Tibiofemoral Cartilage Contact Differences Between Level Walking and Downhill Running

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**Background:** Some studies have suggested that altered tibiofemoral cartilage contact behavior (arthrokine-matics) may contribute to long-term cartilage degeneration, potentially leading to tibiofemoral osteoarthritis. However, few studies have assessed normal tibiofemoral arthrokine-matics during dynamic activities.

**Purpose:** To characterize tibiofemoral arthrokine-matics during the impact phase of level walking and downhill running.

**Study Design:** Descriptive laboratory study.

**Methods:** Arthrokine-matic data were collected on uninjured knees of 44 participants (mean age, 20.7 ± 6.6 years). Using a dynamic stereoradiographic imaging system with superimposed 3-dimensional bone models from computed tomography and magnetic resonance imaging of participant-specific tibiofemoral joints, arthrokine-matics were assessed during the first 15% of the gait cycle during level walking and the first 10% of the gait cycle during downhill running.

**Results:** During level walking and downhill running, the medial compartment had a greater cartilage contact area versus the lateral compartment. Both compart-ments had a significantly less cartilage contact area during running versus walking (medial compart-ment gait cycle affected: 8%-10%; lateral compart-ment gait cycle affected: 5%-10%). Further, medial and lateral compart-ment tibiofemoral contact paths were significantly more posterior and longer during downhill running.

**Conclusion:** There was a decreased tibiofemoral cartilage contact area during downhill running compared with level walking, suggesting that underlying bone morphology may play a key role in determining the size of cartilage contact regions.

**Clinical Relevance:** This study provides the first data characterizing tibiofemoral cartilage contact patterns during level walking and downhill running. These results provide evidence in support of performing biomechanical assessments during both level walking and downhill running to obtain a comprehensive picture of tibiofemoral cartilage behavior after clinical interventions.

**Keywords:** knee; gait analysis; articular cartilage biomechanics; dynamic cartilage motion

Tibiofemoral osteoarthritis (OA) represents a common musculoskeletal disease process affecting a significant proportion of the population. For every 100,000 persons in the United States, approximately 69 every year go on to develop severe enough OA to require primary joint replacement surgery.25

Altered joint biomechanics are believed to be a common mechanical cause of OA, leading to increased and/or abnormal stress in articular cartilage.3 The characterization of native knee cartilage contact kinematics (or arthrokine-matics) is therefore critical for better understanding the mechanical factors that may precede radiographic evidence of OA as well as for developing treatment strategies. To date, numerous studies have investigated physiological load-bearing cartilage contact behavior in the tibiofemoral and patellofemoral joints using 3-dimensional (3D) magnetic resonance imaging (MRI), 3D computed tomography (CT), dual biplanar radiography, or a combination of these methods.15,17 These studies have described cartilage contact area, tracking, and deformation without load
bearing or in the setting of static load bearing (single-legged stand, quasistatic lunge). There have also been cadaveric and computational studies assessing tibiofemoral joint contact mechanics. However, no in vivo studies to date have accurately assessed tibiofemoral cartilage contact during level-plane walking at physiological speeds or during running, which are the most common activities of daily living that load the knee joint.

The purpose of this study was to compare the articular cartilage contact area and the path of the center of cartilage contact in the medial and lateral compartments of the knee during the impact phase of level walking and downhill running. It was hypothesized that tibial cartilage contact area in the medial compartment would be greater than in the lateral compartment during walking and running, that the cartilage contact area would increase in both compartments during running versus walking, and that the cartilage contact path would be shifted posteriorly during running versus walking.

METHODS

Data Collection and Data Processing

The data for this study were collected as part of a randomized clinical trial assessing knee kinematics after anterior cruciate ligament reconstruction (ClinicalTrials.gov identifier: NCT01319409). The present analysis focused exclusively on the contralateral uninjured knee of all participants. A total of 44 participants (mean age, 20.7 ± 6.6 years; 15 female; 44 knees [21 right]) with a normal body weight (mean body mass index, 24.9 ± 3.4 kg/m² [range, 19.0-35.1 kg/m²]) who provided informed consent to participate in this institutional review board–approved study were included in the present analysis. Participant arthrokinematics were assessed during the first 15% of the gait cycle during level walking on a treadmill (1.3 m/s at a 0° slope) and the first 10% of the gait cycle during downhill running (2.5 m/s at a 10° slope). Foot strike (beginning of the gait cycle) was determined via vertical ground-reaction force sensors from a dual-belt instrumented treadmill, collected at 1000 Hz (Figure 1).

