Sagittal plane movement at the tibiofemoral joint influences patellofemoral joint structure in healthy adult women

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Summary

Objectives: The influence exerted on cartilage and bone volumes by locomotor patterns is poorly understood, particularly at the patellofemoral joint. The aim of this study was to investigate the relationship between sagittal plane movement at the tibiofemoral joint and patella cartilage and bone volumes during the locomotion of healthy adult females.

Methods: Three-dimensional Vicon gait analyses and magnetic resonance imaging were performed on 20 healthy adult women. The relationships between the degree of tibiofemoral flexion and extension at varying stages of the gait cycle and the concurrent medial, lateral and total patella cartilage and total bone volumes were examined.

Results: For every degree the knee flexed during mid-stance, there was a 62.8 μL (95% confidence interval 3.7–122.0) increase in the medial patella facet cartilage volume after adjustment for age and the body mass index (BMI) (P = 0.04). A similar relationship that approached significance was observed for the lateral patella facet cartilage volume after adjustment for age and the BMI (P = 0.08). No association was observed between the sagittal plane tibiofemoral movements and the patella bone volume.

Conclusions: The association between patella cartilage volume and tibiofemoral knee movement suggests that for every degree increase in knee flexion during mid-stance, there is an associated increase in patella cartilage volume. This may be the result of the geometry of the femoral condyle influencing patella tracking and or the retropatellar load exerted on the patella during walking. These results may have important implications for people who hyperextend their knee during gait and the pathogenesis of patellofemoral osteoarthritis.

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Introduction

Although the relationships between joint structure and biomechanical variables are becoming better understood at the tibiofemoral joint1–4, there is a paucity of data examining biomechanical factors and joint structure at the patellofemoral compartment. For instance, the association between knee flexion and extension and joint structure at the patellofemoral compartment is poorly understood, despite the close anatomical approximation of the patella to the femur.

Few studies have examined the relationship between joint biomechanics and cartilage and bone adaptation in vivo. Recently, we demonstrated that the knee adduction moment during the late-stance phase of gait is a major determinant of medial tibial bone size in healthy adult women5. Nevertheless, there is a paucity of data describing the relationships between knee biomechanics and cartilage and bony properties at the patellofemoral joint. This may be attributable to the difficulty in obtaining a reliable, valid and sensitive measure of cartilage and bone non-invasively in human subjects. However, magnetic resonance imaging (MRI) is now becoming widely accepted as a non-invasive, reliable, valid and sensitive measure of both cartilage and bone volumes in vivo6–9. Despite this, the challenge remains in identifying the biomechanical factors that are associated with healthy joint structure, and whether alteration in these biomechanical factors contributes to the pathogenesis of diseases such as osteoarthritis (OA).
Although the patellofemoral joint is not purely a weight-bearing structure, it is subject to altered joint reaction forces with varying degrees of knee flexion at the tibiofemoral joint[10,11]. This is based on the theory that as knee flexion proceeds from full extension, the pull of the quadriceps and patellar tendons becomes increasingly oblique, compressing the patella against the femur[12]. For example, as the knee flexes to 15° at initial contact during walking, the patellofemoral joint reaction force is reportedly 50% of total body weight[13], while at 60° knee flexion, the retropatellar force may have increased to 3.3 times total body weight[13]. However, it has also been argued that because of the geometry of the lateral femoral condyle, there is better patellar tracking and reduced pressure at the patellofemoral joint, secondary to increased contact area during deep knee flexion[13]. Therefore, although it is not mechanistically well understood, sagittal plane kinematics at the tibiofemoral joint appears to influence patellofemoral joint kinetics. Whether sagittal knee angles are associated with alterations in bone and cartilage properties at the patellofemoral joint is unknown, and may be important in the pathogenesis of patellofemoral joint pathology. We examined the relationship between various tibiofemoral flexion and extension angles encountered during normal walking and patella bone and cartilage volumes in 20 healthy adult women.

Methods

SUBJECTS

Twenty women involved in an existing study of healthy aging[13-15] were recruited through the Jean Hailes Centre (a women’s health clinic) and advertising in the local media. The study was approved by the Alfred and Caulfield Hospital, and La Trobe University Human Research and Ethics Committees. All subjects provided written informed consent.

The exclusion criteria were a history of knee OA or symptoms requiring medical treatment, any knee pain prior to testing, radiographic evidence of knee OA (osteophytes, joint space narrowing or subchondral sclerosis), inflammatory arthritis, planned or previous knee joint replacement, malignancy, fracture in the last 10 years, contra-indication to MRI (e.g., pacemaker, cerebral aneurysm clip, cochlear implant, presence of shrapnel in strategic locations, metal in the eye and claustrophobia), inability to walk 50 feet without the use of assistive devices and hemiparesis.

