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Instability-Associated Changes in Contact Stress and Contact Stress Rates in Human Cadaveric Ankles

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Abstract

Background—Intra-articular fractures can result in articular surface incongruity and joint instability, both of which can lead to post-traumatic osteoarthritis. The purpose of this study was to quantify changes in contact stresses and contact stress rates in incongruous human cadaveric ankles that were either stable or unstable. It was hypothesized that joint instability, superimposed on articular incongruity, would cause significant increases in contact stresses and contact stress rates.

Methods—Intact human cadaveric ankles were subjected to quasi-physiologic stance-phase motion and loading and instantaneous contact stresses were captured at 132 Hz. The anterior one-third of the distal tibia was displaced proximally by 2.0 mm, and testing was repeated. Anterior/posterior forces were modulated during loading to cause incongruous ankles to either remain stable or become unstable during loading. Transient contact stresses and contact stress rates were measured for seven ankles under intact, stable-incongruous, and unstable-incongruous conditions. Peak and 95th percentile values of contact stress and contact stress rates for all three conditions were compared using paired t-tests to determine the pathomechanical effects incongruity and instability.

Results—The addition of instability caused 95th percentile and peak contact stresses to increase between 20% and 25% in unstable-incongruous specimens compared to stable-incongruous specimens. In contrast, the addition of instability increased the magnitude of peak positive and peak negative contact stress rates by 115% to 170% in unstable-incongruous specimens compared to stable incongruous specimens. Likewise, 95th percentile contact stress rates increased 112% in unstable-incongruous specimens compared to stable-incongruous specimens.

Conclusions—In incongruous human cadaveric ankles, instability superimposed on an existing articular surface incongruity caused disproportionate increases in contact stress rates compared to increases in contact stresses.

Clinical Relevance—Cartilage injury, chondrocyte injury, and chondrocyte biosynthetic function have been shown to be particularly sensitive to stress rate. Instability-associated increases in contact stress rates may be important pathomechanical factors that lead to post-traumatic osteoarthritis.

Introduction

Injury-associated articular instability has been closely associated with post-traumatic osteoarthritis¹⁻⁵. Instability can result from residual articular surface incongruity, from residual ligamentous insufficiency, or both. Patients frequently complain of pain or the affected joint “giving way”. The symptoms often occur abruptly and are frequently activity-specific.

While there is substantial clinical evidence linking instability to post-traumatic osteoarthritis, the mechanism(s) by which instability-associated pathomechanical changes cause arthritis are not well understood. It is likely that abrupt changes in the transarticular loading environment play an important etiologic role, but measuring transient contact stresses has been technically difficult in articular injury models. Recently, transient stress transducers have been successfully used to investigate changes in contact stresses and contact stress rates in stable human cadaveric ankles, with simulated incongruity of either the posterior malleolus or anterolateral distal tibia, loaded through a complete stance-phase range of motion⁶⁻⁸. Abnormalities of loading rate are known to be an important mechanical stimulus of chondrocyte metabolic dysfunction, and a determinant of cartilage injury⁹⁻¹¹.

While incongruity and instability are both thought to predispose to post-traumatic arthritis, the relative contribution of these two distinct pathologic phenomena to changes in cartilage contact stress have not been determined. Both phenomena can coexist after an intra-articular fracture, with unstable motion arising from an incongruous reduction. The purpose of this study was to quantify baseline abnormalities in contact stresses and contact stress rates associated with a step-off incongruity (using the human ankle as a model), and then subsequently to measure further abnormalities in contact stresses and contact stress rates in the same specimens when subjected to a superimposed subluxation. It was hypothesized that an instability event occurring in an already-incongruous joint would substantially increase baseline incongruity-associated abnormalities in contact stresses and contact stress rates.

Methods

Seven fresh frozen human cadaveric foot specimens (donor ages 44 to 92 years) were prepared and mounted into an MTS machine (MTS Corporation, Eden Prairie, MN) using an established protocol^{6,7}. Specimens were loaded via a custom-fabricated testing fixture that allowed physiologic motion in the ankle, hindfoot, and midfoot joints (Fig. 1). Ankles had to demonstrate at least 20 degrees of both plantar and dorsiflexion, and had to be free of any obvious morphologic abnormalities. Anterior and posterior capsulotomies were performed to allow insertion of the stress transducer. Previous studies have demonstrated no changes in ankle kinematics resulting from this preparation sequence⁶. Sagittal translation between the tibia and talus was measured with a linear potentiometer.