Volumetric bone data were acquired via high-resolution CT (voxel size: 0.31 × 0.31 × 0.6 mm) and volumetric cartilage data via MRI (3-T Magnetom Trio; Siemens) (near-isotropic 3D dual echo steady state [DESS] with water excitation, circular polarized extremity knee coil, voxel size: 0.45 × 0.45 × 0.70 mm, repetition time: 16.32 milliseconds, echo time: 4.71 milliseconds, flip angle: 25°, 140-mm field of view). Femoral and tibial bone tissue were segmented in 3D DESS MRI sequences and bone tissue in CT sequences using segmentation software (Mimics; Materialise). Participant-specific 3D bone and cartilage models were generated using a combination of automated (thresholding) and manual segmenting techniques and were subsequently coregistered to properly align MRI-derived cartilage models to CT-derived bone models. The tibial anatomic coordinate system was defined by identifying points on the contralateral uninjured knee of all participants. A total of 44 participants (mean age, 20.7 ± 6.6 years; 15 female; 44 knees [21 right]) with a normal body weight (mean body mass index, 24.9 ± 3.4 kg/m² [range, 19.0-35.1 kg/m²]) who provided informed consent to participate in this institutional review board–approved study were included in the present analysis. Participant arthrokinematics were assessed during the first 15% of the gait cycle during level walking on a treadmill (1.3 m/s at a 0° slope) and the first 10% of the gait cycle during downhill running (2.5 m/s at a 10° slope). Foot strike (beginning of the gait cycle) was determined via vertical ground-reaction force sensors from a dual-belt instrumented treadmill, collected at 1000 Hz (Figure 1).

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x-ray sources and detectors arranged to allow for dynamic participant movement (eg, walking, running) at a 1.8-m source-to-detector distance. Biplanar radiographs were obtained at 100 frames per second (walking) or 150 frames per second (running) at 90 kVp, 125 mA, and 1-millisecond pulse duration to eliminate motion blur. This system has been validated in vivo to calculate joint kinematics with an accuracy of 0.3, 0.4, and 0.7 mm for medial-lateral, proximal-distal, and anterior-posterior translation, respectively, and 0.9°, 0.6°, and 0.3° for flexion-extension, external-internal rotation, and abduction-adduction, respectively, during running. An average of 3 trials (foot strike to midstance) was used for each participant. Data were normalized to percentage gait cycle for each participant (0%-15% for level walking, 0%-10% for downhill running).

Arthrokinematics

For each participant, the transformation from MRI-based bone and cartilage models to CT-based bone models (used for tracking bone motion) was determined by coregistering the bone models. After this registration, the position and orientation of the cartilage surfaces were determined throughout the gait cycle. Cartilage contact area in the medial and lateral compartments was calculated from the outline of overlapping areas of femoral and tibial cartilage models and normalized to the total tibial cartilage area in the corresponding compartment (Figure 1). This technique has been validated to estimate cartilage contact areas with a root mean squared error of 8.4% and 4.4% for the medial and lateral compartments, respectively. The center of cartilage contact was determined by the distance-weighted centroid of the overlapping cartilage contact areas as described previously. The paths of the center of cartilage contact on the femur and tibia were plotted along the medial-lateral and anterior-posterior anatomic axes for both the medial and lateral compartments at 1% intervals of the gait cycle.

Statistical Analysis

A mixed-effects analysis of variance (ANOVA) was used to assess the effects of joint compartment (medial vs lateral) and activity (level walking vs downhill running) on cartilage contact area and location, with a Bonferroni correction applied to account for multiple comparisons over each percentage of the gait cycle (0%-15% for walking, 0%-10% for running). A mixed-effects ANOVA was used to assess the effects of downhill running versus level walking on knee flexion over each percentage of the gait cycle (0%-10%), with a Bonferroni correction applied for multiple comparisons. A paired Student t test was used to test for differences in the total contact path distance in the medial and lateral compartments on the tibia and femur during downhill running versus level walking. A paired Student t test was used to test for differences in cartilage area between the medial and lateral tibial compartments. Last, differences in the cartilage contact area and mean contact path location were evaluated between male and female participants. Cartilage contact area was assessed as above, and contact path locations were compared using the mean coordinates over the gait cycle studied for participants in the anterior-posterior and medial-lateral axes during level walking and downhill running. An unpaired Student t test was used to assess contact path location differences between male and female participants.

