, varus knee OA, with preoperative standing anteroposterior (AP) hip-to-ankle radiographs and a computed tomographic scan of the knee, were included in this study. Overall mechanical lower extremity alignment, and TF subluxation were measured on the AP radiographs, while trabecular bone density (TBD) was measured in four regions of interest for both the tibial plateau and distal femur in all patients. The patients were stratified into the following four cohorts: (A) high subluxation, high angulation; (B) high subluxation, low angulation; (C) low subluxation, high angulation; and (D) low subluxation, low angulation. The mean TBD in group B was significantly higher than in groups C and D ($p = 0.003$ and 0.03, respectively). In addition, the mean TBD in group A was significantly higher than in group C. This study highlights the relationship between limb alignment, knee subluxation, and bone density in the osteoarthritic knee. These preliminary results present a proof-of-principle, that bone mineral density affects the degree of coronal alignment and TF subluxation in OA.

Keywords
- knee
- arthroplasty
- subluxation
- angulation

Lower limb alignment, a major determinant of load distribution across the knee articular surface, is considered a significant factor affecting the development of knee osteoarthritis (OA).[1,2] In the normal limb with optimal alignment and load distribution, the tibiofemoral (TF) joint is congruent. The knee is a hinge joint, with motion mainly in the sagittal plane.[3] Therefore, geometrically, coronal limb malalignment with TF angulation can result in TF subluxation. Subluxation in the coronal plane is a common radiological finding in the osteoarthritic knee (►**Fig. 1**). Previous studies have found TF subluxation presence to be predictive of poor Western Ontario and McMaster Universities pain scores.[4] In addition, other studies have hypothesized advanced TF subluxation to increase the risk of tibial spine impingement on the femoral condoyle.[5,6]

Another factor seen in knee OA is changes in trabecular bone properties around the knee.[7,8] These changes may affect the trabecular number, thickness, separation, and

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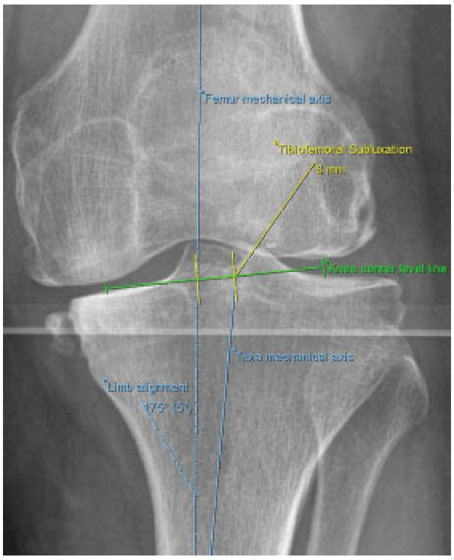

Fig. 1 Radiograph demonstrating tibiofemoral subluxation and the method for measurement.

connectivity.[8] Numerous studies have revealed a significant correlation between limb alignment and bone density in the tibial plateau and femoral condyles,[1,9–11] as limb malalignment can cause changes in the bone architecture, leading to an increased mediolateral difference of proximal tibial bone density.[12] Integration of the data introduced above proposes an interaction between limb alignment, coronal TF subluxation, and bone density. The purpose of this study was to determine if an identifiable interaction exists between coronal limb alignment, TF subluxation, and bone density in the OA. Our hypothesis is that while coronal limb angulation can lead to TF subluxation, the amount of subluxation is directly affected by the bone density around the knee, and its susceptibility to deformation.

Patients and Methods

This study is a retrospective review of an institutional review board–approved database of a single surgeon (A.P.). A total of 120 patients who met the inclusion criteria were enrolled in the study. Inclusion criteria for this study were patients who were (1) candidates for knee arthroplasty due to symptomatic OA with varus angulation, (2) had no previous major knee surgery or injury, and (3) had received standing anteroposterior (AP) hip-to-ankle radiographs and a computed tomographic (CT) scan of the index knee. Gender, body mass index (BMI), and age at the time of the index procedure were recorded for all patients.

Lower limb alignment and TF subluxation were measured on calibrated standing, AP hip-to-ankle rotation controlled radiographs performed at our institution. Measurements were performed, by two independent observers, using a picture archiving and communication system (PACS, Sectra Imtec AB, Linkoping, Sweden). The overall, mechanical alignment of the lower extremity was defined as the angle formed by a line drawn from the center of the femoral head to the center of the femoral notch, and a second line from the center of the tibial plateau to the center of the tibial plafond (►**Fig. 2**). Angulation was defined as the difference between the measured mechanical alignment and the normal mechanical alignment of the lower limb.

