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Reliability of Determination of Bony Landmarks of the Distal Femur on MR Images and MRI-Based 3D Models

Background/Objective: Consistent determination of the anatomical landmarks on image or image-based three dimensional (3D) models is a basic requirement for reliable analysis of the human joint kinematics using imaging techniques. We examined the intra- and inter-observer reliability of determination of the medial and lateral epicondyle landmarks on 2D MR images and 3D MRI-based models of the knee.

Materials and Methods: Sixteen coronal plane MRI recordings were taken from 18 healthy knees using a knee coil with T2-weighted fast spin-echo sequence and 512×512 pixel size. They were then processed by the Mimics software to provide the coronal and axial plane views and to create a 3D image-based model of the femur. Each image was reviewed twice, at least one-day apart. The interclass correlation coefficient, standard error of measurement, and coefficient of variation were calculated to assess the intra- and inter-observer reliability of the landmark determination by six experienced radiologists. A mixed model analysis of variance (ANOVA) with two days of observation as the within-subject factor, and observers (six radiologists) and methods (2D vs. 3D) as between-subject factors were used to test the effect of observer, two days of observation and method of evaluation on landmark determination.

Results: The results indicated that the interclass correlation coefficients for the intra-observer and inter-observer determination of landmarks on images and image-based 3D models were above 0.97. The standard error of measurement ranged between 0.41 and 0.78 mm for x; 1.35 and 3.43 mm for y; and 1.03 and 4.71 mm for z coordinates. Furthermore, the results showed no significant difference for within and between-subject comparisons of each coordinate of the lateral epicondyle as well as x and z coordinates of the medial epicondyle. For the y coordinate of the medial epicondyle, the p value of within-subject comparison was borderlinely significant ($p=0.049$).

Conclusion: It was concluded that the intra- and inter-observer reliability of the bony landmark determination on both image and image-based 3D models were excellent.

Keywords: Reliability Analysis, Femur, Landmark Determination, MRI, 3D Model

Introduction

Three dimensional (3D) kinematic analysis of the human joints is of major interest among researchers from different disciplines, e.g., orthopedic surgery,[1,2] sports medicine and biomechanics.[3-5] A variety of imaging techniques, such as biplanar fluoroscopy, kinematic magnetic resonance imaging (MRI) and cine phase contrast MRI, have been developed to assess the in-vivo kinematics of joints in dynamic and quasistatic conditions.[1,3,6,7] Tracking techniques based on MRI have the advantages of being non-invasive and providing the possibility to recognize soft tissues in addition to bony structures. The validity of MRI against dissection,[8] 3D digitization[9] and combination of radiostereometry and CT scan (RSA/CT)[10] to analyze the knee joint kinematics has been assessed and acceptable

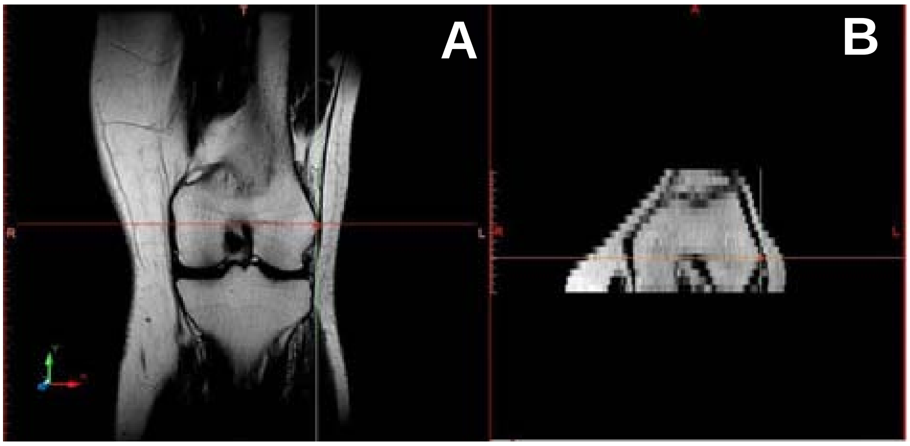

Fig. 1. An illustration of the coronal (A) and axial (B) plane views of the knee provided by Mimics software from MR images. The lateral epicondyle of the femur has been specified on the coronal image, indicating the x and y coordinates, and the axial image, indicating the x and z coordinates.

