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SCIENTIFIC ARTICLE

Coronal tibiofemoral subluxation in knee osteoarthritis

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Abstract
Objective To analyze knees in varying stages of osteoarthritis (OA) for the presence of coronal tibiofemoral (CTF) subluxation and to determine if CTF subluxation severity is related to knee OA worsening.
Methods We retrospectively evaluated CTF subluxation and limb alignment in 113 patients with different stages of knee OA who were being considered for an arthroplasty procedure. Knee OA was classified as "mild" or "severe" according to Kellgren-Lawrence scale. CTF subluxation was measured in the study groups and in 40 knees of healthy controls using software developed specifically on the basis of Iterative Closest Point mathematical algorithm.
Results Mean CTF subluxation in "mild OA" and "severe OA" groups was 3.5 % (±2) and 3.5 % (±5) of the tibial plateau, respectively. For both the mild and severe OA groups, CTF subluxation was significantly increased compared to the 1.4 % (±1) CTF subluxation in the control group, ($p<0.0001$) and ($p=0.012$), respectively. However, there was no significant difference in CTF subluxation between the mild OA and severe OA groups ($p=0.75$). Limb varus malalignment in mild OA and severe OA groups was 3.6° (±2.2) and 5.3° (±2.6), respectively. Both significantly increased comparing to the 1° (±0.7) control group alignment ($p<0.0001$). Varus malalignment in the severe OA group was significantly increased comparing to the mild OA group ($p=0.0003$).
Conclusions CTF subluxation is a radiographic finding related to knee OA which occurs mainly in the early stages of the osteoarthritic process and stagnates as OA progresses.

Keywords Coronal tibiofemoral subluxation · Limb alignment · Knee osteoarthritis

Introduction

Knee osteoarthritis (OA) is a leading cause of disability and is associated with high health care costs [1]. Impaired load transmission through the tibiofemoral joint is an important variable related to OA progression [2]. Multiple factors are known to contribute to impaired load transmission, including tibiofemoral incongruence [3], high body mass index [4], coronal malalignment, [5–7] anterior cruciate ligament insufficiency, and meniscal tears [8]. These conditions may increase the risk for focal stress points across the joint, leading to impaired load transmission and subsequent degenerative changes.

One factor contributing to impaired load transmission and knee OA that is less commonly studied is coronal tibiofemoral (CTF) subluxation. CTF subluxation is a potentially important radiographic finding; previous studies have shown that CTF is related to poor Western Ontario and McMaster Universities (WOMAC) pain scores [9], tibial spine impingement on the femoral condyle [10], and is a possible reason for unexplained pain following unicondylar knee arthroplasty [11]. However, the published data regarding CTF subluxation is limited, and commonly used OA grading systems such as the Kellgren-Lawrence classification [12], (a classification which evaluates: joint space narrowing, osteophytes, sclerosis and bony deformity), do not account for the degree of CTF subluxation when assessing OA progression. In fact, we are not aware of any studies in the English literature which evaluate CTF

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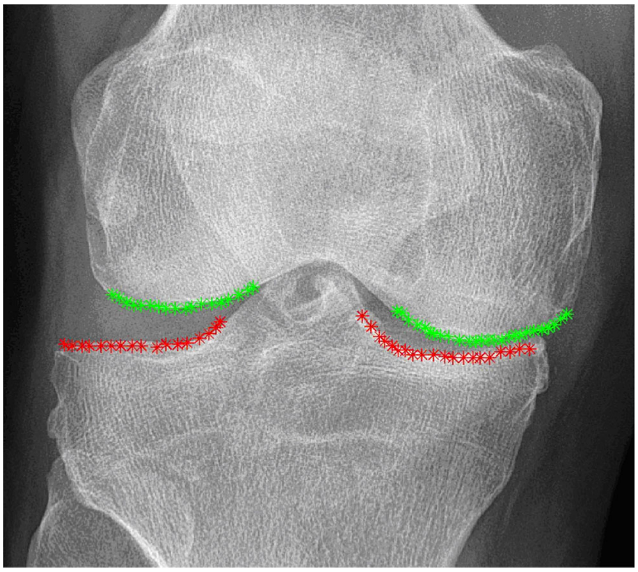


Fig. 1 The digitized femoral (*green*) and tibial (*red*) articular surfaces

subluxation in different stages of knee OA. The purpose of the study was therefore to (1) analyze knees in varying stages of OA for the presence of CTF subluxation; and (2) determine if the severity of CTF subluxation is related to knee OA worsening.

