Published in final edited form as:

J Biomech Eng. 2011 January ; 133(1): 014502. doi:10.1115/1.4002938.

Comparison of MRI-Based Estimates of Articular Cartilage Contact Area in the Tibiofemoral Joint

Christopher E. Henderson,

Center for Biomedical Engineering Research, 201A Spencer Laboratory, University of Delaware, Newark, DE 19716

Jill S. Higginson, and

Center for Biomedical Engineering Research, 201A Spencer Laboratory, University of Delaware, Newark, DE 19716

Peter J. Barrance

Rehabilitation Engineering and Analysis Laboratory, Kessler Foundation Research Center, 1199 Pleasant Valley Way, West Orange, NJ 07052

Christopher E. Henderson: chende@udel.edu; Jill S. Higginson: higginson@udel.edu; Peter J. Barrance: pbarrance@kesslerfoundation.org

Abstract

Knee osteoarthritis (OA) detrimentally impacts the lives of millions of older Americans through pain and decreased functional ability. Unfortunately, the pathomechanics and associated deviations from joint homeostasis that OA patients experience are not well understood. Alterations in mechanical stress in the knee joint may play an essential role in OA; however, existing literature in this area is limited. The purpose of this study was to evaluate the ability of an existing magnetic resonance imaging (MRI)-based modeling method to estimate articular cartilage contact area in vivo. Imaging data of both knees were collected on a single subject with no history of knee pathology at three knee flexion angles. Intra-observer reliability and sensitivity studies were also performed to determine the role of operator-influenced elements of the data processing on the results. The method's articular cartilage contact area estimates were compared with existing contact area estimates in the literature. The method demonstrated an intra-observer reliability of 0.95 when assessed using Pearson's correlation coefficient and was found to be most sensitive to changes in the cartilage tracings on the peripheries of the compartment. The articular cartilage contact area estimates at full extension were similar to those reported in the literature. The relationships between tibiofemoral articular cartilage contact area and knee flexion were also qualitatively and quantitatively similar to those previously reported. The MRI-based knee modeling method was found to have high intra-observer reliability, sensitivity to peripheral articular cartilage tracings, and agreeability with previous investigations when using data from a single healthy adult. Future studies will implement this modeling method to investigate the role that mechanical stress may play in progression of knee OA through estimation of articular cartilage contact area.

Keywords

osteoarthritis; magnetic resonance imaging; contact area

1 Introduction and Background

Tibiofemoral osteoarthritis is a pathological condition that is characterized by a narrowing of the joint space between the tibia and femur, development of osteophytes, and articular cartilage degradation. It has been shown to affect approximately 12% of people greater than 60 years of age, and estimates of annual medical and lost work expenses due to osteoarthritis are greater than \$60 billion in the United States [1].

Previous investigators have suggested that OA represents a failure of the joint to perform necessary cellular maintenance due to excessive local mechanical stresses [2]. In a simplified representation, mechanical stress is directly proportional to the load applied across the joint and inversely proportional to contact area. Consequently, increased stress can be due to increased load or decreased contact area. Data from an instrumented prosthesis have shown that a significant correlation exists between medial contact force and knee adduction moment [3], while another study has identified increased knee adduction moment during gait as a risk factor for progression of knee OA [4]. The results from these studies support the idea that axial loading is a key component in OA progression; however, the relationship between contact area and OA progression is not well understood. Contact area may change in OA due to any combination of factors including increased cartilage compliance, meniscal extrusion, cartilage degradation, or osteophyte formation.

Cadaveric studies involving the use of pressure sensitive film have been a popular in vitro modality for studying tibiofemoral contact area [5,6]. Implications from these studies were limited by the removal of surrounding soft tissues and application of arbitrary loads. More recently, MRI has been used as a tool to assess knee joint contact area in vivo. Studies of knee joint contact area have been performed in several pathological populations including patellar subluxations [7] and anterior cruciate ligament (ACL) deficiencies [8], and a single study was found that indirectly investigated contact area in knee OA [9].

Previous MRI-based studies have estimated cartilage contact area by manually identifying portions of the articular cartilage that appear to be in contact and multiplying this measure by the slice thickness [8,10–12]. This methodology is not ideal as the accuracy of the contact area measure is dependent on the through plane resolution (slice spacing). A recent investigation generated tibiofemoral joint models from nonweightbearing MRI and matched these models to weightbearing coronal and sagittal radiographs while assuming an arbitrary cartilage thickness in order to estimate the contact area as the overlap of the cartilage surfaces [9].