RESULTS

Cartilage Contact Area

During level walking and downhill running, the medial compartment had a greater cartilage contact area across all percentages of the gait cycle (walking: 0%-15%, running: 0%-10%) versus the lateral compartment (Figure 2, A and B). The medial compartment had a significantly smaller cartilage contact area during running versus walking from 8% to 10% of the gait cycle (Figure 2C), and the lateral compartment had a significantly smaller cartilage contact area during running versus walking from 5% to 10% of the gait cycle (Figure 2D). These results were unaffected by normalizing to the total compartmental cartilage area because there was no difference in the total cartilage area between the medial and lateral tibial compartments (P = .11). "

Tibial Cartilage Contact Path

Along the tibial anterior-posterior axis, the medial and lateral compartment cartilage contact paths were significantly more posterior at each percentage of the gait cycle (medial 0%-10%: P < .001; lateral 0%: P = .007; lateral 1%: P = .002; lateral 2%-10%: P < .001) during downhill running versus level walking (Figure 3). Along the tibial medial-lateral axis, the lateral compartment cartilage contact path was significantly more lateral over the first 9% of the gait cycle (0%-6%: P < .001; 7%-8%: P = .002; 9%: P = .003) during downhill running versus level walking. There were no differences identified in the medial-lateral contact location in the medial compartment during level walking versus downhill running (Figure 3). The mean contact path lengths during level walking in the medial (5.2 ± 2.0 mm) and lateral (5.3 ± 1.8 mm) compartments were significantly shorter than during downhill running in the medial (7.3 ± 2.4 mm) and lateral (8.8 ± 2.4 mm) compartments (P < .0001).

Femoral Cartilage Contact Path

Along the femoral anterior-posterior axis, the medial and lateral compartment cartilage contact paths were also significantly more posterior at each percentage of the gait cycle (P < .001) during downhill running versus level walking (Figure 3). Along the femoral medial-lateral axis, the lateral compartment cartilage contact path was significantly more lateral only at foot strike (0%: P < .01) during downhill running versus level walking. There was no difference in the medial-lateral cartilage contact path in the medial compartment during level walking versus downhill running across all percentages of the gait cycle assessed.
The mean cartilage contact path lengths during level walking in the medial (4.3 ± 1.5 mm) and lateral (3.9 ± 1.5 mm) compartments were significantly shorter than during downhill running in the medial (9.6 ± 2.3 mm) and lateral (6.5 ± 2.3 mm) compartments (P < .0001).

(Figure 3). (Figure 2). The tibiofemoral cartilage contact area (A) during level walking, (B) during downhill running, (C) in the medial compartment, and (D) in the lateral compartment. All contact areas are expressed as a percentage of the total tibial cartilage area in each compartment. Shaded regions indicate ±1 SD. **P < .001, *P < .01.

**Figure 3.** The path of the center of the cartilage contact region during walking and running. (Left) Medial and lateral tibial cartilage contact paths over the first 10% of the gait cycle during level walking and downhill running. (Right) Medial and lateral femoral cartilage contact paths over the first 10% of the gait cycle during level walking and downhill running. Negative x-axis = medial side; negative y-axis = posterior direction.

Across the first 10% of the gait cycle, knees were significantly more flexed during downhill running versus level walking (P < .001) (Figure 4).
The aim of this study was to compare cartilage contact locations and areas during the impact phase of the gait cycle between walking and running. We found that the cartilage contact area is greater in the medial versus the lateral compartment at each percentage of the gait cycle studied during both downhill running and level walking. Further, we were unable to find differences between male and female participants in mean contact path locations along either the medial-lateral or anterior-posterior axis ($P > .05$) across the gait cycle studied.

**DISCUSSION**

The trajectory of the contact paths in this study provides novel insight into tibiofemoral motion that cannot be easily inferred from conventional 6 degrees of freedom joint kinematics. Regarding the lateral compartment cartilage contact path, our study results largely agree with prior studies in that most translation was along the anterior-posterior axis without much medial-lateral translation occurring. However, there were conflicting results regarding the medial compartment, in that some studies have reported anterior-posterior translation as the major component of cartilage contact path motion, while others have reported medial-lateral translation as the main component. We found that translation in the medial compartment occurs primarily along the anterior-posterior axis. The variance in results to prior studies might be caused by the small number of participants analyzed (previous studies analyzed only 5 or 6 participants vs 44 participants in the current study) in addition to the different motions studied in prior investigations (deep lunging, nonphysiological load bearing, nonphysiological gait speeds) versus more common knee activities (walking and running) in the current study.