APPARATUS AND PROCEDURE

Gait analyses were conducted at the Musculoskeletal Research Centre, La Trobe University, Australia. A six-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) was used to capture three-dimensional (3D) kinematic data during four walking trials on the dominant leg. For each subject, the dominant knee was selected by determining which knee the subject stepped off from when beginning to walk. Analyses were performed using “PluginGait” (Oxford Metrics, Oxford, UK) which is based on a previously proposed model[16], to obtain joint variables calculated about an orthogonal axis system located in the distal segment of a joint. Inter-ASIS (anterior superior iliac spine) distance was measured using a caliper, causing the medial—lateral and proximal—distal co-ordinates of the hip joint center to be determined by the method previously described[16]. Given that only healthy adult women were included, peak knee flexion during stance was measured at loading response, shortly after initial contact, as well as during swing. Minimum knee flexion was measured at mid-stance, where the knee tended toward full extension (see Fig. 1). Subjects were instructed to walk barefoot at their normal pace.

The body mass index (BMI) (weight/height2, kg/m2) was calculated by measuring weight to the nearest 0.1 kg using a single pair of electronic scales and measuring height to the nearest 0.1 cm using a stadiometer (shoes and bulky clothing removed).

MRI was performed on each subject’s dominant knee. Knees were imaged in the sagittal plane on a 1.5-T whole body magnetic resonance unit (Phillips) using a commercial transmit-receive extremity coil. The following sequence parameters were used: a T1-weighted fat suppressed 3D gradient recall acquisition in the steady state; flip angle 55°; repetition time 58 ms; echo time 12 ms; field of view 16 cm; 60 partitions; 513 × 196 matrix; and one acquisition time 11 min 56 s. Sagittal images were obtained at a partition thickness of 1.5 mm and an in-plane resolution of 0.31 × 0.83 mm (512 × 196 pixels). The image data were transferred to a workstation. The volumes of the individual patella cartilage were isolated from total volume by manually drawing disarticulation contours around the cartilage boundaries. These data were re-sampled by bilinear and cubic interpolation (area of 312 and 312 μm and 1.5 mm thickness, continuous sections) for the final 3D rendering. The volume of the particular cartilage plate was determined by summing the pertinent voxels within the resultant binary volume, and patellar plateau area was determined by creating an isotropic volume from the input images, which were reformatted in the sagittal plane. Areas were directly measured from these reformatted images to obtain each MRI. The coefficient of variation (CV) was 2.1% for patella cartilage volume and 2.2% for patella bone volume.

The number of women eligible for recruitment to this study was limited by the need for their participation. Patella cartilage volume was determined by image processing on an independent workstation using the Osiris software (University of Geneva). Knees were imaged in the sagittal plane on the same 1.5-T whole body magnetic resonance unit (Signa Advantage HiSpeed GE Medical Systems Milwaukee, WIS) using a commercial receive-only extremity coil as previously described[17,18]. Patella bone volume was calculated using the same method described for cartilage volume. Contours were drawn around the patella in images, 1.5 mm apart on sagittal views. Due to the patella’s irregular shape, we decided to measure total bone volume as a measure of bone size. The CV was 2.1% for patella cartilage volume.
volume and 2.2% for patella bone volume. Given the potential for diurnal variation in cartilage properties at the knee\textsuperscript{19}, gait analyses and MRI were performed in the morning, prior to any significant exercise.

**STATISTICAL ANALYSIS**

Prior to performing the analyses, scatterplots of the associations were inspected for features that would impede interpretation such as non-normality of the variables, non-linearity of the associations and outlying observations. Associations between the patella cartilage and bone volumes and the degree of knee flexion/extension angles at three distinct points during gait (loading response, mid-stance and swing) were analysed (see Fig. 1). Multiple linear regression techniques were used to adjust for age and the BMI. All analyses were performed for the dominant leg since combining the right and left legs fails to acknowledge the independence between knees and the potential for asymmetrical alignment of the lower limbs. By selecting the dominant leg, we attempted to control for variables that may be joint specific rather than subject specific, which is a data analysis strategy endorsed by previous commentators\textsuperscript{20}. Results where there were \( P \)-values of less than 0.05 (two-tailed) were considered to be statistically significant. All analyses were performed using SPSS (version 10.0.5, SPSS, Cary, NC).