results have been reported. Furthermore, successful application of MRI based tracking techniques in clinical research studies has been reported.[3,11]

A basic requirement for kinematic analysis of the joints using imaging techniques is the determination of anatomic landmarks on image or image-based 3D bone models. Landmark-matching has been effectively used for registration of bone images to obtain their tracking in successive time intervals.[12] However, even when other registration methods, such as active shape model registration[13] are used, it is still necessary to determine some key bony landmarks manually to set up the joint local coordinate systems, so that the joint motion could be described and interpreted according to existing clinical paradigms. A typical example is the medial and lateral femoral epicondyles, which are used to define the flexion axis of the tibia about the femur in studying the kinematics of the knee joint. Moreover, bony landmarks of the femur and tibia have been used to establish the appropriate orientation of the implant compartments during arthroplasty.[14,15]

The importance of the consistent determination of anatomical landmarks for reliable kinematical analysis of the human joints has been realized and emphasized by several researchers.[16-19] It has been reported that inaccuracy and variability of determination of anatomical landmarks may result in significant error in some planes of motion as well as misinterpretation of the physiological joint motion.[4] However, there are limited studies in the literature concerning the reliability analysis of the bony landmarks determination on MR images. Although 3D kinematical analysis is usually conducted on 3D models of bones, to the best of our knowledge, the reliability of determination of bony landmarks on image-based 3D models has not been examined yet. The aim of this study was to evaluate intra-observer and inter-observer consistency in determination of bony landmarks on 2D MR images as well as the 3D MRI-based bone models.

Materials and Methods

MRI recordings were obtained from 18 knees of 17 subjects with no known abnormalities of the knee [12 male, six female; mean age: 30.7 years (±7.1 SD)] using Genesis Signa 1.5-T MR Scanner (General Electric, Fairfield, Conn). Subjects were excluded if there were any contraindications for MRI, a history of previous fracture as well as any radiological sign of bony lesions. A knee coil was used to generate the T2 fast spin-echo sequence of sixteen coronal plane images with a 512×512 pixel digital image system, 24 cm field of view, 4 mm thickness with no space. The imaging plane was adjusted to be perpendicular to the posterior and distal surfaces of both femoral condyles. The MR images were imported into Mimics software (Materialize Mimics, Asia-Pacific, Malaysia, Selangor) to provide the coronal and axial plane views (Fig. 1), and to create a 3D image-based model of the femur (Fig. 2). All subjects provided informed consent. Ethics approval for the study was obtained from Tehran University of Medical Sciences Human Research Ethics Committee.

A total of 6 experienced radiologists (three male and three female, with the mean age of 42.6 ± 6.2 and working experience of 10.4 ± 7.0 years as a radiologist) participated in this study as observers. They

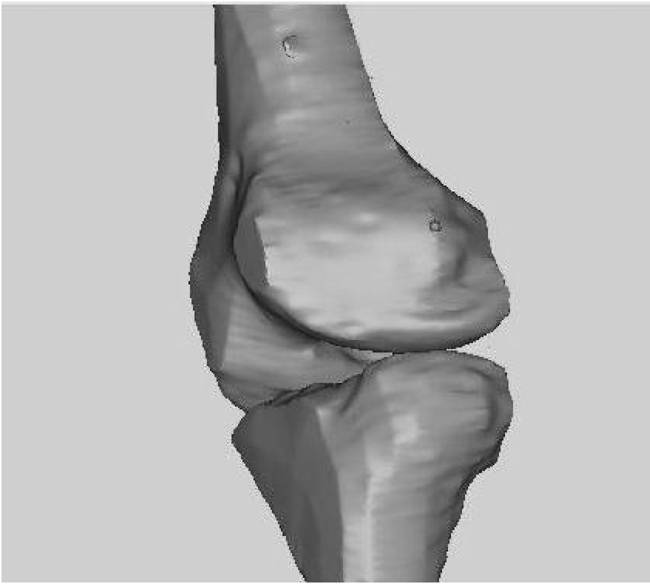

Fig. 2. An illustration of the 3D model of the knee provided by Mimics software from MR images. The lateral epicondyle of the femur has been specified in the 3D space.

