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Dynamic Contact Stress Patterns on the Tibial Plateaus during Simulated Gait: A Novel Application of Normalized Cross Correlation

Hongsheng Wang, PhD^{1,*}, Tony Chen, PhD^{1,*}, Peter Torzilli, PhD², Russell Warren, MD³, and Suzanne Maher, PhD^{1,§}

¹Department of Biomechanics, Hospital for Special Surgery, New York, NY 10021

²Laboratory for Soft Tissue Research, Hospital for Special Surgery, New York, NY 10021

³Sports Medicine and Shoulder Service, Hospital for Special Surgery, New York, NY 10021

Abstract

The spatial distribution and pattern of local contact stresses within the knee joint during activities of daily living have not been fully investigated. The objective of this study was to determine if common contact stress patterns exist on the tibial plateaus of human knees during simulated gait. To test this hypothesis, we developed a novel normalized cross-correlation (NCC) algorithm and applied it to the contact stresses on the tibial plateaus of twelve human cadaveric knees subjected to multi-directional loads mimicking gait. The contact stress profiles at different locations on the tibial plateaus were compared, where regions with similar contact stress patterns were identified across specimens. Three consistent regional patterns were found, among them two most prominent contact stress patterns were shared by 9 to 12 of all the knees and the third pattern was shared by 6 to 8 knees. The first pattern was located at the posterior aspect of the medial tibial plateau and had a single peak stress that occurred during the early stance phase. The second pattern was located at the central-posterior aspects of the lateral plateau and consisted of two peak stresses coincident with the timing of peak axial force at early and late stance. The third pattern was found on the anterior aspect of cartilage-to-cartilage contact region on the medial plateau consisted of double peak stresses. The differences in the location and profile of the contact stress patterns suggest that the medial and lateral menisci function to carry load at different points in the gait cycle: with the posterior aspect of the medial meniscus consistently distributing load only during the early phase of stance, and the posterior aspect of the lateral meniscus consistently distributing load during both the early and late phases of stance. This novel approach can help identify abnormalities in knee contact mechanics and provide a better understanding of the mechanical pathways leading to post-traumatic osteoarthritis.

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[§]Corresponding Author: Suzanne A Maher, PhD, Department of Biomechanics, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021. mahers@hss.edu, Tel: (212) 606-1083.

*Both sharing first authorship equally

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CONFLICT OF INTEREST

The authors have no conflicts of interest to disclose in relation to this study.

Keywords

Contact mechanics; cadaveric model; meniscus function; knee simulator; pressure sensor

INTRODUCTION

Gait analysis based on stereo-photogrammetry (Cappozzo et al., 2005), dual-fluoroscopy (Li et al., 2008) and stereo-radiography (Tashman and Anderst, 2003) has been widely used to characterize in vivo joint kinematics. By combining knee joint kinematics with bony geometry, a connection between the tibiofemoral joint contact kinematics and the health of the cartilage at the site of contact has emerged (Anderst and Tashman, 2009; Beveridge et al., 2013). This has been further enhanced with the inclusion of articular cartilage into the models (DeFrate et al., 2004; Li et al., 2006). To date, an underlying but as yet unproven premise is that as the contact location changes after soft tissue injury (i.e. ACL rupture, meniscus tear), the spatial distribution and local characteristics of contact stresses on the articular cartilage also change, to which the tissue cannot readily adapt. To further explore this concept, a more detailed understanding of the regional contact stress patterns that articular cartilage is exposed to in uninjured knees is required. Unfortunately, patient-based studies do not allow for such measures, and most previous cadaveric studies do not mimic the complex multi-directional loading that knees experience in vivo. Added to this complexity is the fact that different regions of the articular cartilage are loaded and unloaded during different phases of activities of daily living (e.g. walking).

The objective of this study was to determine if common contact stress patterns exist on the tibial plateaus of human knees during gait. To satisfy this objective, we developed a novel normalized cross-correlation (NCC) algorithm and applied it to the contact stresses on the tibial plateaus of twelve human cadaveric knees subjected to multi-directional loads mimicking human gait.