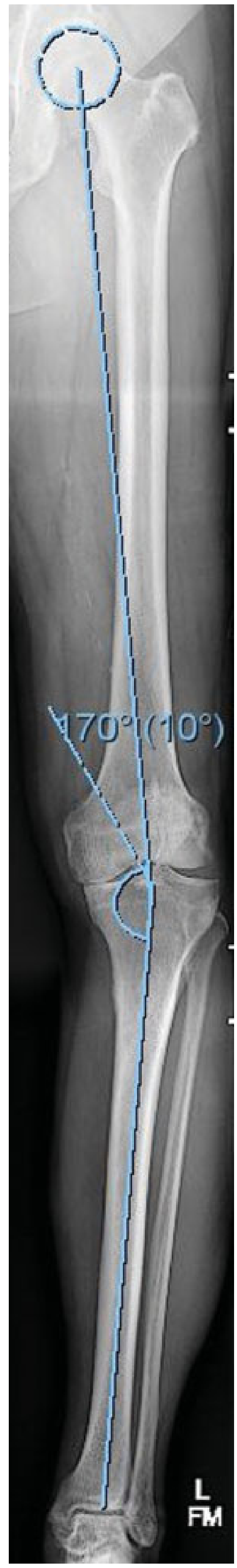

Fig. 2 Radiographs demonstrating measurement of the overall lower limb mechanical alignment.

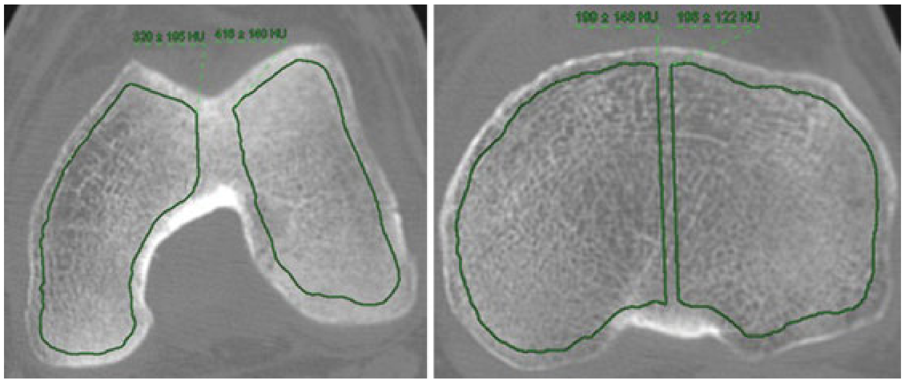

Fig. 3 Computed tomographic scan slices demonstrating the area defined for trabecular bone density measurement.

On the basis of the premise that in the "normal" limb, the mechanical axes of the femur and tibia are continuous lines passing through the center of the knee, and in pure coronal angulation (without subluxation) these axes still intersect at the knee center, we developed our previously published method for measuring TF subluxation based on the standing, AP radiographs.[13] In both knee compartments, the mid-distance pointes between the femoral and tibial condyles were found and horizontal line was drawn between them, the distance between the intersection points of the drawn line and the prior established tibial and femoral mechanical axes was measured and recorded as the TF subluxation (►**Fig. 1**).

Quantitative computed tomography (QCT) is an advantageous method for trabecular bone density (TBD) evaluation, as it is recorded in Hounsfield units (HU). HU have been shown to correlate highly with the TBD.[14,15]

A QCT (General Electric Healthcare, Milwaukee, WI) was used to determine the TBD. To measure the TBD (in HU), we used the Medical image viewer software (GE Healthcare, version 3.7.3.7008). Tibial width (TW) at the level of the tibial plateau was measured on the CT scan, based on the lateral scout the axial slices at the following levels: 15% of TW distal to tibial plateau and 10% of TW proximal to the femoral notch were identified. Using the identified axial slices, TBD measurement was performed in four regions of interest (ROI) of the medial and lateral condyles of the femur and tibia, three times by the same observer. In each ROI, the area for measurement was defined as the whole trabecular bone minus the 2 mm in the periphery closest to the surrounding cortical bone (►**Fig. 3**).