Our study was also the first to demonstrate changes in cartilage contact paths during walking versus running. The observed posterior shift of the contact paths agrees with prior studies showing increased knee flexion-extension during running versus walking in addition to the changing position of the center of contact at different degrees of knee flexion. Further, the finding that contact paths are greater in length during running agrees with the greater flexion-extension, alterations in ankle and hip kinematics, and altered loading profiles across all lower limb joints. However, there have not been any studies assessing the difference in the native cartilage contact area between different modes of knee motion such as walking versus running. Shin et al. assessed the tibiofemoral cartilage contact area in OA and healthy knees, reporting that increased loads resulted in an increased cartilage contact area in both compartments. Alternatively, a study by Hosseini et al. found that keeping loads constant and increasing time of load bearing were the main factors for increased cartilage contact area.

The present study demonstrated that the cartilage contact area in both the medial and lateral compartments decreases during downhill running versus level walking. Further, this decrease in the contact area was accompanied by an increased contact path length along the tibia and femur in both compartments. These differences in cartilage contact between walking and running are in part because of differences in knee flexion that alter the cartilage contact regions independent of applied loads. The known differences in the articular morphology of the posterior versus anterior region of the femoral condyles also likely contribute. Additionally, the observed differences in cartilage contact between walking and running suggest that the time of cartilage contact (as identified by Hosseini et al.) has more influence on the cartilage contact area than the increased joint load (as suggested by Shin et al.) during running.

**Figure 4.** Knee flexion during downhill running versus level walking. Shaded regions indicate ±1 SD. **$P < .001$.**

**Sex-Based Comparisons**

We were unable to find differences between male and female participants in the cartilage contact area across medial and lateral compartments ($P > .05$) during level walking and downhill running across the gait cycle studied. We were also unable to find differences between male and female participants in mean contact path locations along either the medial-lateral or anterior-posterior axis ($P > .05$) across the gait cycle studied.

To date, studies assessing kinematic differences between running and walking have described increased knee flexion-extension, alterations in ankle and hip kinematics, and altered loading profiles across all lower limb joints. However, there have not been any studies assessing the difference in the native cartilage contact area between different modes of knee motion such as walking versus running. Shin et al. assessed the tibiofemoral cartilage contact area in OA and healthy knees, reporting that increased loads resulted in an increased cartilage contact area in both compartments. Alternatively, a study by Hosseini et al. found that keeping loads constant and increasing time of load bearing were the main factors for increased cartilage contact area.

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distance traveled and increased flexion during a running versus walking gait cycle. Given that aberrant cartilage contact biomechanics are proposed to be associated with OA, it is important that cartilage contact be assessed during moderate- to high-demand knee activities, especially in athletes, to monitor/ delay OA development. Most studies that assessed tibiocentral articular: and arthrokine motions after clinical interventions have focused exclusively on low-stress activities such as level walking. The present study demonstrated that tibiocentral articulating surface behavior is significantly different during running compared with walking in healthy knees. This finding indicates that arthrokine motions during walking do not necessarily reflect arthrokine motions during more dynamic and stressful activities. This is a particularly relevant point to consider when assessing functional outcomes for patients desiring a return to a higher level of physical activity during athletics. Given the differences in normal knee biomechanics between level walking and downhill running presented in this study, the restoration of cartilage contact behavior after nonoperative or operative knee interventions assessed with level walking may not be extrapolated to arthrokine motions during more vigorous activities such as downhill running. Our study provides data to support the idea that future investigations assessing common knee interventions (physical therapy and injury observation, arthrosopic injury management) for high-level athletes need to examine the restoration of native biomechanics during more demanding activities. 

The strengths of this study include the use of a validated high-precision measurement of dynamic tibiocentral joint arthrokine motions, the collection of multiple trials per participant, and testing of truly dynamic high-stress knee activities encountered in daily life as well as athletics. Limitations of this study include the fact that the contralateral knee of all participants underwent anterior cruciate liga ment reconstruction 24 months before testing, which may have affected contralateral knee mechanics; only the impact phase of walking and running was assessed; and no pivot motions were studied. Further, results should not be extrapolated to elderly or pathological knees, given that the cohort was restricted to healthy, young uninjured knees. Lastly, the menisci, known stabilizers and load bearers in the tibiocentral joint, were not assessed in the current study.

CONCLUSION

This study demonstrated that the cartilage contact area of the medial compartment is greater than that of the lateral compartment during both level walking and downhill running. The cartilage contact area decreased but the contact path length increased during downhill running versus level walking in both the femur and tibia. The contact path translated along the anterior-posterior axis and shifted in the posterior direction from level walking to downhill running. These results provide a baseline for comparison to knee contact mechanics after an injury, after rehabilitation or surgical repair, and among older age groups. The study findings demonstrate that cartilage contact mechanics are activity dependent and that novel information about tibiocentral cartilage contact can be gained by testing high-demand activities.

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