MATERIALS AND METHODS

1. Experimental Protocol

Twelve normal human cadaveric knees free of visible evidence of chondral defects, meniscus or ligament damage were used in this study (Table 1). The knees were carefully stripped of all soft tissue except for the capsule, collateral ligaments, cruciate ligaments and menisci. After stripping the knees, they were pinned through the epicondylar axis (Fig. 1c); this ensured that the flexion/extension (FE) axis of the knee was aligned with the FE axis of a load-controlled Stanmore Knee Simulator (University College London, Middlesex, UK) (Fig. 1a). The tibia-fibula complex and the femur were then potted into fixtures with polymethylmethacrylate (PMMA) bone cement. An electronic sensor (Model-4010N, Tekscan Inc., Boston, MA, USA) was placed on the tibial plateaus under the menisci and used to measure the contact stresses (Fig. 1b). The pressure sensor is a 22×34 matrix of sensing elements (sensel), and each sensel has a dimension of 2 mm by 2 mm. It was augmented with plastic tabs and sealed between two layers of Tegaderm adhesive dressing (3M, Minneapolis, MN) and calibrated with loads approximating 20% and 80% of the maximum axial load during gait (Brimacombe et al., 2009). The sensor was fixed to the surface of tibial plateau by suturing the augment tabs (Fig. 1b). Approximately 1 cm incisions were made in the meniscotibial ligaments anteriorly and posteriorly of both menisci, which allowed the sensor to be passed underneath the menisci with minimal disruption of the meniscocapsular attachments. The sensor tabs were then sutured in place using 3-0 Ethibond sutures via the tibial insertion of the anterior cruciate ligament (ACL) and the posteroinferior capsule (Bedi et al., 2010). The sensor position was adjusted to

capture loads across the entire plateau under a 1000 N axial load (Fig. 1d). A custom scribe, which was attached through a drill hole in the cement mantle of the tibial potting block, was used to register positions of the sensor on the tibial plateaus ensuring the sensor was positioned consistently for each knee.

The simulator applied synchronized multidirectional loads (Fig. 2), including axial force, anterior-posterior (AP) force and internal/external (IE) torque to the tibia, while controlling the femur flexion/extension to mimic gait, according to ISO 14243-1. The other degrees of freedom of the tibia (medial-lateral translation, varus/valgus rotation) were uncontrolled (Bedi et al., 2010; Cottrell et al., 2008). To ensure reasonable, physiological joint kinematics, reflective markers were rigidly attached to the femoral and tibial fixtures for a sub-set of five knees (Fig. 1a), and their positions relative to the bone were registered with a 3D digitizer (accuracy: 0.23 mm) (MicroScribe; Immersion, San Jose, California). Anatomic landmarks (femoral epicondyles, medial/lateral edges of tibial plateau, tibial spine, etc.) were identified using the 3D digitizer to define the reference frames that describe the motion of the femur relative to the tibia (Wang and Zheng, 2010). The motion data were recorded at 50 Hz by a motion capture system (MotionAnalysis Inc., CA) and the normal contact stress was collected by a Tekscan sensor at 100 Hz. Twenty gait cycles were collected from each knee to ensure the sensor and the knee simulator reached steady state (Cottrell et al., 2008).

2. Contact Stress Pattern within Each Knee

To normalize the location of contact stress to individual tibia plateau geometry, the stress maps were aligned to the center of each meniscus and uniformly scaled based on the meniscus size. The meniscus was approximated by fitting a circle to the manually selected points on the periphery of each meniscus. This method was validated (medial $r^2 = 0.68$, lateral $r^2 = 0.72$, $p < 0.01$, 5 knees) by comparing the radius of the best fitting circle to that measured from 3D meniscus models segmented from MR images (3D CUBE scan, voxel size: $0.3 \times 0.3 \times 0.6 \text{ mm}^3$) (Gold et al., 2007). The raw contact stress data at each sensel was then low-pass filtered (4th order zero-lag low-pass Butterworth) with a cut-off frequency of 6 Hz to remove high-frequency noise. The degree of similarity between the stress patterns of any two sensels was determined using cross-correlation, which has been widely used for pattern recognition in computer vision (Nakhmani and Tannenbaum, 2013). To remove the effect of contact stress magnitude on the pattern recognition algorithm, a normalized cross-correlation (NCC) algorithm was used (eq. 1). A custom MATLAB program (Mathworks Inc, Natick, MA) was used for data analysis.

$$NCC = \frac{\sum_{t=u}^{t_N=u+N-1} (f(t) - \bar{f}_u)(\tau(t-u) - \bar{\tau})}{\sqrt{\sum_{t=u}^{t_N=u+N-1} (f(t) - \bar{f}_u)^2 \sum_{t=u}^{t_N=u+N-1} (\tau(t-u) - \bar{\tau})^2}} \quad (1)$$

where t is the frame number, N is the total number of frames during a gait cycle ($N = 200$), u is the time-shift, f is the function describing the pattern of interest (here denotes the contact stress profile at a comparison sensel- $S_{k,l}$, Fig. 3a), $\bar{f}_u$ is the mean of the current time window, τ is the template function (here denotes the contact stress profile at the template sensel- $S_{i,j}$), and $\bar{\tau}$ is the mean of the current template function.

