Accepted

Knee Surgery, Sports Traumatology, Arthroscopy 22/5/2012

Title

The relationship between patellofemoral and tibiofemoral morphology and gait biomechanics following arthroscopic partial medial meniscectomy

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Abstract

Purpose: To examine the relationship between tibiofemoral and patellofemoral joint articular cartilage and subchondral bone in the medial and gait biomechanics following partial medial meniscectomy.

Methods: For this cross-sectional study, 122 patients aged 30-55 years, without evidence of knee osteoarthritis at arthroscopic partial medial meniscectomy, underwent gait analysis and MRI on the operated knee once for each sub-cohort of 3 months, 2 years, or 4 years post-surgery. Cartilage volume, cartilage defects, and bone size were assessed from the MRI using validated methods. The 1st peak in the knee adduction moment, knee adduction moment impulse, 1st peak in the knee flexion moment, knee extension range of motion, and the heel strike transient from the vertical ground reaction force trace were identified from the gait data.

Results: Increased knee stance phase range of motion was associated with decreased patella cartilage volume ($B = -17.9$ (95% CI-35.4, -0.4) $p = 0.045$) while knee adduction moment impulse was associated with increased medial tibial plateau area ($B = 7.7$ (95% 0.9, 13.3) $p = 0.025$). A number of other variables approached significance.

Conclusions: Knee joint biomechanics exhibited by persons who had undergone arthroscopic partial meniscectomy gait may go some way to explaining the morphological degeneration observed at the patellofemoral and tibiofemoral compartments of the knee as patients progress from surgery.

Level of Evidence: III

Keywords

osteoarthritis; magnetic resonance imaging; gait; biomechanics

Introduction

Meniscectomy is a common surgical procedure used to treat a symptomatic meniscal tear. It is well established that meniscectomy is a risk factor for the development of tibiofemoral osteoarthritis. There is also evidence that individuals who have undergone meniscectomy have a greater prevalence of radiographic osteoarthritis of the patellofemoral joint [13]. Furthermore, Wang and colleagues [36] reported that compared with controls, individuals that have undergone arthroscopic partial medial meniscectomy have a greater prevalence of cartilage defects in medial tibiofemoral and patellofemoral compartments, and greater medial tibial plateau bone area. Time from APMM was also found to be positively associated with cartilage defect prevalence in the medial tibiofemoral and patellofemoral compartments, and with medial tibial plateau area. The relationship between gait biomechanics following meniscectomy and the development of patellofemoral osteoarthritis is unclear and requires further study.

Gait biomechanics are thought to play an important role in the initiation and progression of knee osteoarthritis [1,26]. Individuals who have undergone meniscectomy exhibit alterations in gait biomechanics as early as three months post-surgery [32,33]. These altered gait biomechanics following meniscectomy have been implicated as causal factors underlying the high prevalence of tibiofemoral osteoarthritis in these persons compared to the general population [33]. Individuals with knee osteoarthritis exhibit larger adduction moments than healthy controls [35], and the magnitude of the knee adduction moment is positively associated with structural and functional progression of knee osteoarthritis [28,35] [27]. The knee abduction moment impulse and the heel strike transient force are also positively associated with medial knee osteoarthritis

severity [2,17,35] and could be related to this disease development following partial meniscectomy [30]. Much less is known about the relationship between gait biomechanics and the development of patellofemoral osteoarthritis. Biomechanical modeling has demonstrated that patellofemoral joint contact forces are a largely a function of the knee flexion angle and knee flexion-extension moment. In healthy controls, knee flexion-extension range of motion (ROM) during the stance phase [34] is positively associated with patella cartilage volume [23]. It is therefore reasonable to propose that relationships exist between alterations in gait biomechanics following meniscectomy and the development of patellofemoral osteoarthritis.

Magnetic resonance imaging (MRI) based measures are more sensitive to early structural changes in knee OA than standard radiographic measures [6,11,24]. It has previously been demonstrated that decreases in cartilage volume and increases in subchondral bone area [8,20] precede semi-quantitative measures of joint space narrowing measured from x-rays. Other changes that can be identified earlier using MRI include cartilage defects and changes in cartilage volume [9,25].