### Results

**SUBJECTS**

The mean age of the 20 women was 62 ± 5 years and their mean BMI was 25 ± 5 kg/m\(^2\). The mean magnitudes and standard deviations of the sagittal plane tibiofemoral flexion/extension angles and patella cartilage and bone volumes are presented in Table I. Our biomechanical data are similar to those previously reported for normative gait, confirming that our methodology was effective in selecting for normal, healthy adult locomotor patterns\textsuperscript{21}. The relationships between the sagittal knee angles and patella cartilage and bone volumes after adjustment for age and the BMI are presented in Table II.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Mean \pm standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle (loading response)</td>
<td>18.7 ± 4.4</td>
</tr>
<tr>
<td>Knee flexion angle (mid-stance)</td>
<td>0.9 ± 2.8</td>
</tr>
<tr>
<td>Peak knee flexion angle (swing)</td>
<td>60.1 ± 4.7</td>
</tr>
<tr>
<td>Medial patella cartilage volume (( \mu \text{L} ))</td>
<td>708 ± 366.8</td>
</tr>
<tr>
<td>Lateral patella cartilage volume (( \mu \text{L} ))</td>
<td>1274.7 ± 520.5</td>
</tr>
<tr>
<td>Total patella cartilage volume (( \mu \text{L} ))</td>
<td>2212.1 ± 651.3</td>
</tr>
<tr>
<td>Total patella bone volume (( \mu \text{L} ))</td>
<td>19570.2 ± 3246.4</td>
</tr>
</tbody>
</table>

Knee flexion angles are measured in degrees. Total patella cartilage volume is measured from the sagittal MRI and is measured as a whole. It is not simply the addition of medial and lateral volumes as measured from axial views.

### Discussion

The results of this study demonstrated that medial and lateral patella cartilage volumes were positively associated with the minimum degree of knee flexion during gait (i.e., when the knee approached full extension during midstance). This suggests that the degree of tibiofemoral movement at the mid-stance phase of the gait cycle is associated with the patella cartilage volume in healthy adult women. No relationship was observed between the sagittal tibiofemoral angles and patella bone volume.

No previous study has examined the relationship between the sagittal tibiofemoral angles and patella cartilage or bone volume. Nevertheless, a limited number of animal studies have identified several relationships between biomechanical variables and patellofemoral cartilage and bone volumes' variability\textsuperscript{22,23}. In particular, Herzog et al.\textsuperscript{22} found that the patella cartilage thickness of cats was associated with altered patellofemoral contact areas. Human studies have also revealed that physically active children have a greater knee cartilage volume than their sedentary counterparts\textsuperscript{18} and that the rate of knee cartilage accrual in children is positively associated with their level of physical activity\textsuperscript{24}. The current study is the first to provide evidence of a relationship between human tibiofemoral movement and patella cartilage volume in vivo.

Given that the relationship between tibiofemoral movement and patella cartilage volume at mid-stance in this study was mediated by an almost fully extended knee (0.9 degrees knee flexion), it may be that knee extension exerts a greater influence on patella cartilage volume than knee flexion. However, how an almost fully extended knee mediates patellofemoral joint changes is speculative. One plausible biomechanical explanation is that as the tibiofemoral compartment extends, patellofemoral joint incongruency will necessitate increased retropatellar pressure via a smaller contact area\textsuperscript{25}. Previous work substantiates this theory, with one study arguing that because of the geometry of the lateral femoral condyle, there was better patellar...
tracking and reduced pressure at the patellofemoral joint, secondary to increased contact area during deep knee flexion. Thus tibiofemoral extension may reduce contact area and increase pressure at the patellofemoral joint, resulting in altered cartilage properties. Why cartilage is more susceptible than bone to changes in tibiofemoral movements at mid-stance is unclear, but may rely on complex mechanotransduction mechanisms that upregulate genetic elements to alter chondrocyte biosynthesis. Such theories have been supported by in vitro animal studies.

Given that the sagittal plane tibiofemoral movement was associated with patella cartilage volume during mid-stance and not during swing, it is unlikely that geometry alone is sufficient to explain this study’s observations. In particular, the external joint moment, which in part, is established by the location of the ground reaction force, is likely to be important. During the initial period of the gait cycle, there is a net external moment that flexes the knee, creating a retropatellar force that may act as the major determinant of patellofemoral joint load during stance. During swing, the foot no longer contacts the support surface and the ground reaction force disappears, removing its influence on retropatellar load. This may help to explain why the relationship between tibiofemoral movement and patella cartilage volume was