The NCC was used as a metric of similarity in contact stress profile shape between any two sensels within each knee ($0 \leq NCC \leq 1$, 0-no match, 1-identical). Using the algorithm described below, sensels with the NCC values greater than a pre-selected threshold (i.e. 0.93) were identified and grouped together. Briefly, each sensel was assigned two properties: pattern ID and characteristic NCC, the latter being the maximum NCC value

between itself and the previous sensels (Fig. 3a). At the beginning of the algorithm, the first sensel in the matrix was taken as the template sensel ($S_{i,j}$) with an initial pattern ID of 1 and characteristic NCC value of 0. The pattern ID and character NCC were then iteratively updated by calculating the NCC between the template sensel and all remaining comparison sensels ($S_{k,l}$) (Fig. 3a). The comparison sensel was grouped with the current template if its NCC was greater than the threshold (Fig. 2b) and greater than the NCCs with previous template sensels. Once all remaining sensels were compared to the current template, the next sensel in the sensel matrix was taken as the current template and the comparison process was repeated. A series of piecewise comparisons were performed to determine the pattern IDs of all sensels. Pseudo code for the comparisons is given in Appendix-i. Once the NCC for each sensel across the tibial plateaus of each cadaveric knee was calculated, sensels with similar stress profiles were identified and assigned a unique pattern ID (Fig. 3c). For each pattern, an average profile (shape of contact stress during gait) was calculated and used to represent the characteristic contact stress profile of this sensel group. To reduce the number of trivial patterns, we only report patterns which include at least 8 member sensels.

3. Common Contact Stress Patterns among Knees

The characteristic contact stress profiles of each knee were compared between different knees to determine if common patterns existed by using the normalized cross correlation algorithm. Two criteria were used to identify common patterns: occur at the same location and with NCC value greater than the pre-selected threshold (Fig. 4). To assess the profiles of common contact stress patterns between knees, each sensel was assigned a weight based on

the number of knees sharing the same pattern at that sensel location ($w_i = N_i / \sum_{i=1}^n N_i$, where n denotes the total number of member sensels, N_i denotes the number of knees at sensel- i). By using this method, the common contact stress profile was represented by a weighted mean and standard deviation of individual contact stress profiles of all member sensels, calculated as

$$\bar{x}_w = \sum_{i=1}^n w_i \bar{x}_i \quad (2)$$

$$\sigma_w = \sqrt{\frac{\sum_{i=1}^n w_i (\bar{x}_i - \bar{x}_w)^2}{(n-1) \sum_{i=1}^n w_i}} \quad (3)$$

where $\bar{x}_w$ and σ_w denote the weighted mean and standard deviation of the common profile, and $\bar{x}_i$ is the mean individual profile at sensel- i (average of individual knees at sensel- i).

RESULTS

The tibiofemoral kinematics of cadaveric knees was computed as the motion of the femur relative to the tibia (Fig. 5). It was compared to the in vivo knee motion during stance phase previously reported by Kozanek et al. using dual fluoroscopic technique (Kozanek et al., 2009) and by Wang et al. using skin markers (Wang et al., 2013). To minimize the variances in reference position between the current study and that reported in literature, the kinematic components were normalized to their values at 0% of gait. In general, the kinematics of our cadaveric knees resembled in vivo kinematics of Kozanek et al. study; while differences did exist in flexion/extension (FE) and internal/external (IE) profiles, the values reported in the current study were consistent with those by (Wang et al., 2013).