Methods

Institutional Review Board approval was obtained prior to the commencement of the study. We reviewed the senior author's prospective surgical arthritis database for patients who had undergone total or unicondylar knee arthroplasty between 1 January 2010 and 1 January 2012. Inclusion criteria were (1) patients who had preoperative weight bearing hip to ankle radiographs of the affected knee with adequate resolution, (2) patients with osteoarthritic changes on knee radiographs, (3) patients with varus alignment in the operated knee. Patients with a history of trauma or inflammatory arthropathy were excluded. To control limb rotation, we utilized our standard of care radiographs protocol at our institution in which the limb is internally rotated approximately 5° until a line between the femoral epicondyles is parallel to the cassette, and the tibial eminence is seen in the center of the intercondylar fossa. Preoperative weight-bearing knee radiographs of the patients who met our criteria were graded according to the Kellgren-Lawrence scale [12]. The study group was divided into a "Mild OA group" (Kellgren-Lawrence grade I and II) and "Severe OA group" group (Kellgren-Lawrence grade III and IV). To serve as a healthy control group for purposes of comparison, we evaluated the contralateral, uninjured knee in patients who had undergone bilateral standing radiographs prior to anterior cruciate ligament reconstruction (ACL) at our institution. Such bilateral standing lower extremity films are routinely done at our institution preoperatively for ACL reconstruction patients. All patients in the control group were younger than 40 years and had no complaints or any sign of OA in the contralateral, uninjured knee.

Since the tibiofemoral joint lacks anatomic landmarks which enable accurate measurement of CTF subluxation, a new measuring software code (Matlab, MathWorks Inc., Natick, MA, 2012) based on the Iterative Closest Point (ICP) mathematical algorithm was developed. The ICP algorithm is a commonly used method for matching surfaces and curves [13]. The algorithm seeks to minimize the sum of the square distances between two clouds of points and attempts to find

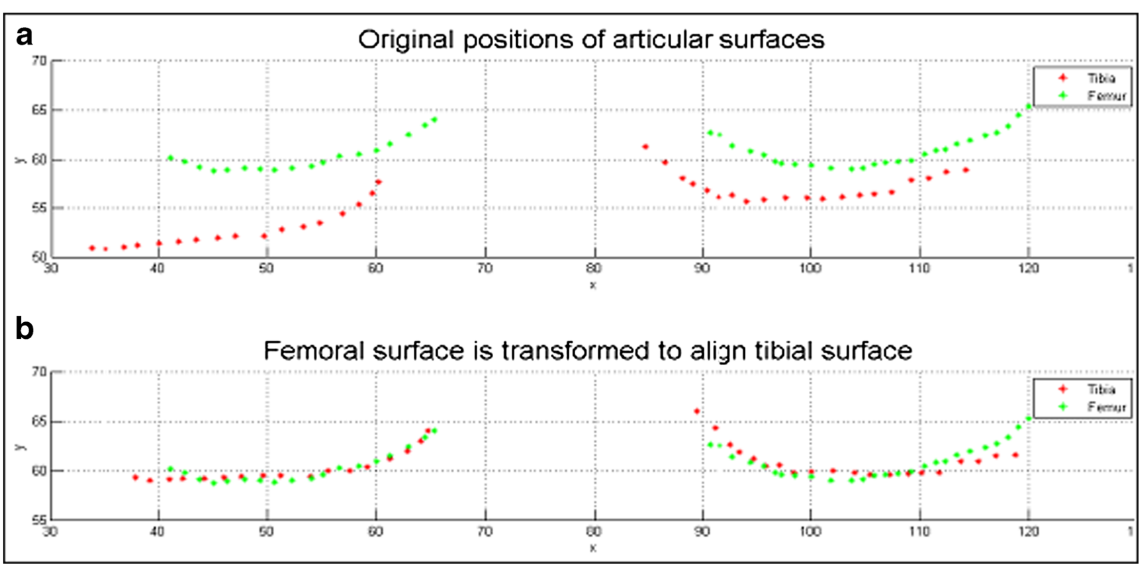


Fig. 2 Digitized articular surfaces presented on cords system (**a**). Femoral articular surface is rigidly transformed to align the tibial articular surface (**b**)

the rigid transformation (translation and rotation) that best aligns these two clouds. The specially developed software enables manual digitization of distal femur and proximal tibial articular surfaces (Fig. 1) and represents them as the two scattered clouds of points (Fig. 2a). It was also designed to automatically align the tibial plateau perpendicular to the vertical axis of coordinates system and to calculate translation and rotation needed for the femoral surface to fit the tibial surface optimally (Fig. 2b). In addition, it automatically measures the width of the tibial plateau. Therefore, the horizontal translation measured by the ICP algorithm divided by the tibial plateau width, represented the percentage of CTF subluxation and the angulation represented the angle between the tibial and femoral articular surfaces. The new method for CTF subluxation measurement was validated using cadaveric knees and published in a previous study. [14]

Using the hip to ankle standing radiographs, overall lower extremity mechanical alignment was measured in the study group. The measurement was performed by drawing a line connecting the center of the femoral head to the center of the femoral notch which formed by a line of the femoral mechanical axis. The tibial mechanical axis was formed by line connecting the center of the talus to the center of the tibial plateau. The angle formed between the femoral and tibial mechanical axes was recorded as the overall lower extremity mechanical alignment (Fig. 3).The CTF subluxation measurements, including articular surfaces digitization, were performed by two independent observers for both the study and control groups.

