Coronal tibiofemoral subluxation: a new measurement method

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ABSTRACT

Background: Coronal tibiofemoral (CTF) subluxation is a common finding in knee osteoarthritis (OA) which can be related to poor pain scores and tibial spine impingement. In this study we describe a new method for measuring CTF subluxation and present validation of the method using cadaveric knees.
Methods: A prototype software code based on the ICP mathematical algorithm was developed to measure CTF subluxation; the code finds the rigid transformation that best aligns the articular surfaces, measures CTF subluxation and the angle between articular surfaces. For validation, three stripped fresh frozen cadaveric knee specimens were transfixed to a specially designed knee fixation device where tibiofemoral angle and CTF subluxation can be measured directly. Fluoroscopic images were obtained with the tibiofemoral joint in neutral alignment and with 5, 10 and 15 (mm) of medial and lateral subluxation. This procedure was repeated with a neutral tibiofemoral angle, 10° of varus and 10° of valgus. All images were analyzed independently by two investigators using the prototype software.
Results: The interclass correlation coefficient between the two investigators for CTF subluxation and tibiofemoral angle was 0.93 and 0.99 respectively. The CTF subluxation and tibiofemoral angle measured by the software correlated to the CTF subluxation and tibiofemoral angle were defined using the knee fixation device, with Pearson product moments of 0.86 and 0.94 respectively.
Conclusion: Our suggested prototype software is precise, repeatable and reliable at measuring CTF subluxation and tibiofemoral angle. It may prove to be a useful tool to evaluate CTF subluxation in a clinical setting.

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1. Introduction

Osteoarthritis (OA) of the knee is a leading cause of chronic disability [1,2] with a multifactorial etiology [2]. Previous studies have shown that altered tibiofemoral mechanics due to lower limb malalignment [3–5], obesity [6], meniscal injuries [7], and other factors causing tibiofemoral incongruence [8] may increase the risk for focal stress points across the joint and lead to degenerative joint changes. Lower limb malalignment is frequently accompanied by medial or lateral coronal tibiofemoral (CTF) subluxation, a common finding in knee OA, that may exacerbate tibiofemoral incongruence, cause impingement of the tibial spine on the femoral condyle [9], and result in inferior Western Ontario and McMaster Universities (WOMAC) pain scores [10].

The anatomy of the tibiofemoral joint lacks specific landmarks for accurate measurement of medial and lateral translation in the coronal plane. A previous study that analyzed radiographs of normal lower limb alignment was unable to define the center of the knee in the coronal plane and suggested five different points that had a maximum separation of 5 mm [11].

The Iterative Closest Point (ICP) algorithm is a commonly used method for matching 2-dimensional (2D) and 3-dimensional (3D) surfaces and curves [12]. The algorithm is based on the principle that any surface or curve can be digitized and represented as a cloud of points on a coordinate system; the algorithm then seeks to minimize the sum of square distances between two clouds of points (in this study the two clouds of points represent the digitized articular surfaces of the tibia and femur obtained from knee radiographs), and finds the rigid transformation (translation and rotation) that best aligns these two clouds of points.

To our knowledge, an accurate and repeatable validated method for measuring CTF subluxation has not been described in the literature. The purpose of this study was to describe and validate a new method for measuring CTF subluxation.

2. Methods

A special prototype software code (Matlab, 2012a, MathWorks, Natick, MA) was developed to measure CTF subluxation. Using knee radiographs the software enabled manual digitization of the tibial and

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femoral weight bearing surfaces around the knee into X and Y coordinates (Fig. 1 A). Each articular surface was represented as "Cloud of Points" with known coordinates (Fig. 1 B). The prototype software code also included an ICP algorithm which performed a rigid transformation that best aligned the digitized tibial surface to the femoral surface. The tibiofemoral joint line was defined as the horizontal axis of the coordinate system. Therefore, horizontal translation as measured by the ICP algorithm represented CTF subluxation and the rotation represented the angle subtended by the femoral and tibial articular surfaces (Fig. 1 C).

For the purposes of validation, three fresh frozen cadaveric knee specimens were stripped of all soft tissue and transfixed to a specially designed knee fixation device (Fig. 2). The femur was stable and the tibia was free to rotate into varus or valgus and translate medially or laterally. A ruler and protractor were attached to the device, enabling direct measurement of the angle between the long axes of the femur and tibia in addition to the medial and lateral tibiofemoral translation. Prior to soft tissue stripping, the fixation device was calibrated by placing the knee specimen in a neutral position. As a baseline, fluoroscopic imaging (General Electric Healthcare, WI, USA) was obtained with the femur in neutral alignment relative to the tibia with all soft tissues intact. After calibration and soft tissue stripping, the tibia was translated 5, 10 and 15 mm in a medial direction followed by a lateral direction. This procedure was repeated, with the same subluxation values, with the knee in 10° of varus and 10° of valgus. Fluoroscopy images were taken in each position and the values of subluxation and angulation were recorded.