A custom-designed ankle contact stress transducer (5033, TekScan Inc., Boston, MA) was used to measure the intra-articular contact stress distribution during motion. The TekScan insert consisted of a thin mylar sheet that encased two orthogonal arrays of parallel electrical conductors, separated by a piezoresistive elastomer layer. The electrical resistance at any site (sensel) in the row/column intersection grid varied according to the instantaneous local contact stress. The grid of 46×32 (1472) sensels spanned a 27 mm (medial to lateral) by 39 mm (anterior to posterior) surface, yielding a spatial resolution of 0.694 mm^2 per sensel. The sensors sampled contact stresses at 132 Hz. Each sensor was calibrated on a sensel-by-sensel basis by applying a known uniform load and determining a calibration factor for each individual sensel.

Pilot studies determined that full-width 2.0 mm coronal step-offs of the anterior one-third of the distal tibia, combined with transection of the anterior talofibular ligament, resulted in anterior subluxation of the talus into the anterior distal tibial defect during normal ankle plantar/

dorsiflexion in axially loaded specimens (Fig. 2). Therefore, to prevent spontaneous anterior talar subluxation in incongruous ankles, a constant anteriorly-directed 30 N stabilization force was applied to the tibia throughout the entire testing cycle by a pneumatic cylinder (Airpot Corporation, Norwalk CT) (Figs. 2 and 3). Subluxation was induced in step-off conditions by applying a separate posteriorly-directed subluxation pulse to the tibia via a second pneumatic cylinder. Subluxation pulses were ramped linearly from 0 N to their specified magnitude and then back down to 0 N, between the 45% (0.9 sec) time point and 70% (1.4 sec) time point in the duty cycle, corresponding to the heel-off phase of gait (Fig. 3).

Initially, all specimens were loaded intact over a two-second period, during which the ankle was rotated through stance-phase range of motion, beginning at 10 degrees plantarflexion, coursing to 15 degrees plantarflexion, reversing to 15 degrees dorsiflexion, and finally coursing back to 10 degrees plantarflexion at toff (Fig. 3). Contact stress distributions were sampled at 132 Hz. All specimens were axially loaded to 300 N throughout the entire duty cycle. The 30 N anteriorly-directed stabilization force was applied and held constant throughout the entire test. Subsequently, subluxation pulses between 0 N and 120 N, in 20 N increments, were randomly applied. Each subluxation pulse magnitude was applied during two separate sets of tests to establish the repeatability of testing. No subluxation occurred in any of the intact specimens over this entire range of subluxation pulses.

The anterior one-third of the distal tibia was then osteotomized using a custom cutting guide. Fragments were precisely displaced proximally 2.0 mm and were rigidly stabilized with an anterior-to-posterior lag bolt (Fig. 2). The anterior talofibular ligament was cut. The testing sequence was repeated under identical loading and motion conditions with random application of subluxation pulses between 0 N and 120 N (each 20 N increment of subluxation pulse was randomly applied twice to confirm the repeatability of testing). All seven specimens subluxated once a specimen-specific subluxation pulse magnitude was exceeded. The lowest-magnitude subluxation pulse that caused the specimen to subluxate was defined as that specimen's instability threshold. The trial with a subluxation pulse 20 N less than the instability threshold was defined as that specimen's metastable limit. For all specimens, the magnitude of the instability threshold and metastable limit did not change when the testing was repeated. Therefore, each specimen had its contact stress distribution history measured both intact and subsequently with a 2 mm step-off of the anterior distal tibia while subjected identical motion and loading except for an additional 20 N of posteriorly-directed force applied to the tibia that distinguished the instability threshold from the metastable limit. These loading parameters defined several conditions: intact specimens subjected to the metastable limit subluxation pulse, intact specimens subjected to the instability threshold subluxation pulse, stable-incongruous specimens (those with the 2.0 mm step-off, subjected to the metastable limit subluxation pulse, that remained stable), and unstable-incongruous specimens (those with the 2.0 mm step-off, subjected to the instability threshold subluxation pulse, that subluxated).