Statistical analysis

Interclass correlation coefficients (ICC) were calculated to evaluate interobserver reliability for CTF subluxation and rotation measurements. The ICC's were graded using previously described semi-quantitative 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 $0.0 \leq p \leq 0.24$ [15] . Single factor ANOVA test and Student's t-tests were used to detect CTF subluxation differences and lower limb alignment differences between the study and control group. A p-value <0.05 was considered statistically significant.

Results

As illustrated in Table 1, the control group included 40 knees with mean CTF subluxation of 1.4 % (±1) of the tibial plateau and mean mechanical alignment of 1° (±0.7). The mild OA group (Fig. 4a) included 62 knees with CTF subluxation of 3.5 % (±2) of the tibial plateau and mean mechanical malalignment of 3.6° (±2.2). The severe OA group (Fig. 4b) included 51 knees with CTF subluxation of 3.5 % (±5) of the tibial plateau and mean mechanical alignment of 5.3° (±2.6). ANOVA test showed significant CTF subluxation variance between the three groups (p=0.004). Both, the mild OA and severe OA groups had significantly higher CTF subluxation percentage compared to the control group, (p<0.0001) and (p=0.012), respectively. However, there was no significant CTF subluxation difference between the mild OA and severe OA groups (p=0.75).

There was a significant variance between the three groups regarding mechanical alignment (p<0.0001). The varus

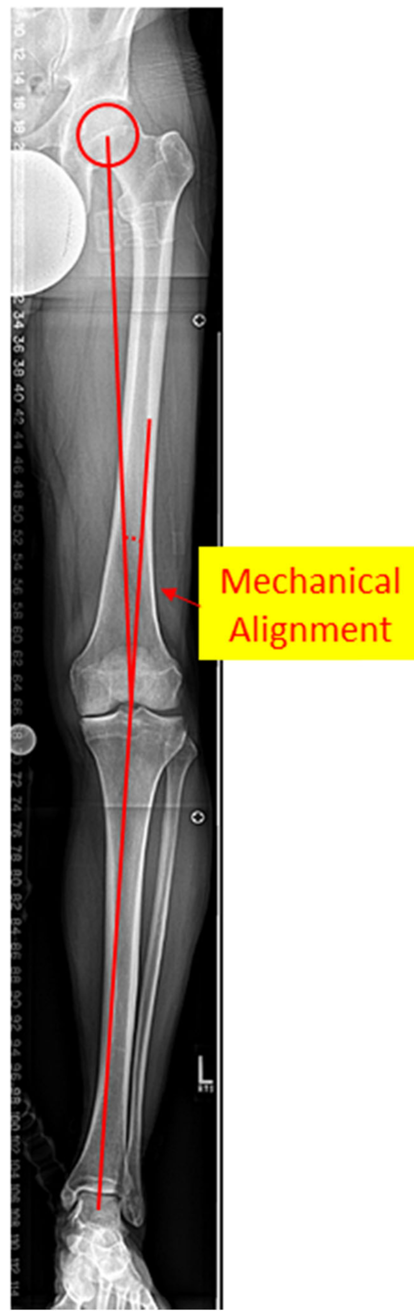


Fig. 3 lower extremity mechanical alignment measurement using hip to ankle radiographs

Table 1 Percentage of *subluxation* and *lower limb varus alignment* is compared for the three studied groups

	Control group (n=40)	Mild OA (n=62)	Severe OA (n=51)	
CTF Subluxation[a]	1.4 % (±1)	3.5 %(±2)	3.5 % (±5)	p=0.004
Lower limb varus alignment	1° (±0.7)	3.6° (±2.2)	5.3° (±2.6)	p<0.0001

[a] Percentage of coronal tibiofemoral subluxation relative to tibial plateau width

malalignment was significantly higher in the mild OA and severe OA groups as compared to the control group with (p<0.0001) in both cases. In addition, the varus malalignment was significantly higher in the severe OA group comparing to the mild OA group (p=0.0003). The interobserver correlation coefficients for the measurements of CTF subluxation and the lower limb mechanical alignment were 0.95 and 0.91 respectively.