The aim of this study was to identify whether biomechanical gait variables were related to morphological changes in the patellofemoral and medial tibiofemoral compartments of the knee following arthroscopic partial meniscectomy. It was hypothesized that adduction moment related variables would be related to the medial tibiofemoral related morphological variables, while knee sagittal plane variables and the heel strike transient would be related to patellofemoral related morphological variables.

Materials and Methods

Participants from three separate studies were included, two based in Perth, Australia and one based in Melbourne, Australia. This was the same cohort as described in the study by Wang et al. [36]. All studies used the same inclusion and exclusion criteria. The protocols were approved by University of Western Australia and University of Melbourne Human Research Ethics Committees. All participants provided informed written consent prior to starting the study. Individuals were identified by their surgical billing codes. Initially, medical and surgical records of individuals who had undergone arthroscopic partial meniscectomy (APM) at orthopaedic clinics in Perth or Melbourne were screened using the following exclusion criteria: younger than 30 or older than 55 years; lateral meniscal resection; > 33% of their medial meniscus resected; > 2 tibiofemoral cartilage lesions; tibiofemoral cartilage lesion(s) greater than 10 mm in diameter or exceeding 50% of cartilage thickness (i.e., > 2a cartilage lesion); concomitant knee ligament damage and/or signs of knee osteoarthritis. Individuals that met the initial inclusion criteria were sent an information sheet by mail prior to being contacted by telephone approximately 1 week later and invited to undergo further screening. During the telephone screening the following secondary exclusion criteria were applied: previous lower limb bone or joint injury (other than that leading to the meniscectomy); history of knee pain; clinical or structural signs of lower limb osteoarthritis; post-operative complications; cardiac, circulatory or neuromuscular conditions; diabetes; stroke; multiple sclerosis and contraindication to MRI. One hundred and fifty-eight people met the eligibility requirement and provided their written informed consent to participate

in the study however 36 were excluded from the analyses due missing/incomplete data sets resulting in a sample of 122 participants.

Three independent groups were created (Table 1). The *four year post-surgical group* based in Perth underwent surgery between July 2000 and May 2001 and had MRIs taken 41-75 months post-surgery. The *two year post-surgical group* based in Melbourne underwent surgery between April 2005 and December 2006 and MRI 25-32 months post-surgery. The *three month post-surgical group* based in Perth underwent surgery between June 2005 and January 2008 and MRI 1-7 months post-surgery.

Table 1 Study population characteristics

	3 Month Group N = 41	2 Year Group N= 56	4 Year Group N=25
Age (years)	42.6 (5.6)	43.2 (5.4)	46.4 (6.5)
Time From Surgery to MRI (months)	3.8 (1.2)	28.2 (1.5)	53.9 (9.4)
Height (m)	1.78 (0.08)	1.75 (0.08)	1.76 (0.09)
Body Mass (kg)	83.5 (12.1)	82.2 (13.5)	82.1 (13.9)
Male, (n)	35 (85)	49 (87)	18 (72)
Medial Tibia Bone Area (mm ²)	2,442 (253)	2,433(291)	2,481(336)
Patella Bone Volume (mm ³)	19,483 (4,017)	20,226 (3,824)	19,225 (3,709)
Medial Tibial Cartilage Volume (mm ³)	1,931 (432)	1,849 (395)	1,908 (382)
Patella Cartilage Volume (mm ³)	3,749 (753)	3,892 (770)	3,861 (820)
Medial Tibiofemoral Cartilage Defects (n)	18 (43)	28 (50)	15 (60)
Patellofemoral Cartilage Defects (n)	4 (9)	11 (19)	2 (20)
Knee Range of Motion (°)	16.8 (5.3)	15.4 (5.4)	20.0 (10.4)
Peak Knee Adduction Moment (Nm)	41.6 (16.0)	34.9 (15.7)	49.5 (19.9)
Knee Adduction Moment Impulse (Nms)	13.2 (6.4)	12.6 (5.8)	16.9 (8.2)
Peak Knee Flexion Moment (Nm)	66.3 (27.8)	71.6 (26.6)	46.8 (24.2)
Heel Strike Transient Force (N)	666.5 (160.0)	551.5 (125.6)	614.5 (254.0)

Values expressed as mean (SD) or n (% of total)

MRI Assessment

MRI of the participants' operated knee was performed on 1.5-T whole body magnetic resonance units (City 1: Magnetom Symphony, Siemens, Erlangen, Germany; City 2: Phillips, Philips Medical Systems, Eindhoven, the Netherlands), using the sequence and parameters as previously described [25]. Body mass and height were measured in light clothing with no footwear, and body mass index (BMI) calculated.