were asked to identify two bony landmarks, the medial and lateral epicondyle of the femur, on the MR images and the 3D bone models. For the former, the observers first selected the most appropriate coronal slice among the sixteen available slices (Fig. 1A), indicating the z coordinate of the landmark, and then identified the most prominent point of the epicondyle within this slice, indicating the x and y coordinates of the landmark. The reconstructed axial view (Fig. 1B) was also used to confirm the x and z coordinates. For the latter, the observers could rotate the 3D bone model to any desired orientation to inspect the geometry of the model from different viewpoints and specify the landmarks in 3D space (Fig. 2). This procedure was repeated twice for each observer with at least a one day time interval to examine the intra-observer reliability. All coordinates were indicated in one-tenth of a millimeter.

The standard error of the measurement and interclass correlation coefficient were calculated for the three coordinates of each landmark in order to assess the intra-observer and inter-observer reliability. A mixed model analysis of variance (ANOVA) with two days of observation as the within-subject factor and observers (six radiologists) and methods (2D vs. 3D) as between-subject factors were used to test the effect of observer, two days of observation and method of evaluation on landmark determination. Furthermore, the effect of method-observation and their interactions were examined by ANOVA. The level of significance was set at 0.05. All statistical analyses were conducted using the SPSS statistical software package (version 16.0, SPSS Inc., Chicago, IL).

Results

The interclass correlation coefficients for the intra-observer and the inter-observer determination of each coordinate for each landmark on MR images and image-based 3D models were above 0.97 in all cases. There was no significant difference between two trails of observation using each method. The standard errors of measurement (SEM) for intra-observer and inter-observer variation of landmarks determination are indicated in Table 1. The range of SEM for x, y and z coordinates of the lateral and medial epicondyle landmarks were 0.41-0.78, 1.35-3.43 and 1.03-4.71 mm, respectively. In almost all cases, the SEM for determination of lateral epicondyle was less than the medial epicondyle.

Comparing means of each one of the lateral epicondyle coordinates, we ran a three way Mixed Model ANOVA in which we considered factors of method (2D vs. 3D) and observers (six radiologists) as between-subject factors—assessing the similarity of independent variables as inter-observer reliability—and different days of observation, as within-subject factor—assessing the similarity of dependent variables as intra-observer reliability.

Therefore, we totally had 24 different groups (six radiologists×2 methods×2 days) For the x coordinate, the p value of within-subject comparison was 0.31 and the p values for between-subject comparisons were 0.95 and 0.99 for method and radiologist factors, respectively. The same analysis was done for y and z coordinates of the lateral epicondyle and three coordinates of the medial epicondyle. The results are demonstrated in Table 2. The results showed no significant difference for within and between-subject comparisons of x, y and z coordinates of the lateral epicondyle as well as x and z coordinates of the medial epicondyle. For the y coordinate of the medial epicondyle, the p value of within-subject comparison was borderlinely significant ($p=0.049$).

Discussion

Kinematic analysis of the human joints can provide quantitative measures valuable for the development of new techniques in order to assess the level of injury and/or to evaluate the effectiveness of a particular treatment. For instance, the anterior tibial subluxation is widely used as a secondary sign to confirm the diagnosis of a ruptured anterior cruciate ligament, using 2D MRI images.[20,21] Furthermore, an accurate knowledge of the in vivo three dimensional kinematics of a joint can improve our understanding of the biomechanical behavior. Again the 3D positional relationships between the femur and the tibia can provide insight into the biomechanical function of the ACL.

An important source of error in kinematic analysis of the joints is due to the uncertainty in landmark determination. This is thought to affect the position and orientation specification of the joint axes considerably and to produce unreliable kinematic results. Several stereophotogrammetry and video-based motion analysis studies have consistently shown that inaccuracy and uncertainty in anatomical landmark determination may result in significant errors in joint kinematic measurement.[18,19] It has been suggested that image based kinematic analysis techniques may reduce such errors as a result of direct observation of the bony landmarks.[4] The results of the present study confirm this suggestion by demonstrating excellent consistency within an observer and between observers in the determination of bony landmarks from MR images and three dimensional bone models. Lerner et al.[22] also reported good reliability with an average SEM of 0.51 mm for inter-observer and 0.41 mm for intra-observer reliability in determining nine bony landmarks from MR images.