### Table II

<table>
<thead>
<tr>
<th></th>
<th>Univariate analysis regression coefficient</th>
<th>Multivariate analysis* regression coefficient</th>
<th>95% CI</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial cartilage volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle (LR)</td>
<td>36.8</td>
<td>32.3</td>
<td>-7.0–71.6</td>
<td>0.10</td>
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<tr>
<td>Knee flexion angle (MS)</td>
<td>47.4</td>
<td>62.8</td>
<td>3.7–122.0</td>
<td>0.04</td>
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<tr>
<td>Peak knee flexion angle (Sw)</td>
<td>15.7</td>
<td>7.8</td>
<td>-33.9–49.5</td>
<td>0.70</td>
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<tr>
<td>Lateral cartilage volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle (LR)</td>
<td>34.9</td>
<td>30.5</td>
<td>-31.4–92.4</td>
<td>0.31</td>
</tr>
<tr>
<td>Knee flexion angle (MS)</td>
<td>65.2</td>
<td>80.2</td>
<td>-11.7–127.2</td>
<td>0.08</td>
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<tr>
<td>Peak knee flexion angle (Sw)</td>
<td>1.0</td>
<td>7.5</td>
<td>-69.2–54.9</td>
<td>0.80</td>
</tr>
<tr>
<td>Total cartilage volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle (LR)</td>
<td>53.8</td>
<td>57.6</td>
<td>-25.4–140.7</td>
<td>0.16</td>
</tr>
<tr>
<td>Knee flexion angle (MS)</td>
<td>59.9</td>
<td>105.0</td>
<td>-41.6–251.7</td>
<td>0.15</td>
</tr>
<tr>
<td>Peak knee flexion angle (Sw)</td>
<td>-9.6</td>
<td>-36.6</td>
<td>-121.8–48.7</td>
<td>0.37</td>
</tr>
<tr>
<td>Total bone volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle (LR)</td>
<td>182.3</td>
<td>160.1</td>
<td>-284.6–604.8</td>
<td>0.45</td>
</tr>
<tr>
<td>Knee flexion angle (MS)</td>
<td>59.9</td>
<td>105.0</td>
<td>-41.6–251.7</td>
<td>0.15</td>
</tr>
<tr>
<td>Peak knee flexion angle (Sw)</td>
<td>-79.2</td>
<td>-36.6</td>
<td>-121.8–48.7</td>
<td>0.37</td>
</tr>
</tbody>
</table>

S = stance; LR = loading response; MS = mid-stance; Sw = swing phase.
*Multivariate analysis with age and BMI in regression equation.
†Change in cartilage or bone volume per degree increase in knee flexion angle.

Fig. 2. Scatterplots of the association between tibiofemoral angle and medial patella cartilage volume at mid-stance. (A) The relationship between medial patella cartilage volume and the knee flexion angle during mid-stance (Pearson’s correlation coefficient \( r = 0.37, P = 0.1 \)). (B) The relationship persisted after adjusting for the confounders BMI and age. To illustrate this, the residuals of medial patella cartilage volume, after adjusting for the BMI and age (unstandardised residual) have been plotted against knee flexion angle during the mid-stance phase of gait. In this case, an even clearer relationship between medial patella cartilage volume and knee flexion during mid-stance is observed (Pearson’s correlation coefficient \( r = 0.46, P = 0.04 \).
apparent during mid-stance, and not during the swing phase of gait.

A potential limitation of this study was the relatively small sample size. While we had sufficient power to demonstrate an association between tibiofemoral movement and patella cartilage volume, we cannot exclude the possibility of a similar, yet weaker effect for bone. Recent studies examining the tibiofemoral compartment have indicated that the effect of mechanical loading, via the knee adduction moment, if any, is significantly less for cartilage volume than for bone size. However, given that the patellofemoral compartment theoretically bears less load than the tibiofemoral compartment during mid-stance, the effects of biomechanical variables on joint structure may differ markedly between the two compartments of the knee joint throughout the gait cycle. Additionally, because this study only examined healthy adult women, further work is required to determine whether similar biomechanical relationships are apparent with varying age groups, as well as in males, and in the presence of arthritis. Finally, cartilage volume change per degree tibiofemoral movement may not be operative over the entire range of movement. This study has noted an association only during the mid-stance phase of gait, where the knee approached full extension. Whether this association is only apparent over a discrete range of movement is unclear and requires further investigation.

This study has demonstrated an association between sagittal tibiofemoral movement during the mid-stance period of gait and patella cartilage volume. For every degree the knee flexed at mid-stance, there was an associated increase in both medial and lateral patella cartilage volumes. While these results can be expected by altered patellar load and/or the geometry of the patellofemoral joint is unclear and will require further work. Nonetheless, individuals who hyperextend their knee during stance may be at particular risk for developing patellofemoral OA.

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