The time taken for manual digitization of each fluoroscopic image and running the code, i.e. the time needed for the prototype software code to perform the data analysis and compute the rotation and translation measurements, was recorded. CTF subluxation measurements using the prototype software code were done twice by two different investigators. The final digitization time, translation and rotation values were calculated by averaging the results obtained by each investigator.

2.1. Statistical analysis

Interclass correlation coefficients (ICC) were calculated to evaluate inter observer reliability for the code results and graded using
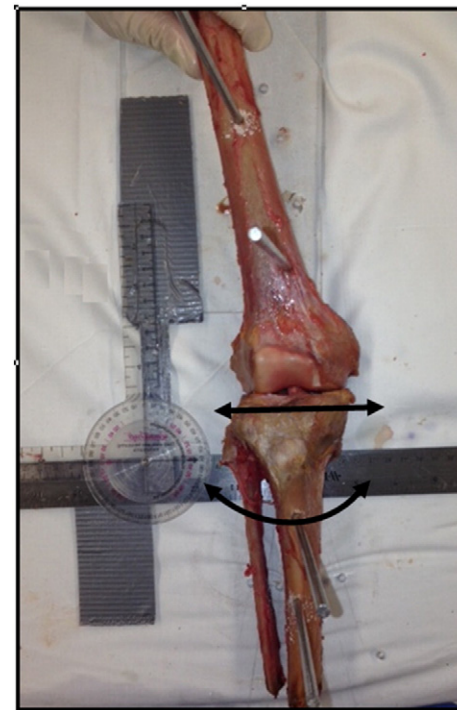

Fig. 2. Knee fixation device. The femur is stable and the tibia can be rotated and translated.

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 $0.0 \leq p \leq 0.24$ [13]. The Pearson product moment correlation was used to determine the correlation between horizontal translation and rotation as calculated by the prototype software and values for horizontal translation and rotation as measured in the knee fixation device.
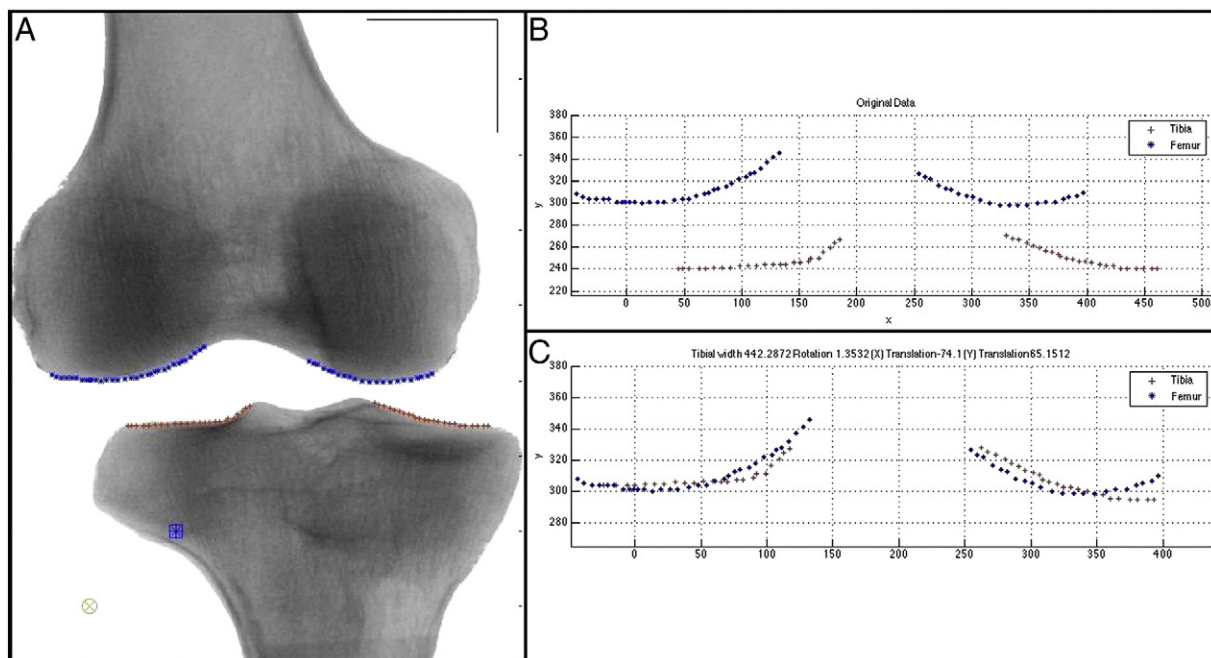