Time-variant contact stress distributions for the intact, stable-incongruous, and unstable-incongruous conditions were collected for all seven ankles. Contact stress rates were calculated from instantaneous mask-filtered contact stress values using a Lagrange four-point central differencing formula¹². Peak and 95th percentile values of contact stresses and contact stress rates were determined for each specimen. Please refer to the electronic appendix for detailed data analysis.

To spatially characterize the incongruity- and instability-associated abnormalities in contact stresses and contact stress rates, individual specimen contour plots of contact stresses and contact stress rates were made for the intact, stable-incongruous, and unstable-incongruous conditions at each time frame. Contour plots for each of the conditions could then be compared

to map regions of maximum contact stress and contact stress rates under intact, stable-incongruous, and unstable-incongruous conditions.

Statistical Methods

Individual values of peak global contact stress, 95th percentile global contact stress, peak global positive contact stress rate, peak global negative contact stress rate, and 95th percentile distribution window of contact stress rate were determined for each of the seven specimens for the intact, stable-incongruous, and unstable-incongruous conditions. Individual specimen values for each parameter for the stable-incongruous condition were compared to corresponding values from the intact condition subjected to the metastable limit subluxation pulse using a paired t-test. Likewise, individual specimen values for each parameter from the unstable-incongruous condition were compared to the corresponding values for the intact condition subjected to the instability threshold subluxation pulse using a paired t-test. Finally, the individual specimen values from the stable-incongruous condition and the unstable-incongruous condition were compared using a paired t-test.

Results

Tibiotalar displacement increased linearly ($R^2 > 0.95$) over the entire range of subluxation pulses (0 to 120 N), without any subluxation, in the intact specimens (Fig. 4). Incongruous specimens demonstrated a sigmoidal pulse-displacement relationship, with subluxation resulting from pulses ranging from 40 N to 80 N over the seven specimens (Fig. 4). The peak tibial displacement averaged 2.8 ± 0.8 mm in the stable-incongruous condition and 8.2 ± 3.5 mm in the unstable-incongruous condition.

Peak and 95th percentile contact stresses in intact specimens subjected to both subluxation pulse levels (metastable limit pulse and instability threshold pulse) were identical, measuring 2.0 ± 0.5 MPa and 1.6 ± 0.4 MPa, respectively (Table 1). Peak contact stresses increased to 2.4 ± 0.3 MPa in the stable-incongruous condition and to 3.0 ± 0.4 MPa in the unstable-incongruous condition ($p = 0.04$ and 0.01 respectively compared to corresponding intact values). Likewise, 95th percentile contact stresses increased to 1.9 ± 0.3 MPa in the stable-incongruous condition and to 2.3 ± 0.4 MPa in the unstable incongruous condition ($p = 0.06$ and 0.02 respectively compared to corresponding intact values). Therefore, the superimposed instability event caused peak stresses to increase 25% ($p = 0.06$) and 95th percentile contact stresses to increase 21% ($p = 0.02$) in incongruous specimens that subluxated, compared to incongruous ankles that remained stable (Fig. 5).

Global peak positive contact stress rates in intact specimens measured 32.7 ± 7.6 MPa/sec and 41.8 ± 17.2 MPa/sec in specimens subjected to the metastable limit and instability threshold subluxation pulses respectively. Corresponding global peak negative contact stress rates in intact specimens subjected to the two pulse levels measured -36.7 ± 15.3 MPa/sec and -41.3 ± 15.1 MPa/sec, respectively (Table 2). The magnitude of global peak positive and peak negative contact stress rates increased in the stable-incongruous condition, to 61.3 ± 17.7 MPa/sec and -50.0 ± 13.5 MPa/sec ($p = 0.001$ and 0.02 respectively compared to corresponding intact values). In the unstable-incongruous condition, global peak positive contact stress rates increased to 131.6 ± 20.1 MPa/sec and the global peak negative contact stress rates decreased to -134.9 ± 36.8 MPa/sec ($p = 0.0004$ and 0.001 respectively compared to corresponding intact values). Therefore, superimposition of an instability event in incongruous specimens increased global peak positive contact stress rates by 115% ($p = 0.001$) and increased global peak negative contact stress rates 170% ($p = 0.001$), compared to incongruous specimens that remained stable (Fig. 5).