The mean coronal angulation and mean subluxation were calculated, the patients were divided into four groups based on calculated means for both coronal angulation and TF subluxation (►**Table 1**). Group A: patients with a TF subluxation > mean and coronal angulation > mean; Group B: patients with a TF subluxation > mean and coronal angulation < mean; Group C: patients with a TF subluxation < mean and coronal angulation > mean; and Group D: patients with a TF subluxation < mean and coronal angulation < mean. Patients with a coronal angulation higher or lower than the calculated mean were referred to as having "high angulation" or "low angulation," respectively. While patients with knee subluxation higher or lower than the calculated mean were referred to as having "high subluxation" or "low subluxation," respectively. For each group, the mean TBD was calculated in HU based on the software readings in the four ROIs. The TBD differences were evaluated between the groups; in addition, gender differences regarding TBD, subluxation, and angulation were evaluated within and between the groups.

Statistical Analysis

Interclass correlation coefficients (ICCs) were calculated to evaluate interobserver reliability for the radiographic measurements. The ICCs were graded using previously described semiquantitative criteria. Excellent for $0.9 \leq p \leq 1.0$, good for $0.7 \leq p \leq 0.89$, fair/moderate for $0.5 \leq p \leq 0.69$, low for $0.25 \leq p \leq 0.49$, and poor for $0.0 \leq p \leq 0.24$.[16] Statistical analysis of variance was used for evaluation of age, BMI, and gender differences between the groups. Student *t* test was used to evaluate the TBD differences between the study groups, and the gender differences regarding TBD, angulation, and subluxation within and between the groups. A *p* value < 0.05 was considered statistically significant.

Table 1 Table demonstrating tibiofemoral subluxation, limb angulation, and trabecular bone density in all study groups

	Group A ($n = 30$)	Group B ($n = 33$)	Group C ($n = 32$)	Group D ($n = 25$)
Subluxation	> Mean (3.9 mm)	> Mean (3.9 mm)	< Mean (3.9 mm)	< Mean (3.9 mm)
Angulation	> Mean (7.6 degrees)	< Mean (7.6 degrees)	> Mean (7.6 degrees)	< Mean (7.6 degrees)
TBD (mean ± SD)	200 ± 80 HU	209 ± 83 HU	179 ± 77 HU	184 ± 91 HU

Abbreviations: TBD, trabecular bone density; HU, Hounsfield units; SD, standard deviation.

Table 2 Table demonstrating tibiofemoral subluxation, limb angulation, and trabecular bone density differences between females and males in all study groups

		TBD (HU)	Subluxation (mm)	Alignment (degree)
Group A	Female	185 (± 28)	6.3 (± 2.4)	10.3 (± 1.7)
	Male	210 (± 59)	5.7 (± 1.6)	10.4 (± 1.8)
	p Value	0.18	0.43	0.9
Group B	Female	207 (± 47)	5.4 (± 1.5)	4.4 (± 1.7)
	Male	210 (± 49)	5.6 (± 2.4)	4.2 (± 1.8)
	p Value	0.88	0.84	0.65
Group C	Female	161 (± 40.8)	1.7 (± 1.3)	10.34 (± 1.8)
	Male	193 (± 36.5)	1.77 (± 1)	10.97 (± 2.5)
	p Value	0.02	0.98	0.15
Group D	Female	153 (± 50)	1.8 (± 1.7)	5.2 (± 1.6)
	Male	204 (± 56)	2.1 (± 1.2)	4.9 (± 2.1)
	p Value	0.03	0.64	0.75

Abbreviations: HU, Hounsfield units; TBD, trabecular bone density.

Results

Application of our inclusion criteria yielded 120 patients with a mean varus angulation of 7.6 degrees (± 3.5) and mean subluxation of 3.9 (± 2.5) mm. After dividing the patients into the four cohorts as described earlier, group A included 30 patients (males = 18, females = 12), group B included 33 patients (males = 11, females = 22), group C included 32 patients (males = 18, females = 14), and group D included 25 patients (males = 15, females = 10) (►**Table 1**). There was no significant difference regarding age, BMI, and gender between all study groups. As displayed in ►**Table 1**, the mean TBD in group B (high subluxation and low angulation) was significantly higher than groups C and D (those patients with low subluxation), $p = 0.003$, 0.03, respectively. The mean TBD in group A (high subluxation and high angulation) was significantly higher than group C (low subluxation and high angulation), $p = 0.03$ but did not differ significantly than group B (high subluxation and low angulation) and group D (low subluxation and low angulation) with $p = 0.43$ and $p = 0.15$, respectively.

As illustrated in ►**Table 2**, there were no significant differences regarding subluxation or angulation between females and males within all study groups. The TBD did not differ significantly between females and males within groups A and B; however, it was significantly higher in males compared with females in groups C and D, $p = 0.02$ and 0.03, respectively.