Fig. 1. Digitization of femoral and tibial articular surfaces (A). The digitized surfaces on coordinate system (B). The results after running the ICP algorithm producing optimally aligned articular surfaces (C).

Table 1
Demonstrates the Pearson product moments and Interclass correlation coefficients for the measurements of the coronal tibiofemoral subluxation and the angle between articular surfaces.

	Pearson product moment	Interclass correlation coefficient
Coronal tibiofemoral subluxation	0.86	0.93
Angle between articular surfaces	0.94	0.99

3. Results

As illustrated in Table 1, the interclass correlation coefficient (ICC) between the two investigators for CTF subluxation was 0.93. The ICC between the two investigators for the angle between femoral and tibial articular surfaces was 0.99. The CTF subluxation as measured by the prototype software correlated to horizontal tibial subluxation measured using the knee fixation device (Pearson product moment $r^2 = 0.86$). The angle between the femoral and tibial articular surfaces measured using the prototype software also correlated to the tibiofemoral angle measured using the knee fixation device ($r^2 = 0.94$). The mean time for digitization of the fluoroscopy images and running the ICP algorithm was 108 (± 8) seconds.

4. Discussion

Coronal tibiofemoral (CTF) subluxation and lower limb malalignment are common radiographic findings in OA of the knee. The current study has shown a strong correlation between CTF subluxation as measured by a prototype software code based on an ICP algorithm and CTF subluxation measured directly using a knee fixation device. A strong correlation was also found between tibiofemoral rotation measured using the prototype software and the angle between femoral and tibial axes measured using a knee fixation device. We propose that the prototype software described in this study is a reliable and repeatable tool for measuring CTF subluxation and lower limb alignment on antero-posterior knee radiographs without the need for full length hip to ankle radiographs.

Previous studies have discussed the clinical implications of CTF subluxation, including pain scores and tibial spine impingement [9,10,14] without presenting a method for measurement. In the current study we present a method for CTF subluxation measurement based on a highly precise mathematical algorithm which may provide an invaluable means for assessing the effect of CTF subluxation on multiple different knee pathologies.

The ICP algorithm is commonly used for evaluation of geometrical relationships and symmetry between surfaces. A high degree of accuracy has been shown using the ICP algorithm for matching bone surfaces [15,16] and orthopedic implants [17,18]. In addition, the presented method uses multiple points digitized from articular surfaces for calculation of CTF subluxation and therefore is highly accurate. The uniqueness of the method presented in the current study is its ability to analyze two variables, namely tibial rotation and translation, and to provide a highly precise measurement of each variable.

The 0.86 and 0.93 values of the Pearson product moment reported in the current study indicate a very high positive correlation in medical research literature [19,20], including a study presenting new methods for radiographic measurements around the knee [21]. In addition excellent ICC values 0.93 and 0.99 show that the presented method is highly reproducible when run multiple times by different observers.

This study has several limitations. Firstly, the presented method is based on a 2D imaging modality to describe a three dimension phenomenon. However, it does provide a method which can be used on 2D standing radiographs, which are commonly used in the clinical setting. Secondly, this method requires multiple points (nearly 80) on the articular surfaces, to be digitized in order to run the developed software code. However, the whole process of digitization and running the code was less than 2 min (average 108 s) in duration. Further, the use of multiple points minimized errors and showed a high inter observer

reliability. Thirdly, since the articular cartilage is not visible on radiographs, we relied on the assumption that the subchondral bone is parallel to the cartilage surface for the purposes of digitization. Therefore we believe that this method at present should only be used as a research tool with potential clinical applications in the future. In addition, it may be combined with other methods presented previously [22] in the literature for evaluation of the tibiofemoral joint with OA changes.

Despite the aforementioned limitations, this study presents a novel method for measuring CTF subluxation and tibiofemoral angle. We propose that the ICP-based method described in this study should be considered for use in future clinical and biomechanical studies investigating CTF subluxation, as it is accurate, precise and highly repeatable.

Conflicts of interest

None to declare.

Acknowledgments

None.

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