In the intact condition, the 95th percentile distribution windows of contact stress rates were 25.4 ± 6.8 MPa/sec and 27.2 ± 7.8 MPa/sec, in specimens subjected to the two subluxation pulse magnitudes. This value increased to 34.3 ± 6.4 MPa/sec in the stable-incongruous condition and to 72.3 ± 15.0 MPa/sec in the unstable-incongruous condition ($p = 0.003$ and 0.0003 respectively compared to corresponding intact values) (Table 2). Therefore, the instability event caused the 95th percentile distribution window of contact stress rates to increase by 112% compared to incongruous specimens that remained stable ($p = 0.001$) (Fig. 5).

Representative contour plots of contact stresses and contact stress rates, for three test conditions (intact condition subjected to the instability threshold pulse, stable-incongruous, and unstable-incongruous), at four time points through the simulated stance phase, are illustrative of the instability-associated abnormalities (Fig. 6). The first time point was one sampling frame (1/132nd of a second) prior to application of the subluxation pulse (Figure 6a). The second time point corresponded to the onset of subluxation in the unstable-incongruous condition (Fig. 6b). The third time point corresponded to the frame of maximum contact stress magnitude on the anterior displaced tibial fragment in the unstable-incongruous condition (Fig. 6c). This occurred four to five time frames (0.030 to 0.038 seconds) subsequent to the second time point in all seven specimens. The fourth time point corresponded to the frame when the subluxation pulse had returned to 0 N (Fig. 6d).

Prior to applying the subluxation pulse, contact stresses and contact stress rates were low-magnitude and homogenous for all three conditions. For the stable-incongruous and unstable-incongruous conditions, the delineation of stresses at the osteotomy border was evident (Fig. 6a). At the onset of subluxation for the unstable-incongruous condition, contact stress peaks moved anteriorly and were concentrated along the osteotomy border in both incongruous conditions (Fig. 6b). For the intact and stable-incongruous conditions, contact stress rates remained low-magnitude and homogenous. In contrast, a sharp focus of negative contact stress rate occurred along the posterior lip of the osteotomy in the unstable-incongruous condition, presumably due to the talus “falling off” this region of cartilage as it subluxated anteriorly (Fig. 6b). At the instant of maximum subluxation (Fig. 6c), peak contact stresses and contact stress rates in the intact and stable-incongruous conditions were essentially unchanged compared to corresponding values at the onset of subluxation (four frames earlier). In contrast, for the unstable-incongruous condition, a focus of peak contact stress on the osteotomized fragment is evident. Likewise, a sharp focus of elevated positive contact stress rates was evident on the anterior fragment as the talus impacted this region during subluxation. The corresponding sharp focus of negative contact stress rates along the posterior lip of the osteotomy was still evident. After the subluxation pulse had returned to baseline, contact stresses and contact stress rates returned to the low-magnitude and homogenous levels measured prior to subluxation for all test conditions with the talus reduced under the intact posterior two-thirds of the distal tibia (Fig. 6d).

Closer temporal resolution of the anterior subluxation of the talus in the unstable-incongruous condition is depicted in four sequential frame-by-frame contour plots (a 0.030 second time span) of contact stress and contact stress rates (Figure 7). Just prior to subluxation, contact stresses are concentrated on the posterior border of the osteotomy. The focus of stress contacting the anterior fragment can be seen rapidly developing over the subsequent 3 frames (0.023 second span) (Fig. 7a). Corresponding changes in contact stress rates during subluxation clearly demonstrate high-magnitude negative values as the talus subluxates off the posterior border of the osteotomy, and rapidly increasing positive contact stress rates on the anterior fragment, as the talus collides with this fragment during subluxation (Fig. 7b).

Discussion

It was hypothesized that instability would appreciably exacerbate the elevations of contact stress and contact stress rate elevations otherwise existing for a step-off incongruity. Compared to the stable-incongruous condition, peak and 95th percentile contact stresses increased by approximately 20% to 25%, for the unstable-incongruous condition. In contrast, instability-associated increases in peak positive and negative contact stress rates were 115% and 170%, respectively, for the unstable-incongruous condition, as compared to the stable-incongruous condition. Likewise, the 95th percentile contact stress rates increased by 112% in the unstable-incongruous condition compared to the stable-incongruous condition.