Cartilage defects were graded in the medial tibiofemoral and patellofemoral compartments using a classification system where grade 0 represents normal cartilage and grade 4 full-thickness cartilage wear with exposure of subchondral bone [9]. A cartilage defect was defined as a score of ≥ 2 at any site. Intra- and inter-observer reliability (expressed as intra-class correlation coefficient) of this classification system are 0.89 to 0.94, and 0.85 to 0.93, respectively [9] with the method shown to have high sensitivity when compared to arthroscopic cartilage defect identification [10,40].

Patellar cartilage and bone volumes and medial tibial plateau cross sectional area were measured using Osiris (University Hospitals of Geneva, Switzerland), while medial tibial cartilage volume was measured using ImageJ (National Institutes of Health, USA), using our previously described techniques [21,37,38]. All measurements were performed by independent trained observers, with independent random cross checks blindly performed by a different trained observer, all blinded to clinical and group status. Coefficients of variation (CVs) of these measurements are: 3.4% for medial tibial cartilage volume, 2.6% for patellar cartilage volume [21], 2.3% for medial tibial plateau area [38] and 2.2% patellar bone volume [21]. Cartilage volume measurement from MIR are accurate

to within 5% [5]. The morphological variables extracted were: medial tibiofemoral cartilage defect status; patellofemoral cartilage defect status; medial tibial cartilage volume; patella cartilage volume; medial tibial plateau area; and patella bone volume.

Gait Assessment

Gait assessments were undertaken within one week of the MRI at the University of Western Australia or the University of Melbourne biomechanics laboratories. Both laboratories utilise VICON MX three-dimensional motion capture systems (VICON, Oxford UK) and multiple force plates (AMTI, Watertown, MA) and employed the UWA biomechanical model to acquire and process 3D gait data [4]. Briefly, gait assessment involved participants being fitted with retro-reflective markers, completing a series of calibration trials, and six natural pace walking trials. The UWA model has also been shown to be accurate and reliable, with test-retest coefficients of multiple determination greater than 0.7 for all variable assessed and accuracy to within 1° in controlled dynamic tasks [4,12]. The following gait variables were extracted from the stance phase of each trial and averaged across each participant's 6 trials: 1st knee adduction moment peak; knee adduction moment impulse; 1st knee flexion moment peak; stance phase knee extension range of motion; and the vertical heel strike transient. Moments were defined as external moments.

Statistical Analysis

Multivariate regression analyses were utilized to identify relationships between morphological and gait variables. All regression models were adjusted for age, time from surgery, gender, height, body mass and MRI resource, while cartilage volume and defect models were also adjusted for bone size. Linear regression was

used to examine relationships between cartilage volume, medial tibial plateau area and bone volume with gait variables analyses while logistic regression was used to examine relationships between cartilage defect prevalence and gait variables while. As height and body mass were adjusted for in the models, gait variables were not normalized prior to being entered into the analysis [23]. All analyses were performed using the SPSS statistical package (version 16.0, SPSS, Chicago, IL) with significance accepted at $p < 0.05$.

Results

There were no gait variables significantly predictive of prevalence of either patellofemoral or medial tibiofemoral cartilage defects (Table 2). A decrease in patella cartilage volume was associated with an increased knee extension range of motion (Table 3). No other significant cartilage volume relationships were identified. An increase in medial tibial plateau bone area was related to an increase in the knee adduction impulse (Table 3). No other significant bone area or bone volume relationships were identified.

Table 2: Relationship between gait variables and prevalence of cartilage defects.

	Patellofemoral Prevalence		Medial Tibiofemoral Prevalence	
	Odds Ratio (95% CI)	P Value	Odds Ratio (95% CI)	P Value
Adduction Moment	1.01 (0.97,1.05)	n.s.	1.03 (1.00,1.05)	n.s.
Adduction Impulse	1.05 (0.99,1.17)	n.s.	1.03 (0.96,1.11)	n.s.
Flexion Moment	1.03 (1.00,1.07)	n.s.	1.01 (0.99,1.02)	n.s.
Knee Extension	1.00 (0.91,1.11)	n.s.	1.04 (0.98,1.11)	n.s.
Range of Motion				
Heel Strike Transient	1.00 (0.99,1.01)	n.s.	1.00 (0.99,1.01)	n.s.
Adjusted for age, time from surgery, gender, height, weight, MRI resource (City 1 or City 2 scanner), cartilage volume and bone size				

Table 3: Relationship between gait variables and cartilage volume, patella bone volume and medial tibial plateau bone area.