The findings of the present study also show that anatomical landmarks may be specified with excellent reproducibility and repeatability on image-based 3D bone models if an accurate segmentation algorithm is being used. Such an image-based 3D bone

Table 1. The Intra-Observer and Inter-Observer Standard Errors of Measurement for Each Coordinate of Landmarks

	X (mm)		Y (mm)		Z (mm)	
	Image	Model	Image	Model	Image	Model
Intra-observer						
MEP	0.46	0.46	2.56	3.43	4.71	3.08
LEP	0.41	0.54	1.8	2.08	1.03	1.29
Inter-observer						
MEP	0.44	0.45	2.09	3.07	3	2.9
LEP	0.41	0.78	1.35	2.47	1.28	1.33

MEP: Medial Epicondyle
LEP: Lateral Epicondyle

Table 2. Results of Three Way Mixed Model ANOVA Considering Successive Evaluations as Within-Subject Factors and Two Methods and Different Radiologists as Two Between-Factors.

Bony Landmark	Coordinate	Range of Means	Within Subject Contrast (Day 1 vs. Day 2)	P-Value	Between-Subject Contrast 1: Method (2D vs. 3D)	P-Value	Between-Subject Contrast 2: Radiologist (Six Radiologists)	P-Value
Lateral Epicondyle	X	118.9-123.3	119.2 vs 119.5	0.31	119.1 vs 119.6	0.95	119.1 up to 120.3	0.99
	Y	111-112.6	120.1 vs 118.8	0.08	119.7 vs 119.2	0.86	116.4 up to 121	0.93
	Z	-13.3--11.2	-12.27 vs -12.30	0.77	-12.2 vs -12.4	0.97	-12.8 up to -11.4	0.99
Medial Epicondyle	X	128.2-128.7	128.47 vs 128.48	0.83	128.4 vs 128.5	0.98	128.47 up to 128.57	0.99
	Y	112.7-118.6	115.5 vs 115.9	0.05	115.6 vs 115.9	0.92	114.4 up to 116.6	0.99
	Z	-20.3--14.2	-16.8 vs -16.4	0.26	-17.3 vs -15.9	0.7	-17.5 up to -15.2	0.99

model may provide continuous geometry of bony segments, so a more accurate determination of the bony landmarks might be expected to achieve by the possibility of landmark specification between the slices. However, the results of our study suggest that the level of uncertainty is not improved in this method and in fact the landmark determination procedure is more difficult and time consuming on 3D models in comparison with the plane images.

A detail investigation of the results of Table 1 shows that the error margin was higher for the y coordinate of the bony landmark than the other coordinates (x and z) using both methods. It may be partly due to the fact that the lateral and medial epicondyles have complicated morphologies consisting of elliptical surfaces extended in the superior-inferior direction. Therefore, they are difficult to be determined as single points particularly in the superior-inferior direction (y coordinate) which has a lower geometrical gradient. Furthermore, our results indicated a higher error margin for identification of the medial epicondyle compared to the lateral epicondyle which is probably due to the more inconspicuous morphology of the medial epicondyle.[23] Undoubtedly, a more clarified definition for the epicondyle could improve the accuracy of the landmark determination. In addition, by suggesting a predefined strategy including the imaging plane adjustment procedure, the subject's positioning procedure, the landmark determination procedure could lead to further refinement of the landmark specification on MR images and the 3D bone model.

In conclusion, our results suggest that the bony landmarks may be determined reliably on both MR images and image-based methods. There is some difference between the results of the two methods; however, these differences are most likely of no clinical significance.