It is unlikely that these increases in contact stresses and contact stress rates in the unstable-incongruous condition compared to the stable-incongruous condition resulted simply from algebraic superposition of an additional 20 N of anteriorly directed force, since the corresponding difference in the resultant force vector (vector addition of the axial force and the anterior/posterior force) between the unstable-incongruous condition and the stable-incongruous condition was less than 4 N. Secondly, for the intact conditions, global peak contact stress and 95th percentile contact stress measurements were identical in specimens subjected to the metastable-limit and instability-threshold subluxation pulse magnitudes. Likewise, peak positive contact stress rates, peak negative contact stress rates, and 95th percentile distribution windows of contact stress rate increased by only 27%, 13%, and 8%, respectively under intact conditions subjected to the instability threshold pulse compared to the metastable limit pulse. Rather, the differences in contact stresses and contact stress rates between the unstable-incongruous and stable-incongruous conditions were instead due to the subluxation event. The present model vividly demonstrates that a superimposed subluxation event in an already-incongruous joint most significantly increases contact stress rates. Instability-associated increases in contact stress rates were six to eight times greater than instability-associated increases in contact stresses. This observation suggests that injury-associated abnormality of contact stress rates may be an important pathomechanical consideration in unstable joints.

Potential numerical differentiation-associated artifact in contact stress rate calculations was estimated by examining contact stress rate calculations made from tests performed under static loading conditions, for which the contact stress rates should ideally be zero. Under static loading, the 95% distribution window of contact stress rates was three to eight times less than values calculated under experimental conditions. Likewise, peak contact stress rates under static conditions were three to ten times less than experimental conditions. Therefore, compared with the signals of interest, the differentiation-associated artifact introduced in the contact stress rate calculations was low-magnitude, and did not invalidate the differences in stress rates that existed between the different experimental conditions.

The instability event studied in this experiment was admittedly somewhat idiosyncratic. Subphysiologic axial and anterior/posterior loads were applied because consistent fractures occurred in the remaining dome of the distal tibia after the osteotomy was made in specimens subjected to higher axial loads. Increases in contact stress rates could have been falsely elevated by artificially abrupt application of the subluxation pulse. However, the subluxation pulse was ramped to its maximum magnitude over 200 msec (Fig. 3), and the actual subluxation occurred over approximately 20 to 30 msec (Fig. 7), making it unlikely that overly abrupt application of the subluxation pulse affected contact stress rates. Contact stress measurements were mask-filtered to minimize error due to fluctuations of sensel output. These calculations presumably attenuated peak values somewhat, but any such effects would have been similar for all testing conditions.

Acute impact injury¹³⁻¹⁶ and chronic abnormal cartilage stresses resulting from residual articular instability and incongruity¹⁷⁻²⁰ are thought to be the primary injury-associated factors that cause post-traumatic arthritis. Chronic pathologic changes in cartilage stress can result from changes in articular surface congruity and stability. Patients with chronic articular instability, but with presumably normal joint congruity, consistently develop post-traumatic arthritis in the ankle, knee, shoulder, and elbow^{1,3,21,22,23,24}. Patients sustaining tibial plateau fractures, with residual incongruity as great as one centimeter, fared well in 90% of cases, provided that knee alignment and stability were maintained²⁵. In contrast, malaligned and unstable knees in patients sustaining tibial plateau fractures fared poorly regardless of articular congruity^{2,26,27}. Compared to the knee, residual incongruity is much less tolerated in patients sustaining acetabular fractures, with an increase incidence of post-traumatic arthritis in patients with residual incongruity as small as one millimeter^{4,5}. In summary, clinical evidence shows instability is poorly tolerated in all major joints. In contrast, the effect of incongruity is less well known and is more likely joint-specific.