In this study, we applied a MRI-based method to estimate articular cartilage contact area at the tibiofemoral joint. In this method, a three-dimensional model is used to generate estimates of contact area from MR images acquired during standing [13–15]. This method has been previously validated for the measurement of joint kinematics [16]; however, its ability to estimate articular cartilage contact area has not been thoroughly investigated. Intra-observer reliability, sensitivity to cartilage tracings, and a comparison to previous, similar studies was performed. It was hypothesized that the method would produce measurements of articular cartilage contact area in a single, healthy subject similar to those found in the literature at both full extension and across a range of knee flexion angles.

2 Methods

A single female subject (age: 52 years, height: 1.68 m, weight: 72.3 kg, and BMI: 25.7 kg/m²) with no history of knee pathology was recruited from the local community for participation in this study. Approval of this study was granted by the University of

Delaware's Human Subjects Review Board, and the subject signed an informed consent form prior to participating.

Imaging data were acquired using a 0.6 T open MRI scanner (Upright Multi-position MRI, Fonar Corporation, Melville, NY). T1 fast spin echo sequence, weightbearing scans comprised of 30 3 mm thick sagittal slices, spaced 3.3 mm apart, with a field of view of 25 cm, echo time of 20 ms, repetition time of 355 ms, and a display matrix of 512×512 were acquired. For each scan, calibration of the scanner took 1 min and imaging data were acquired in approximately 4.5 min. Scans were oriented along the long axis of the femur, and the 15th slice was aligned with the femoral notch. Both knees were imaged in full knee extension at approximately full weightbearing (patient table at 5 deg inclined back from vertical) and partial weightbearing (patient table at 45 deg from vertical). Partial weightbearing scans were also acquired with 15 deg and 30 deg knee flexion relative to subject specific full extension. Data collection for the eight MRIs lasted at approximately 2 h.

Structures within the MR images were traced using a digitizing tablet (Wacom Technology Corporation, Vancouver, WA) and IMOD software [17]. Surfaces of the distal femur, proximal tibia, and their respective medial and lateral compartment articular cartilage surfaces were identified. The medial and lateral compartments were separated by the sagittal MRI slice that contained the femoral notch. The digitized points were input into an existing three-dimensional modeling method [13–16]. Joint coordinate systems were applied to determine actual knee flexion angles [18].

Articular cartilage contact area was estimated for each compartment independently. A two-dimensional 100×100 grid was created from the tibial cartilage of the respective compartment. Within each grid space, the distance from the surface of the tibial cartilage to the surface of the nearest femoral cartilage was determined. If the minimum distance was not greater than 0.5 mm, the grid space was considered to be in contact.

2.1 Method Sensitivity

Subject motion during imaging has the potential to generate suboptimal images, which in turn can make it difficult to accurately assess the cartilage surfaces. The method's sensitivity to this motion was evaluated by removing tibial and femoral cartilage digitalizations on image slices and evaluating their effect on the articular cartilage contact area estimate. The images that comprised the medial compartment were separated into thirds (medial, middle, and lateral). Within each third, four variations of cartilage tracings were deleted: tibial cartilage on one slice, femoral cartilage on one slice, both tibial and femoral cartilage on one slice, and both tibial and femoral cartilage on two slices. Sensitivity was assessed by determining the relative change in articular cartilage contact area that resulted from the deletion of the cartilage tracings.

2.2 Intra-Observer Reliability

Reliability of the manual tracings was assessed by retracing the set of MRIs after a period of 30 days had passed. The articular cartilage contact area estimates were compared, and the correlation coefficient was used to estimate intra-observer reliability. The mean coefficient of variation (CV) for each compartment was also determined.

2.3 Comparison to Previous Investigations

A comprehensive search of online databases was performed to identify previous studies that investigated tibiofemoral contact area. Only studies that reported on healthy subjects were

included and investigations that included meniscal contact were excluded. Both overall magnitudes of contact area as well as relationships with knee flexion were identified.