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References

1. Defrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, Li G. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. Am J Sports Med 2006;34(8):1240-6.
2. Mishima S, Takahashi S, Kondo S, Ishiguro N. Anterior tibial subluxation in anterior cruciate ligament-deficient knees: quantification using magnetic resonance imaging. Arthroscopy 2005;21(10):1193-6.
3. Barrance PJ, Williams GN, Snyder-Mackler L, Buchanan TS. Altered knee kinematics in ACL-deficient non-copers: a comparison using dynamic MRI. J Orthop Res 2006;24:132-40.
4. Andriacchi TP, Alexander EJ. Studies of human locomotion: past, present and future. J Biomech 2000;33(10):1217-24.
5. Andriacchi TP, Briant PL, Bevill SL, Koo S. Rotational changes at the knee after ACL injury cause cartilage thinning. Clin Orthop Relat Res 2006;442:39-44.
6. Dennis DA, Mahfouz MR, Komistek RD, Hoff W. In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics. J Biomech 2005;38(2):241-53.
7. Scarvell JM, Smith PN, Refshauge KM, Galloway H, Woods K. Comparison of kinematics in the healthy and ACL injured knee using MRI. J Biomech 2005;38(2):255-62.
8. Iwaki H, Pinskerova V, Freeman MA. Tibiofemoral movement 1: the shapes and relative movements of the femur and tibia in the unloaded cadaver knee. J Bone Joint Surg Br 2000 Nov;82(8):1189-95.
9. Martelli S, Pinskerova V. The shapes of the tibial and femoral articular surfaces in relation to tibiofemoral movement. J Bone Joint Surg Br 2002 May;84(4):607-13.
10. McPherson A, Kärrholm J, Pinskerova V, Sosna A, Martelli S. Imaging knee position using MRI, RSA/CT and 3D digitisation. J Biomech 2005;38(2):263-8.
11. Sheehan FT, Zajac FE, Drace JE. In vivo tracking of the human patella using cine phase contrast magnetic resonance imaging. J Biomech Eng 1999;121(6):650-6.
12. Shefelbine SJ, Ma CB, Lee KY, Schrumpf MA, Patel P, Safran MR, Slavinsky JP, Majumdar S. MRI analysis of in vivo meniscal and tibiofemoral kinematics in ACL-deficient and normal knees. J Orthop Res 2006;24(6):1208-17.
13. Meakin JR, Smith FW, Gilbert FJ, Aspden RM. The effect of axial load on the sagittal plane curvature of the upright human spine in vivo. J Biomech 2008;41(13):2850-4.
14. Lotke PA, Ecker ML. Influence of positioning of prosthesis in total knee replacement. J Bone Joint Surg Am 1977;59(1):77-9.
15. Longstaff LM, Sloan K, Stamp N, Scaddan M, Beaver R. Good alignment after total knee arthroplasty leads to faster rehabilitation and better function. J Arthroplasty 2009;24(4):570-8.
16. Manal K, McClay I, Richards J, Galinat B, Stanhope S. Knee moment profiles during walking: errors due to soft tissue movement of the shank and the influence of the reference coordinate system. Gait Posture 2002;15(1):10-7.
17. Stagni R, Fantozzi S, Cappello A, Leardini A. Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects. Clin Biomech (Bristol, Avon) 2005;20(3):320-9.
18. Sangeux M, Marin F, Charleux F, Durselen L, Ho Ba Tho MC. Quantification of the 3D relative movement of external marker sets vs. bones based on magnetic resonance imaging. Clin Biomech (Bristol, Avon) 2006;21(9):984-91.
19. Cappozzo A, Catani F, Leardini A, Benedetti MG, Croce UD. Position and orientation in space of bones during movement: experimental artefacts. Clin Biomech (Bristol, Avon) 1996;11(2):90-100.

20. Niitsu M, Kuramochi M, Ikeda K, Fukubayashi T, Anno I, Itai Y. [Secondary signs of anterior cruciate ligament tear at MR imaging]. Nippon Igaku Hoshasen Gakkai Zasshi 1995;55(6):375-9.
21. Vahey TN, Hunt JE, Shelbourne KD. Anterior translocation of the tibia at MR imaging: a secondary sign of anterior cruciate ligament tear. Radiology 1993;187(3):817-9.
22. Lerner AL, Tamez-Pena JG, Houck JR, Yao J, Harmon HL, Salo AD et al. The use of sequential MR image sets for determining tibiofemoral motion: reliability of coordinate systems and accuracy of motion tracking algorithm. J Biomech Eng 2003;125(2):246-53.
23. Griffin FM, Math K, Scuderi GR, Insall JN, Poilvache PL. Anatomy of the epicondyles of the distal femur: MRI analysis of normal knees. J Arthroplasty 2000;15(3):354-9.