Stresses and deformation in loaded cartilage are particularly sensitive to stress rates^{28,29}. Likewise, cell stress and deformation of individual chondrocytes are also rate-sensitive^{30,31}. Furthermore, the biosynthetic response of chondrocytes is also very stress rate-sensitive. Studies have consistently demonstrated that matrix and DNA synthesis from chondral specimens and individual chondrocytes is dependent on stress rate^{11,32}. Similarly, cartilage matrix damage and chondrocyte death also have been shown to be stress rate-dependent in cartilage injury models. Experimental evidence has consistently shown that osteochondral specimens subjected to pathologic stresses at high stress rates consistently develop overt matrix damage and superficial layer chondrocyte death. In contrast, specimens loaded to similar stresses at lower stress rates had much less matrix damage with full-thickness cell death^{9,10}. In summary, chondrocyte biotransduction appears to be sensitive to local stress rates. Likewise, injury-associated cellular and structural damage within the cartilage interstitium also appears to be exquisitely sensitive to local stress rates. Therefore, the significant increases in contact stress rates, such as those resulting from the instability event in this experiment, may be important pathomechanical factors that lead to post-traumatic arthritis.

In conclusion, instability caused pronounced increases in contact stress rates in human cadaveric ankles with an articular surface step-off. Instability-associated increases in contact stress were significantly less than corresponding increases in contact stress rates. Such instability-associated increases in contact stress rates may play an important role in the mechanical etiology of post-traumatic arthritis.

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Appendix

Detailed data analysis is available with the electronic version of this article, on our web site at jbjs.org (go to the article citation and click on Supplementary Material) and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM).

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Figure 1.

The custom testing fixture applied axial load and directed plantardorsi flexion of the ankle via an MTS. The anterior-posterior forces were applied by two separate pneumatic cylinders. The forefoot and heel were rigidly secured with PMMA allowing unconstrained motion of the ankle, midfoot, and hindfoot.

Figure 2.

The anterior one-third of the distal tibial articular surface was osteotomized and displaced 2.0 mm proximally and secured with a lag bolt to create potentially unstable incongruous specimens. A 30 N anteriorly directed force (grey arrows) had to be applied to the tibia to prevent spontaneous anterior subluxation of the talus during axial loading. To create subluxation, a posteriorly-directed pulse (black arrows) was increased in magnitude until subluxation occurred. The subluxation pulse varied between 0 N and 120 N in 20 N increments and were randomly applied. The smallest subluxation pulse that caused subluxation (large black arrow) was defined as that specimen's specific instability-threshold subluxation pulse. The subluxation pulse 20 N less than the instability-threshold pulse (smaller black arrow) was defined as that specimen's specific metastable-limit subluxation pulse. Intact specimens were subjected to the same anteriorly-directed stabilization forces and posteriorly-directed subluxation pulses.

Figure 3.

Ankles coursed through physiologic motion of the gait cycle. During the heel-off phase of the gait cycle, the posteriorly-directed subluxation pulse was ramped linearly from 0 N to its specified magnitude and back down to 0 N (representing the 45% to 70% phase of the gait cycle).

Tibiotalar Displacement

Figure 4.

Tibiotalar sagittal displacement in intact conditions demonstrated a linear relationship over the entire range of subluxation pulses. Intact specimens were never observed to subluxate. In incongruous conditions, specimens remained stable until the subluxation pulse exceeded a critical limit (instability-threshold) and rapid increases in tibiotalar displacement were measured. In the specimen depicted in the figure, the metastable-limit pulse is 60 N and the instability-threshold pulse is 80 N.

Changes in Contact Stress Paramteres (+/-100% = postive and negative values in Intact)

Figure 5.

Peak and 95th percentile contact stresses and contact stress rates are shown as a percentage of corresponding intact condition values. Both peak and 95th percentile contact stresses in the unstable-incongruous condition were only modestly elevated compared to the stable-incongruous condition. In contrast, instability-associated changes in peak and 95th percentile contact stress rates in the unstable-incongruous condition were substantially elevated compared to the stable-incongruous condition. The data clearly demonstrate that instability had a substantially greater effect on contact stress rates compared to contact stresses in incongruous specimens.

Contact Stress

Contact Stress Rates

Contact Stress

Contact Stress Rates

Figure 6.