	Patella Cartilage Volume*		Medial Tibial Cartilage Volume*		Patella Bone Volume^		Medial Tibial Plateau Bone Area^	
	Regression coefficient (95% CI)	P Value	Regression coefficient (95% CI)	P Value	Regression coefficient (95% CI)	P Value	Regression coefficient (95% CI)	P Value
Adduction Moment	-6.5 (-14.1,1.1)	n.s.	-0.5 (-4.6,3.6)	n.s.	22.7 (-12.2,57.6)	n.s.	2.1 (-0.3,4.5)	n.s.
Adduction Impulse	-10.4 (-30.4,9.7)	n.s.	-0.9 (-11.7,9.9)	n.s.	3.2 (-89.4,95.8)	n.s.	7.7 (0.9,13.3)	0.025
Flexion Moment	1.2 (-4.0,6.4)	n.s.	-0.3 (-3.1,2.4)	n.s.	22.1 (-1.2,45.4)	n.s.	1.3 (-0.3,2.9)	n.s.
Knee Extension Range of Motion	-17.9 (-35.4,-0.4)	0.045	-0.2 (-9.5,9.1)	n.s.	48.8 (-32.1,129.7)	n.s.	-3.3 (-8.8,2.2)	n.s.
Heel Strike Transient	-0.6 (-1.0,0.5)	n.s.	-0.2 (-0.6,0.2)	n.s.	3.2 (-89.4,95.8)	n.s.	-0.1 (-0.3,102)	n.s.

* Adjusted for age, time from surgery, gender, height, weight, MRI resource (City 1 or City 2 scanner), and bone size.

^ Adjusted for age, time from surgery, gender, height, weight, and MRI resource (City 1 or City 2 scanner).

Discussion

The main findings of this study were 1) decreases in patella cartilage volume was associated with an increase in the knee extension range of motion through stance and 2) an increased knee adduction impulse was related to an increase in medial tibial plateau bone area. While these were the only two significant predictors they can provide some insight into the relationship between gait biomechanics and patellofemoral and tibiofemoral knee health following APM.

There have been a number of studies investigating biomechanical factors related to tibiofemoral osteoarthritis, in particular the knee adduction moment [27,28,35].

The results from this study support the theory that the adduction moment, and its impulse, is related to the development of tibiofemoral osteoarthritis following arthroscopic partial meniscectomy. However the only significant relationship for the adduction load was between the adduction impulse and medial tibial plateau area. Expansion in the subchondral bone has been shown to occur prior to gross morphological changes occurring in the cartilage [8,20]. This expansion may reflect structural changes in the bone, as have been observed in the arthroscopic partial medial meniscectomy population [39]. This may affect the mechanical properties of the bone, and therefore the cartilage, leading to development of osteoarthritis [7,9,37]. As the follow up period in this study is less than the study by Miyazaki and colleagues [27] we may be observing early morphological changes which have the potential to progress to medial tibiofemoral osteoarthritis, however further work is needed. The shorter follow up period may also explain the lack of significant relationship between the peak adduction moment and the prevalence of medial tibiofemoral cartilage defects observed in this study. An

1 increase in the 4 year cohort size or the addition of a subsequent cohort may result
2 in a significant relationship between adduction moments and medial tibiofemoral
3 cartilage defects.