The mean TBD in the females of group B (high subluxation and low angulation) was 208 (HU), significantly higher than the 160 (HU) mean TBD in group C females and the 153 (HU) mean TBD in group D females, with $p = 0.003$ and 0.005, respectively. Mean TBD in males of groups A and B (high subluxation) were higher (210.3 and 210 HU, respectively) than the 193.7 mean TBD in group C (low subluxation and high angulation) and the 204 mean TBD in group D (low subluxation and low angulation), although these differences were not significant ($p > 0.05$).

Interobserver correlation coefficients for both overall mechanical alignment and TF subluxation were excellent and good, with values of 0.95 and 0.86, respectively.

Discussion

This study describes the relationship between three factors which significantly affect biomechanics and load transmission across the knee: alignment, subluxation, and bone density. Numerous studies have evaluated each of these factors separately, and their role in knee OA. However, few studies have attempted to integrate their respective effects. Limb malalignment is associated with the initiation of knee OA, progression, and severity.[17,18] It predicts disability and decline in physical function[1,9,19] can impact treatment choices,[20,21] and affect the clinical outcomes of knee arthroplasty.[22–25] In the previous studies, the presence of TF subluxation has been associated with increased knee pain[4] and intercondylar notch impingement.[5,6] However, we are not aware of published studies suggesting a standardized method for its measurement. TBD is associated with joint cartilage changes[26] and space narrowing,[27] it is also related to the risk of implant loosening[28] and component migration.[29] Therefore, TBD should be considered during knee arthroplasty preoperative planning and decision making regarding implant materials[30] and methods of fixation.[31] In our study, we showed a significant relationship between the overall coronal alignment, TF subluxation, and TBD. In general, as the mean bone density increased, the degree of TF subluxation also increased. For example, the mean bone density in group B (low angulation and high subluxation) was significantly higher than both groups with low subluxation (groups C and D) $p = 0.003$ and $p = 0.03$, respectively. In addition, group A (high angulation and subluxation) had significantly higher bone density than group C (high angulation and low subluxation), but there was no significant TBD difference when group A was compared with group B or D.

Our results show highest bone density in group B (209 HU), where apparently only small changes of the bone architecture is allowed, therefore, low angulations will be translated to high subluxations. However, in group A the TBD (200 HU) is lower than group B (not statistically significant different, probably due to the small sample size), therefore, the possibility for bone architecture changes is higher than group B, and high angulation is needed to get high subluxation.

Therefore, TBD does not have an isolated effect on only coronal angulation, or only TF subluxation, but rather all three factors appear to be integrated in affecting the overall appearance of the osteoarthritic knee.

An overall observation may tell us that coronal angulation in OA knee has to be "compensated" by combination of TF subluxation and bone compression and architecture changes; knees with relative low bone density group C will permit bone compression with minimal subluxation, even with high angulation. On the contrary, knees with high bone density, as in group B, will permit minimal bone compression and minor angulation will bring high subluxation.

Interestingly, female patients had significantly lower TBD in groups C and D (low subluxation) when compared with males TBD in the same group. In addition, the mean TBD of the females in groups C and D were significantly lower than the mean TBD in group B (low angulation and high subluxation). This apparently related to the fact that osteoporosis is more common and significant in women comparing to men.[32–34] Therefore, angulations are expected to be compensated mainly by changes in bone architecture in females with low bone density, whereas in males, the angulations will be translated to TF subluxations mainly.

There are a few limitations to our study. First, the study was a retrospective review, and did not possess a control group. Second, our measurements were performed using AP, standing, hip-to-ankle radiographs, which are subject to rotational errors that may affect the accuracy of our measurements. The third limitation is related to measurement of bone density, which was based on two slices of CT scan, and did not measure the whole bone density around the knee. In conclusion, this study highlights the relationship between limb alignment, knee subluxation, and bone density in the osteoarthritic knee. These preliminary results present a proof-of-principle that bone mineral density affects the degree of coronal alignment and TF subluxation seen in patients. In the future, these results could prove helpful both when indicating patients for total knee arthroplasties, and in preoperative planning. Patients with high bone mineral density may be more susceptible to TF subluxation, and the potential of ligamentous instability, and thus earlier surgical intervention may be indicated in these patients. In addition, measurement of coronal alignment and TF subluxation may help in predicting the quality of bone around the knee, and in predicting possible complications and difficulties with ligamentous balancing, and implant fixation. Further studies are necessary to better elucidate the understanding of this topic, and its potential clinical applications.

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