Multiple common contact stress patterns were found across 12 knees. Nine to twelve knees shared the same pattern at the posterior aspect of the medial tibial plateau (*pattern-6*, Fig 6). The contact stress pattern consisted of a single peak with an average magnitude of 1.30 ± 0.40 MPa (mean $\pm$ SD) during the stance phase of gait, which corresponded to the timing of the first axial force peak during normal gait (~14% of the gait cycle). Another prominent pattern was found at the central-posterior aspect of the lateral tibial plateau from 8~11 knees (*pattern-5*). It had two peaks that corresponded to the timing of two peaks of applied axial forces; the first and second peak stresses were 1.66 ± 0.62 MPa and 1.75 ± 0.75 MPa respectively. Finally, a third strongest pattern was found at the anterior aspect of the cartilage-to-cartilage contact region on the medial plateau (*pattern-7*), it consisted of two peaks with the second one significantly higher than the first. There were several less strong patterns located at various locations on tibial plateaus (*pattern 1-4, 7*). Although the number of knees sharing the same pattern changes with the pre-selected correlation thresholds, the identification of the most prominent patterns are unaffected (results for threshold at 0.90, 0.93, 0.94, 0.95 were shown in Appendix ii).

DISCUSSION

In this study, we identified common contact stress patterns on tibial plateau surfaces of 12 human cadaveric knees during simulated gait by using a novel normalized cross correlation algorithm. Seven recurring contact stress patterns were found on the tibial plateaus. Two of them were most prominent and located at posterior aspect of the medial plateau and central-posterior aspect of the lateral plateau, respectively. Since the characteristic contact stress profiles represents the weighted average (eq. 2) of all the sensels that share the common pattern, the peak stresses in the current study are much lower than those in our previous study (Bedi et al., 2010). It should be noted that the average peak contact stresses across the entire plateau, are within the range of that previously reported.

On the medial tibial plateau, a single-peak contact stress pattern was located near the posterior horn of the medial meniscus. The peak stress occurred at 14–18% of the gait cycle suggesting that the medial meniscus consistently distributes high joint load during the early phase of stance. Another prominent pattern was located at the central-posterior (*Pattern-5*) aspect of the lateral tibial plateau which is partially covered by the posterior horn of lateral meniscus. The pattern consisted of two peaks which occurred at 14% and 45% of the gait cycle corresponding to the peaks of axial loading. This finding suggests the lateral meniscus provides consistent load distribution during both the early and late phase of stance. The different roles of the medial and lateral menisci are most likely due to differences in meniscal attachment and plateau surfaces. The elongated “C”- shaped medial meniscus has attachments to the medial collateral ligament and joint capsule in addition to the root attachments to the tibial plateau. On the other hand, the lateral meniscus is more circular in shape, relatively smaller in size than the medial meniscus, and it has no attachments to the lateral collateral ligament or joint capsule. Coupled with the convex surface of the lateral tibial plateau, the lateral meniscus is more mobile than its medial counterpart (Renstrom and Johnson, 1990). It can be retracted with the femoral condyle for load transmission and joint stabilization during the late phase of stance when the knee approaches terminal extension. Moreover, according to a kinematic study by Koo and Andriacchi (Koo and Andriacchi, 2008), the knee joint center of rotation is predominantly on the lateral side (lateral pivot) during normal walking. That indicated a greater anterior excursion of the medial femoral condyle on the tibial plateau surface than the lateral condyle at the later phase of stance, which may separate it from the posterior aspect of the medial meniscus. Of note, both prominent common patterns (*pattern-5, 6*) were located in the inner half region of the tibial plateau (close to the tibial spine), where the cartilage is thicker than that of the peripheral regions (Andriacchi et al., 2009; Li et al., 2005). Following ACL or meniscus injuries, the

local contact stress patterns may shift or be altered following changes in joint kinematics. These predictable changes may lead to deleterious loading that the underlying cartilage cannot quickly adapt to; thus could predispose the cartilage to accelerated damage.

There were several limitations in this study. First, we selected a NCC threshold of 0.93 as the criteria for determining similarity. Since there is no standard in the literature that recommends an appropriate threshold, we computed the contact stress patterns at different threshold values (0.90, 0.93, 0.94 and 0.95; see Appendix). Different thresholds still resulted in the same patterns located in similar regions, suggesting that the NCC algorithm is not highly sensitive to the threshold. Second, our model does not take into account knee-to-knee variability in joint forces for example caused by variations in body weight, walking speed and muscle activation), neither do we control for medial-lateral translation or varus/valgus rotation.