4 The significant relationship between increased knee extension range of motion
5 and decreased patella cartilage volume is supported by the work by Teichtahl and
6 colleagues [34]. They found that a reduction in the minimum knee angle during
7 late stance was related to increased patella cartilage volume. This reduction in
8 angle would result in a lower knee extension range of motion. Therefore our
9 current results are the corollary of this; increased knee extension range of motion
10 and decreased patella cartilage volume. The potential mechanism through which
11 knee range of motion can affect patella cartilage volume is altered patellofemoral
12 loads. Even though we found no difference in peak knee flexion moments, for the
13 same flexion moment patellofemoral loads increase as the knee angle increase
14 [23]. If the increased stance phase range of motion is due to an increase in peak
15 knee flexion angle, an increased or equivalent moment may result in higher
16 patellofemoral loading at these more flexed angles. Interestingly arthroscopic
17 meniscectomy patients have been shown to have smaller ranges of motion at the
18 knee than healthy controls at three months post-surgery [33]. Individuals who
19 have a more normal knee range of motion may increase their likelihood of
20 developing patella osteoarthritis following arthroscopic partial medial
21 meniscectomy. Furthermore, we have also shown that partial meniscectomy
22 patients have higher levels of extensor-flexor co-contraction which may also
23 increase total muscle forces and therefore patellofemoral loading [32]. Further
24 investigation is required to verify the mechanics causing patellofemoral cartilage

1 volume changes and defects, probably using neuromuscular skeletal model of the
2 knee to estimate the patellofemoral loading [3,22].

3 The main limitation of this study is its cross-sectional nature. Pre-surgery MRI
4 and gait was not obtained, thus we were unable to address the changes in knee
5 morphology prior to and after the APMM. We also utilised gait collected on the
6 same day as the MRI. As the patient moves further away from surgery their gait
7 patterns may begin to resemble those of healthy controls. Furthermore, if this is
8 not the case the small number of subjects in the 4 year group, with the poorest
9 outcomes in terms of knee health may mask any potential relationships. The ideal
10 approach for this study would be to track changes in both patients gait and
11 biomechanics across time. Another limitation of the study is the lack of
12 information regarding the preoperative status of the meniscus, such as whether it
13 experienced a traumatic or degenerative tear, and the morphological
14 characteristics of the tear. These features might have an effect on the
15 morphological changes to which we are attempting to relate gait characteristics to.
16 However, we restricted our study population to those with isolated arthroscopic
17 partial medial meniscectomy to control for the confounding of arthroscopic partial
18 lateral meniscectomy and excluded participants with moderate or severe cartilage
19 lesions, concomitant knee ligament damage or signs of knee osteoarthritis at
20 arthroscopic partial medial meniscectomy. Lastly, we did not investigate the
21 relationship of knee alignment in the frontal plane (varus/valgus) to tibiofemoral
22 or patellofemoral morphology. However, alignment is one factor that influences
23 the magnitude of the knee adduction moment, with poor alignment causing large
24 frontal plane lever arm lengths and thus implicitly produces large knee adduction
25 moment measures.

1 The results from this study suggest that interventions targeting gait biomechanics
2 following APMM may result in improved patient outcomes. Interventions such
3 as gait retraining [18,31], valgus thrust braces [19,29], modified footwear [14]
4 and lateral wedge insoles [15,16] have been shown to reduce knee adduction
5 moments. These may reduce the risk of the APMM patients developing medial
6 tibiofemoral osteoarthritis osteoarthritis, which should be the focus of future
7 studies.

8 **Conclusions**

9 Increased medial tibial bone area was associated with increased adduction
10 moment impulse, while decreased patella cartilage volume was associated with
11 increased knee extension range of motion. The altered knee joint biomechanics
12 observed in arthroscopic partial meniscectomy patients may go some way to
13 explaining the more pathological morphology observed in the patellofemoral and
14 tibiofemoral compartments of the knee in patients further from surgery. The
15 results have potential implications for rehabilitation following arthroscopic partial
16 meniscectomy. Consideration may need to be given to the use of load-modifying
17 interventions such as braces, gait retraining, modified footwear and lateral wedge
18 insoles.

19 **Acknowledgements**

20 This work was funded by Australian National Health and Medical Research
21 Council, Australian Research Council, Western Australian Medical Health and
22 Research Infrastructure Fund. We thank the following surgeons for recruitment:
23 Mr Keith Holt, Mr Greg Witherow, Mr Greg Janes, Mr Peter Annear, Mr Hari
24 Goonatillake, Mr Dermot Collopy, Mr David Colvin, Mr Peter Campbell, Mr

1 Hayden Morris, Mr Andrew Shimmin, Mr Jim Keillerup, Mr Julian Feller and Mr
2 Adrian Trivett. We thank Dr Stephen Davis, Simone Mattfield, Iryna Bushwood
3 and Vi Thuy for radiology.

4 **Conflict of Interest**

5 No authors have a conflict of interest.

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Accepted Copy

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