3 Results

3.1 Method Sensitivity

The results from the assessment of sensitivity of the method are shown as a percentage difference from the original baseline contact area estimate (Table 1). Decreases in medial compartment articular cartilage contact area estimates of 3.2–28.6% across both knees were seen in the medial third, while the contact area estimate increased slightly in some permutations and decreased 8.9% maximally in the middle third. The lateral third of the medial compartment was found to be most sensitive to the cartilage tracings. Deletions of cartilage surfaces in this third were found to decrease the compartment cartilage contact area by 19.2–49.3%.

3.2 Intra-Observer Reliability

The original tracings and retracings after 30 days had passed were found to have a correlation coefficient of 0.86 for the eight scans of the medial compartment and 0.95 when the contact area estimates of both compartments were considered (Fig. 1). Mean CV of the medial and lateral compartments were found to be 15.1% and 19.9%, respectively. At full weightbearing and full extension, mean articular cartilage contact areas of $511.0 \pm 143.1 \text{ mm}^2$ and $256.4 \pm 40.3 \text{ mm}^2$ were found for the medial and lateral compartments of both knees, respectively. Partial weightbearing scans (Fig. 2) demonstrated a decrease in both medial and lateral compartment articular cartilage contact area with increasing knee flexion.

3.3 Comparison to Previous Investigations

Two cadaver and three MRI-based investigations were identified in the literature that studied articular cartilage contact area at full extension. Within the five investigations, medial and lateral compartment articular cartilage contact area averaged 373 mm^2 and 213 mm^2 at full extension while experiencing a mean 137 N external load, respectively (Table 2).

A single cadaveric study and two MRI-based studies were found in the literature that investigated articular cartilage contact area at a range of knee flexion angles. A mean external load of 62 N was applied in these studies. At 0 deg knee flexion, medial and lateral compartment articular cartilage contact area averaged 447 mm^2 and 265 mm^2 , respectively. At 15 deg knee flexion, medial compartment articular cartilage contact area averaged 378 mm^2 , while the lateral compartment averaged 268 mm^2 within the literature. At 30 deg, articular cartilage contact area averaged 278 mm^2 and 132 mm^2 in the medial and lateral compartments, respectively (Table 3).

4 Discussion

4.1 Method Sensitivity

Cartilage tracings on slices were deleted in order to simulate subject motion and evaluate the effect that this might have if the observer were unable to identify the surface on a particular slice. The results suggest that the outer sagittal slices of the compartment are most sensitive to incomplete cartilage tracings while deletions of cartilage in the middle third of the compartment have a relatively low effect on the method's ability to estimate articular cartilage contact. It is important to keep in mind that although this test did attempt to quantify the sensitivity of the method, it is highly unlikely that there would be enough motion for no cartilage surface to be traced on even a single slice. Subject motion could lead

to incomplete cartilage digitization on a single slice, but would rarely if ever obscure the complete cartilage surface on a single slice.

4.2 Intra-Observer Reliability

Acceptable intra-observer reliability for cartilage contact area was found. Previous studies have reported mean CVs of 3.0% for intra-observer reliability for the patellofemoral joint [11] and 5.0% on a MRI phantom [12]. Our overall mean CV of 17.5% is much higher than previous studies; however, since we attempted to model the complex geometry of the tibiofemoral joint, this is to be expected. The investigators were unable to find a previous study that specifically assessed their ability to measure this contact area and as such makes it difficult to determine the acceptability of this measure.

4.3 Comparison to Previous Investigations

Our articular cartilage contact area estimate matches well with previous literature. Our reported contact areas at full knee extension were slightly higher than the literature averaged; however, the greater external load experienced by our subject may account for the difference. It is important to keep in mind that generating a mean external load for each study does not accurately identify the load across the joint. The MRI-based studies also have internal loads generated from the soft tissues and muscles spanning the joint that would need to be accounted for in order to accurately determine the load across the joint.

The literature produced greater contact area estimates at all three knee flexion angles investigated in spite of a decreased external load when compared with the current study. The three investigations that were found that studied contact area across several knee flexion angles were a subset of the studies that investigated contact area at full knee extension. Without contact area data from the other investigations at these knee flexion angles, it is not possible to conclude whether the magnitude of the external load explains the difference in contact area across the methodologies.