In summary, this study presented a method to determine common dynamic contact stress patterns within the tibiofemoral joint under simulated gait load. Two prominent common patterns were found in regions close to the posterior horns of menisci. This novel approach may better identify abnormalities in cartilage contact mechanics in order to understand the mechanical pathways leading to post-traumatic osteoarthritis. In future studies, we will investigate the alterations in knee joint contact stress patterns after ACL injuries or/and meniscus tears.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Experimental setup for measuring the dynamic tibiofemoral joint contact stresses using a cadaveric model

(a) The femur and tibia were potted into fixtures with polymethylmethacrylate bone cement and mounted on a Stanmore knee simulator, the simulator applied dynamic axial forces, anterior-posterior (AP) forces, internal/external (IE) torques, and flexion/extension angle to mimic normal gait. (b) A Tekscan™ pressure sensor was augmented with plastic tabs and sealed between two layers of adhesive dressing. It was then placed on the tibial plateau by suturing the tabs to anterior cruciate ligament and posterior capsule. (c) Position of the femoral epicondyles in x-ray. (d) The contact stresses on the tibial plateau under 1000 N axial load.

Figure 2. Inputs of dynamic knee simulator

The simulator applies flexion/extension rotation, anterior-posterior force, axial force and internal/external torque. The forces and torque were applied on the tibia, and the flexion and extension was applied on the femur. The other degrees of freedom – varus/valgus rotation and medial-lateral translation were not controlled.

Figure 3. The process of finding contact stress patterns on the tibial plateaus within each knee using a normalized cross correlation (NCC) algorithm

(a) *First row* – starting with the first sensel (green square) as the template, all of the remaining sensels (white square) are individually compared to the template. *Second row* – the next sensel is then taken as the template and the above process is repeated. This process is repeated until the contact stress profiles of all sensels are compared. (b) Two representative scenarios are shown: first, for a comparison sensel whose contact stress pattern is considered different from the template, the NCC is smaller than the threshold value and is therefore not grouped with the template sensel; second, for a comparison sensel with a similar contact stress profile as the template, thus is grouped with template sensel and

assigned the same pattern ID. (c) After completing the comparisons, sensels with similar contact stress profiles are grouped together and assigned a unique pattern ID (same color).

Figure 4. Schematic representation depicting the process for identifying the common contact stress patterns among different knees

The characteristic contact stress profiles within each knee are identified. The profiles are compared between the knees using normalized cross correlation (NCC). To consider two individual profiles from different knees as a common pattern, they must meet two criteria: first, they are at the same location; second, the NCC must be greater than the threshold. For the example shown in the plot, groups 2, 5 satisfied these two criteria, thus considered common patterns between these two knees. The process was repeated until all knees were compared.

Figure 5. Showing 6 DOFs of tibiofemoral kinematics of cadaveric knees during the stance phase of a simulated gait cycle

The kinematics here represents the motion of femur relative to tibia. Shaded area stands for mean $\pm$ a standard deviation. All values are normalized to the values at 0% gait. The results are compared to in vivo kinematics from Kozanek et al. (solid blue) (Kozanek et al., 2009) and Wang et al. (dash red) (Wang et al., 2013).

Figure 6. The location and contact stress profiles of the common patterns found on the tibial plateaus of intact knees

The characteristic profile stands for the weighted mean $\pm$ standard derivation of all sensels sharing the same pattern. Colors in heat map stand for the number of knees sharing this pattern at each sensel location. Seven consistent regional patterns were found, among them two most prominent contact stress patterns were shared by 9 to 12 of all the knees. One pattern was located at the posterior aspect of the medial tibial plateau and had a single peak stress that occurred during the early stance phase (*pattern-6*). Another pattern was located at the central-posterior aspects of the lateral plateau and consisted of two peak stresses coincident with the timing of peak axial force at early and late stance (*pattern-5*).

Table 1

Demographics of the knee joint donors.

Knee #	Side	Sex	Age	Weight (kg)	Height (m)
1	R	F	39	63.5	1.68
2	L	M	53	90.7	1.73
3	R	F	56	104.3	1.70
4	R	M	58	90.3	1.78
5	R	F	62	40.8	1.63
6	L	F	41	45.4	1.60
7	R	M	74	57.2	1.73
8	L	M	58	90.3	1.78
9	L	F	62	40.8	1.63
10	R	M	64	49.9	1.80
11	L	F	56	75.7	1.57
12	L	M	55	77.1	1.80
Average $\pm$ SD			56.5 $\pm$ 9.5	68.8 $\pm$ 22.2	1.70 $\pm$ 0.08