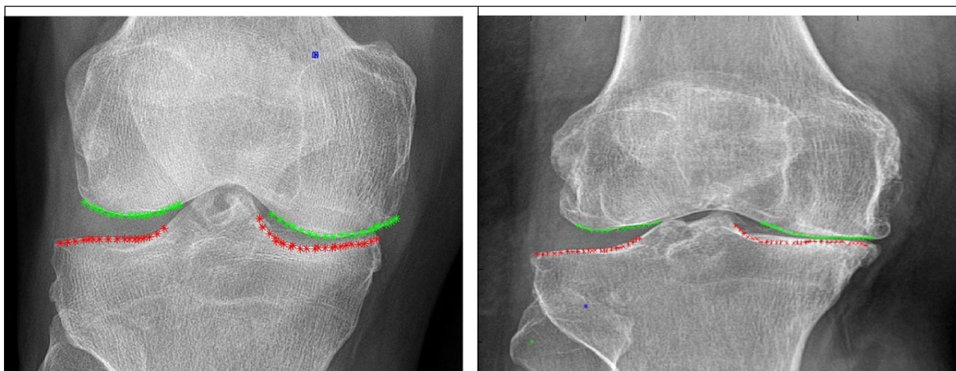
Discussion

Our data suggest that CTF subluxation is a radiographic finding related to knee OA. A significant increase in CTF subluxation was noticed in knees with mild and severe OA compared to the control group; however, a statistically significant difference in CTF subluxation between knees with mild and severe OA was not found. The lower limb varus malalignment was found to be increased significantly as the severity of the radiographic signs of OA increased.

Lower limb malalignment is an important biomechanical factor which has been investigated broadly and has shown to be related to progression of OA [16–18]. A previous study reported that 3 to 5° of increased tibial varus alignment may result in a 50 % increase of the force transmitted across the medial tibiofemoral compartment [19]. Halder et al. [20] studied the forces transmitted across the knee after total knee arthroplasty and found a 5 % increase of medial force for 1° of varus deviation from neutral alignment. In contrast to lower limb malalignment, CTF subluxation is rarely reported and the publications discussing its clinical implications are limited.

The data of the current study suggest that the CTF subluxation occurs mainly in the early stages of OA, perhaps when the soft tissues around the knee still have some inherent laxity. However, in severe knee OA the soft tissue stiffness and ankylotic changes around the knee may prevent further CTF subluxation. A recent study which evaluated CTF subluxation after unicondylar knee arthroplasty [11] suggested that CTF subluxation might be influenced by bone density around the knee. Osteoarthritic knees with hard, sclerotic subchondral bone may not permit any structural bone changes; therefore, deforming forces across the knee will be translated into severe CTF subluxation.

Measurement of CTF subluxation may be considered as an additional tool in the radiographic evaluation of knee OA. In arthritic knees being considered for an arthroplasty procedure, measuring CTF subluxation may help in the assessment of bone quality and soft tissue laxity, potential predicting difficulties in knee balancing and implantation. In cases where a CTF subluxation measuring tool is not available, we believe that subjective assessment of this parameter during the interpretation of clinical knee radiographs is valuable and important. In this study, we present a new method for measuring CTF subluxation. The ICP mathematical algorithm used is highly precise and is commonly used for measurements based on matching bone surfaces [21, 22] and orthopedic implants [23, 24].



A CTF measurement in "Mild OA", CTF = 3.4% of tibial plateau

B CTF measurement in "Severe OA", CTF = 3.2% of tibial plateau

Fig. 4 CTF subluxation in mild (**a**) and severe (**b**) knee OA

There are a few limitations of the current study. First, the study was a retrospective radiographic review and did not evaluate clinical outcomes. Second, although the weight-bearing radiographs were obtained following a standardized protocol, these radiographs are still subjected to rotational variations which may influence the measurements. Third, the measurements were performed on coronal radiographs of the knee and did not include sagittal plane evaluation. Fourth, since radiographs are the only weight-bearing imaging modality available in the clinical setup, we relied on the assumption that the subchondral bone is parallel to the cartilage surface. Furthermore, the absence of age-matched controls does not allow evaluation for normal change over time as a "normal age-related" CTF subluxation. Finally, we are not able to determine the clinical impact of changes in the CTF subluxation in this study. Despite these limitations, this study highlights a common finding in knee OA and presents a unique measurement method.

In conclusion, our data suggests that CTF subluxation is a radiographic finding related to knee OA occurring mainly in the early stages of the osteoarthritic process of the knee and stagnating as OA progresses. However, malalignment is an ongoing process throughout all the various stages of OA which may contribute to OA progression. Further studies should be conducted for a deeper understanding of CTF subluxation and to reveal the clinical consequences related to this finding.

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Compliance with ethical standards None

Conflict of interest No conflict of interest

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