Decreasing articular cartilage contact area with increasing knee flexion in the medial compartment of the tibiofemoral joint agrees with a previous cadaveric study [6] and MRI-based investigations [7,12], while results on the effect of knee flexion on the articular cartilage contact area in the lateral compartment have been mixed. Previous investigations found that increasing knee flexion decreased [6], increased [7], or had a negligible effect [12] on lateral compartment contact area. It is also important to keep in mind that our results are from a single subject, and incorporation of more subjects would increase accuracy in our estimate of articular cartilage contact area and its relationship with knee flexion.

5 Conclusions

Tests to establish confidence in the ability of an existing MRI-based knee modeling method to estimate articular cartilage contact area were performed. Intra-observer reliability was found to measure 0.95, and the method was found to be sensitive to incomplete cartilage digitalizations on the peripheries of the compartment. As a result of the sensitivity to peripheral cartilage digitalizations, cartilage surfaces should be digitized and modeled twice, with an average taken to more closely estimate articular cartilage contact area. Data from a single, healthy subject were found to be comparable to previous studies in both magnitude of contact area and the relationship with knee flexion. Future studies will apply this method to osteoarthritic joints in order to elucidate differences with the healthy population and garner an improved understanding of the differences in cartilage contact area that result from the pathology.

Acknowledgments

The investigators would like to thank Diagnostic Imaging Associates for use of their MRI scanner and our funding source NIH through Grant No. 2P20-RR16458.

References

1. Buckwalter JA, Saltzman C, Brown T. The Impact of Osteoarthritis: Implications for Research. *Clin. Orthop. Relat. Res.* 2004; 427S:S6–S15. [PubMed: 15480076]
2. Brandt KD, Dieppe P, Radin EL. Etiopathogenesis of Osteoarthritis. *Rheum. Dis. Clin. North Am.* 2008; 34(3):531–559. [PubMed: 18687271]
3. Zhao D, Banks SA, Mitchell KH, D'Lima DD, Colwell CW Jr, Fregly BJ. Correlation Between the Knee Adduction Torque and Medial Contact Force for a Variety of Gait Patterns. *J. Orthop. Res.* 2007; 25(6):789–797. [PubMed: 17343285]
4. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic Load at Baseline Can Predict Radiographic Disease Progression in Medial Compartment Knee Osteoarthritis. *Ann. Rheum. Dis.* 2002; 61(7):617–622. [PubMed: 12079903]
5. Fukubayashi T, Kurosawa H. The Contact Area and Pressure Distribution Pattern of the Knee: A Study of Normal and Osteoarthrotic Knee Joints. *Acta Orthop. Scand.* 1980; 51(1–6):871–879. [PubMed: 6894212]
6. Kettelkamp DB, Jacobs AW. Tibiofemoral Contact Area—Determination and Implications. *J. Bone Jt. Surg., Am. Vol.* 1972; 54(2):349–356.
7. Hinterwimmer S, Gotthardt M, von Eisenhart-Rothe R, Sauerland S, Siebert M, Vogl T, Eckstein F, Graichen H. In Vivo Contact Areas of the Knee in Patients With Patellar Subluxation. *J. Biomech.* 2005; 38(10):2095–2101. [PubMed: 16084210]
8. Shefelbine SJ, Ma CB, Lee KY, Schrupf 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):1208–1217. [PubMed: 16652339]
9. Segal NA, Anderson DD, Iyer KS, Baker J, Torner JC, Lynch JA, Felson DT, Lewis CE, Brown TD. Baseline Articular Contact Stress Levels Predict Incident Symptomatic Knee Osteoarthritis Development in the MOST Cohort. *J. Orthop. Res.* 2009; 27(12):1562–1568. [PubMed: 19533741]
10. Besier TF, Draper CE, Gold GE, Beaupré GS, Delp SL. Patellofemoral Joint Contact Area Increases With Knee Flexion and Weight-Bearing. *J. Orthop. Res.* 2005; 23(2):345–350. [PubMed: 15734247]
11. Gold GE, Besier TF, Draper CE, Asakawa DS, Delp SL, Beaupre GS. Weight-Bearing MRI of Patellofemoral Joint Cartilage Contact Area. *J. Magn. Reson Imaging.* 2004; 20(3):526–530. [PubMed: 15332263]
12. Patel VV, Hall K, Ries M, Lotz J, Ozhinsky E, Lindsey C, Lu Y, Majumdar S. A Three-Dimensional MRI Analysis of Knee Kinematics. *J. Orthop. Res.* 2004; 22(2):283–292. [PubMed: 15013086]
13. Barrance, P.; Pepe, TM.; Buchanan, TS. In Vivo Kinematics Measured in Weight-Bearing Flexion Using Standing Magnetic Resonance Imaging. *Proceedings of the 2005 Summer Bioengineering Conference*; Vail, CO. 2005.
14. Barrance, PJ.; Buchanan, TS. Knee Cartilage Contact Determination Using Weightbearing MRI. *Proceedings of the 2006 Summer Bioengineering Conference*; Amelia Island, FL. 2006.
15. Barrance, PJ.; Benoit, DL.; Twomey, J.; Buchanan, TS. MRI-Based Modeling of Changes in Knee Positioning and Cartilage Contact Related to Injury and Weightbearing. *Proceedings of the 2006 World Congress of Biomechanics*; Munich, Germany. 2006.
16. Barrance, P.; Pohl, M.; Noehren, B.; Barrios, J.; Davis, I. Bone Surface Tracking for Standing Knee MRI: A Validation Study. *Proceedings of the 2007 American Society of Biomechanics Annual Conference*; Stanford, CA. 2007. p. 1-10.
17. Kremer JR, Mastronarde DN, McIntosh JR. Computer Visualization of Three-Dimensional Image Data Using IMOD. *J. Struct. Biol.* 1996; 116(1):71–76. [PubMed: 8742726]