Contact stress and contact stress rate contour plots demonstrate feature differences between intact, stable-incongruous, and unstable-incongruous conditions. **Fig. 6a:** Just prior to application of the subluxation pulse, contact stresses and contact stress rates are homogenous in all three conditions. The osteotomy border is clearly delineated in incongruous conditions. **Fig. 6b:** At the onset of subluxation in the unstable-incongruous condition, contact stresses have shifted anteriorly in all conditions with contact stress concentration aligned at the osteotomy border in the incongruous conditions. In the intact and stable-incongruous conditions, contact stress rates are low-magnitude and homogenous. In the unstable-incongruous condition, a sharp focus of negative contact stress rate along the posterior border of the osteotomy is evident (black arrow). **Fig 6c:** At the point of maximum subluxation, the focus of contact stress on the anterior fragment is evident in the unstable-incongruous condition. However, contact stress magnitudes are similar between all three conditions. Contact stress rates remain uniformly low and homogenous in the intact and stable-incongruous conditions. In contrast, a sharp focus of positive contact stress rate is obvious on the anterior fragment with a corresponding focus of negative contact stress rate on the posterior border of the osteotomy in the unstable-incongruous condition. **Fig 6d.** After the subluxation pulse had returned to 0 N, and the unstable-incongruous condition had reduced, contact stresses and contact stress rates had returned to previous homogenous low-level values in all conditions.

Frame 1

Frame 2

Frame 3

Frame 4

Frame 1

Frame 2

Frame 3

Frame 4

Figure 7.

Representative contact stress and contact stress rate contour plots during the subluxation event in the unstable-incongruous condition. **Fig. 7a.** Four consecutive contour plots demonstrate how the talus perches on the posterior border of the osteotomy and subsequently subluxates anteriorly over 0.023 seconds contacting the anterior fragment. **Fig 7b.** Four consecutive contour plots of contact stress rates clearly depict the subluxation event. As the talus subluxates anteriorly, it appears to rapidly unload the posterior border of the osteotomy. High negative contact stress rates are measured along this border. As the talus abruptly contacts the anterior osteotomized fragment, a rapid rise in positive contact stress rate occurs on this fragment.

Table 1

Mean values (range) and standard deviations of 95th percentile and peak contact stress values in intact, stable-incongruous, and unstable-incongruous conditions

Loading Condition	95th Percentile Contact Stress (MPa)	Peak Contact Stress(MPa)
Intact (Metastable-Limit Pulse)	1.6 (1.2 - 2.5) (s.d.= +/- 0.4)	2.0 (1.5 - 3.0) (s.d.= +/- 0.5)
Intact (Instability-Threshold Pulse)	1.6 (1.1 - 2.6) (s.d.= +/- 0.5)	2.0 (1.6 - 3.1) (s.d.= +/- 0.5)
Stable -Incongruous	1.9 (1.6 - 2.3) (s.d.= +/- 0.3)	2.4 (2.2 - 2.8) (s.d.= +/- 0.3)
Unstable-Incongruous	2.3 (1.7 - 2.8) (s.d.= +/- 0.4)	3.0 (2.4 - 3.5) (s.d.= +/- 0.4)

Table 2

Mean values (range) and standard deviations of peak positive, peak negative, and 95th percentile distribution width of contact stress rate values in intact, stable-incongruous, and unstable-incongruous conditions

Loading Condition	95 th Percentile Distribution Width of Contact Stress Rate (MPa/sec)	Peak Positive Contact Stress Rate (MPa/sec)	Peak Negative Contact Stress Rate (MPa/sec)
Intact (Metastable-Limit Pulse)	25.4 (19.6 - 37.9) (s.d.= +/- 6.8)	32.7 (24.2 - 42.7) (s.d.= +/- 07.6)	-36.7 (-23.3 - -68.0) (s.d.= +/- 15.3)
Intact (Instability-Threshold Pulse)	27.2 (20.7 - 42.7) (s.d.= +/- 7.8)	41.8 (23.1 - 69.7) (s.d.= +/- 17.2)	-41.3 (-24.3 - -68.9) (s.d.= +/- 15.1)
Stable-Incongruous	34.3 (27.4 - 44.1) (s.d.= +/- 6.4)	61.3 (40.4 - 87.4) (s.d.= +/- 17.7)	-50.0 (-34.6 - -69.8) (s.d.= +/- 13.5)
Unstable-Incongruous	72.3 (53.0 - 96.4) (s.d.= +/- 15.0)	131.6 (104.0 - 156.8) (s.d.= +/- 20.1)	-134.9 (-85.2 - -188.1) (s.d.= +/- 36.8)