18. Grood ES, Suntay WJ. A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee. *ASME J. Biomech. Eng.* 1983; 105(2):136–144.
19. Périé D, Hobatho MC. In Vivo Determination of Contact Areas and Pressure of the Femorotibial Joint Using Non-Linear Finite Element Analysis. *Clin. Biomech. (Bristol, Avon)*. 1998; 13(6): 394–402.

Fig. 1.
Correlation of two tracings of same MRI set after 30 days had passed

Fig. 2. Articular cartilage contact area estimate at partial weightbearing. Points represent mean of original and retracing. Both compartments demonstrate a decrease in articular cartilage contact area with increasing knee flexion.

Table 1

Results of evaluation of method sensitivity. Modeling method was found to be most sensitive to cartilage tracings on the periphery of the compartment.

	Slices with tibial cartilage removed	Slices with femoral cartilage removed	Percent difference from baseline		
			Right knee	Left knee	Average
Medial 1/3	1	0	10.7	3.9	10.6
	0	1	9.0	3.2	
	1	1	10.7	3.8	
	2	2	28.6	15.3	
Middle 1/3	1	0	-1.7	5.7	2.4
	0	1	3.8	-2.4	
	1	1	1.6	0.7	
	2	2	2.8	8.9	
Lateral 1/3	1	0	25.0	20.1	27.6
	0	1	22.2	19.2	
	1	1	24.9	20.7	
	2	2	49.3	39.2	

Table 2

Summary of articular cartilage contact area results at full extension found in the literature. Note: ~ Identifies data interpreted from figures.

Investigators	Study technique	Number of subjects	External load applied (N)	MC contact area (mm ²)	LC contact area (mm ²)
Hinterwimmer et al. [7]	MRI	12	0	487	220
Kettelkamp and Jacobs [6]	Cadaver	14	29–79	~480	~300
Fukabayashi and Kurosawa [5]	Cadaver	7	500	240	160
Patel et al. [12]	MRI	10	133	374	276
Périé and Hobatho [19]	MRI	1	0	283	111
Current study	MRI	1	365	511	256

Table 3

Summary of articular cartilage contact area results across range of knee flexion angles found in the literature.
 Note: ~ Identifies data interpreted from figures.

Investigators	Study technique	Number of subjects	External load applied (N)	0 deg flexion (mm ²)		15 deg flexion (mm ²)		30 deg flexion (mm ²)	
				MC	LC	MC	LC	MC	LC
Hinterwimmer et al. [7]	MRI	12	0	487	220			404	299
Kettelkamp and Jacobs [6]	Cadaver	14	29–79	~480	~300	~400	~270	~380	~250
Patel et al. [12]	MRI	10	133	374	276	~355	~265	~340	~270
Current study	MRI	1	259	393	191	335	162	278	132